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Amorphous Silicon Photovoltaic Manufacturing Technology – Phase 2A

Annual Subcontract Report
1 May 1993 – 30 April 1994

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PREFACE

This is the second Annual Technical Progress Report for the program titled "Amorphous Silicon Photovoltaic Manufacturing Technology - Phase 2A", funded under National Renewable Energy Laboratory (NREL) subcontract No. ZM-2-11040-06. This report describes the work done in the period from May 1, 1993 to April 30, 1994.

This program is part of the Photovoltaic Manufacturing Technology (PVMaT) project, Phase 2A, which address problems that are process-specific and are generally unique to a technology. Utility Power Group (UPG) and Advanced Photovoltaic Systems, Inc. (APS) are engaged in a unique collaborative effort which integrates the strengths of both organizations, and its implementation will help to ensure that the U.S. PV industry enhances its world leadership role in the commercial development and manufacture of photovoltaic systems. The synergistic relationship that exists between UPG and APS is possible due to the similarities of the PV products produced by the two organizations. Both UPG and APS utilize glass superstrates as the structural base for their PV modules, both have chosen amorphous silicon as the semiconductor material in the PV cell, and both have demonstrated the manufacturability and reliability of their PV products in an electric utility setting as demonstrated by the Photovoltaics for Utility Scale Applications (PVUSA) project. Many of the innovations developed by UPG for its PVUSA Emerging Module Technology (EMT) array were subsequently incorporated by APS into their PVUSA Utility Scale (US) system. The innovations in manufacturing technology of UPG coupled with the large capacity manufacturing facility of APS serve to form the basis for this collaborative PVMaT effort.

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EXECUTIVE SUMMARY

Utility Power Group (UPG), and its lower-tier subcontractor, Advanced Photovoltaic Systems, Inc. (APS) have conducted efforts in developing their manufacturing lines. UPG has focused on the automation of encapsulation and termination processes developed in Phase I. APS has focused on completion of the encapsulation and module design tasks, while continuing the process and quality control and automation projects. The goal is to produce 55 watt (stabilized) EP50 modules in a new facility.

In the APS Trenton EUREKA manufacturing facility, APS has:

- Developed high throughput lamination procedures;
- Optimized existing module designs;
- Developed new module designs for architectural applications;
- Developed enhanced deposition parameter control;
- Designed equipment required to manufacture new EUREKA modules developed during Phase II;
- Improved uniformity of thin-film materials deposition; and
- Improved the stabilized power output of the APS EP50 EUREKA module to 55 watts.

In the APS Fairfield EUREKA manufacturing facility, APS has:

- Introduced the new products developed under Phase I into the APS Fairfield EUREKA module production line;
- Increased the extent of automation in the production line;
- Introduced Statistical Process Control to the module production line; and
- Transferred progress made in the APS Trenton facility into the APS Fairfield facility.

Task 7 POWERGLASS Module Encapsulation

Utility Power Group has evaluated the advanced substitute materials and processes for thin-film module encapsulation identified in Task 1. All materials were evaluated in terms of the level of environmental protection provided to the thin-film module, manufacturing cost reduction, and PV system related factors such as the effect on module weight and module mounting within a panel or sub-array. UPG has designed an automated encapsulation station utilizing the advanced processing method and material identified in Task 1 and anticipates delivery of this equipment before the end of Phase 2.

UPG has applied the advanced encapsulation material to prototype modules utilizing tempered substrate glass for qualification (SERI/TR-213-3624) testing. In addition, UPG has investigated the use of alternative materials as PV module superstrates which will not require heat tempering.

The goal of this task was to obtain a cost reduction of 50% (cumulative) in the UPG encapsulation process. UPG has significantly improved upon that goal by demonstrating an encapsulation system which is 72% lower in cost than the previous glass/EVA/glass system.

Task 8 POWERGLASS Module Termination

UPG has optimized the materials and processes utilized in the electrical termination of the POWERGLASS modules. All terminal components have been designed for use with automated insertion and assembly equipment. The terminal design has been analyzed in terms of manufacturing cost reduction. UPG has designed and is in the process of assembling an automated termination station for the application of the advanced termination systems designed in Task 2 and optimized in this task.

The goal of this task was to yield an optimized termination system for the POWERGLASS module capable of demonstrating a cost reduction of 70% (cumulative) in the UPG termination process. UPG has improved upon this goal through the realization of a 81% reduction in termination cost.

Task 9 EUREKA Module Design

Advanced Photovoltaic Systems, Inc. has continued to optimize the designs of the new EUREKA power modules and has carried out a critical examination of products with emphasis being given to market demand, quality, and manufacturing cost. Market demand for the PV modules has been analyzed through consideration of the existing global market offerings for similar products and through detailed interviews with established product distributors. Based on customer feedback, new module designs have been developed. At least one new design is for architectural applications. An experimental series of each design has been manufactured on the Eureka system. The final stage of costing has occurred for optimized designs with a comparison made with existing technology. This required a detailed cost analysis of the existing technology. A minimum of 20 modules, of each design, were manufactured on the EUREKA system. These modules were then evaluated for cost and quality improvements over the existing EUREKA modules.

Drawings, performance specifications and cost analysis were supplied to NREL early in the development cycle. Upon completion of prototype modules, comparisons were made of designed versus actual performance and similarly of designed versus actual costs once the product was manufactured at the APS Fairfield manufacturing facility. Status reports on qualification testing were provided to NREL. Design Reports were prepared for each new EUREKA module design. The Design Reports contained the following information for both the current and the new EUREKA module design:

- Discussion of market/application;
- Discussion of customer feedback;
- Assembly/mechanical drawings;
- Performance specifications; and
- Cost analysis demonstrating the benefit of the new design.

Task 10 EUREKA Process and Quality Control

Advanced Photovoltaic Systems, Inc. has established a high degree of process and quality control within the EUREKA manufacturing system in order to improve quality, yield, and throughput of the line. The general areas addressed were the thin-film deposition and module encapsulation processes. Statistical Process Control (SPC) was introduced into the APS Fairfield manufacturing facility. At least four of the critical control points identified in Task 4 were investigated with the objective to increase the yield at each point to at least 97% in a manufacturing mode in the APS Fairfield manufacturing facility. In part, tighter control of the process has allowed a higher power product to be produced; a goal of 55 watts for the EP50 has been reached for the Trenton facility.

Task 11 EUREKA Power Module Encapsulation and Termination

Advanced Photovoltaic Systems, Inc. has, based upon the results of Tasks 3 and 5, further developed the encapsulation and termination processes applied to the EUREKA manufacturing system. The cost and power improvements initiated in Task 5 were continued with a significant labor cost (per watt) reduction in the APS Fairfield manufacturing facility. Additional labor cost reductions were achieved by greatly reducing the cleaning required after module fabrication. A larger active area has added several percent to the module output. APS also undertook weight reduction and mounting development activities. The success of the weight reduction and mounting development activities were evaluated in terms of their impact on the cost of deploying the EUREKA module in the field. APS subjected EUREKA modules fabricated on the EUREKA system utilizing the developments from Tasks 3, 5, and 11 to EUREKA module qualification testing.

Task 12 Automation of the EUREKA Manufacturing Line

Advanced Photovoltaic Systems, Inc. continued to focus on the work begun in Task 6 for automation of glass transport systems. This work covered all aspects of glass movement from entry into the factory, to plate and module production. APS initiated the design, installation, debugging, and demonstration of automated assembly/encapsulation stations of the EUREKA system in the APS Fairfield manufacturing facility. The goals of this task were to increase the automation of glass transport processes to a minimum of 90% coupled with an improvement in yield to 90% in glass transport process steps and a 90 second cycle time.

1.0 PROJECT OBJECTIVES

The objectives of this effort over its (3) three year duration are to:

- Significantly advance the PV manufacturing technologies;
- Reduce module production costs;
- Increase average module performance; and
- Increase the production capacity existing in Utility Power Group (UPG) and Advanced Photovoltaic Systems, Inc. (APS).

UPG has concentrated its efforts on research in the area of encapsulation with consideration given to approaches that do not require a second glass layer, and on automation of electrical termination. APS has concentrated on optimizing the automation of the EUREKA manufacturing line, improving the encapsulation of the EUREKA module, and introducing real time processing and quality control to the EUREKA production line. The tasks were designed to reduce module manufacturing costs and increase module manufacturing yield.

2.0 TASKS 7 & 8 POWERGLASS Module Encapsulation and Termination

Process Development

Utility Power Group has improved upon its Pre-PVMaT encapsulation and termination systems by the simplification of the processes and reduction in direct materials.

Table 1 is a list of the encapsulation and termination steps utilized in the fabrication of PV modules made prior to the PVMaT Project.

Table 1. Pre-PVMaT Encapsulation and Termination Processes

1. PV Plate Complete
2. Solder Copper Ribbon to Plate Busbars
3. Cut and Drill Holes in Raw Back Glass
4. Temper Raw Back Glass
5. Apply EVA to Back Glass
6. Cut Slits in EVA at Holes
7. Feed Ribbons Through Slits/Holes
8. Laminate PV Plate to Back Glass
9. Solder Terminal to Ribbon
10. Apply Silicone Adhesive to Terminal
11. Cure Silicone and EVA in Oven

Modules fabricated with these techniques were installed as an EMT-1 Array at PVUSA Davis.

The termination and encapsulation process begins with a completed PV plate, that is, a glass superstrate with all the thick and thin films required for an active PV module.

The first step is to solder tin-plated copper ribbons to the PV module busbars. The busbars are formed by screen printing silver paste and firing onto the glass surface.

The Back Glass is cut to size, two holes are drilled, and the glass is heat tempered by an outside glass fabricator.

The next step is to apply a sheet of ethylene vinyl acetate (EVA) to the Back Glass. The EVA is tacky and adheres well to the Back Glass during the laminate assembly process.

Holes or slits are cut in the EVA at the location of the holes in the Back Glass.

The PV plate and the Back Glass are brought together while feeding the copper ribbon through the slits in the EVA.

The PV plate and Back Glass are laminated using a vacuum/pressure technique.

A standard off-the-shelf terminal is soldered to the copper ribbon.

Silicone adhesive is applied to the terminal.

The EVA and silicone adhesive are simultaneously cured in an oven.

The result is the termination/encapsulation system represented by Figure 1. This system was utilized in UPG's PVUSA modules which have proven to be quite reliable when compared to the crystalline and polycrystalline silicon PV modules also deployed as EMT-1 arrays at Davis.

Table 2 is a list of the termination and encapsulation steps utilized in the fabrication of PV modules developed through the PVMaT Project.

Table 2. PVMaT Termination and Encapsulation Processes

1. PV Plate Complete
2. Apply Silicone Material onto PV Plate
3. Place Termination Systems on Silicone over Pads
4. Deposit Glass Beads
5. Cure Silicone Material
6. Create Vias in Silicone over Pads
7. Insert Terminal Contacts
8. Pot Terminal Contacts

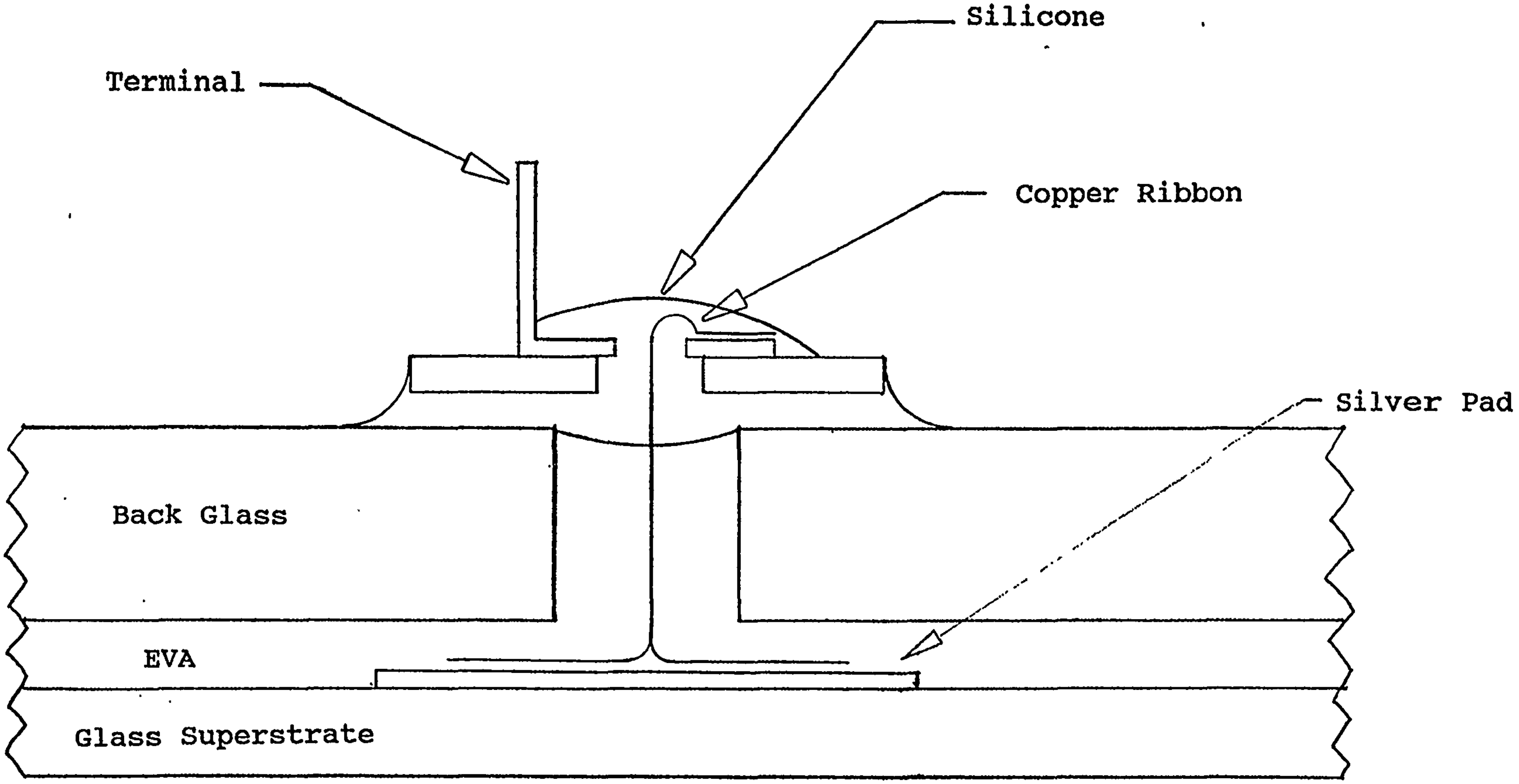
Again, the termination and encapsulation process begins with a completed PV plate, however, this plate must be capable of passing the Hail-Impact Test.

The first step is to apply the silicone material onto the PV plate.

Next, the termination systems are place onto the silicone material over the thick-film silver current-collection pads on the PV plate.

This is followed by the application or deposition of glass beads over the entire back surface of the PV plate.

The silicone is then heat cured in an oven.



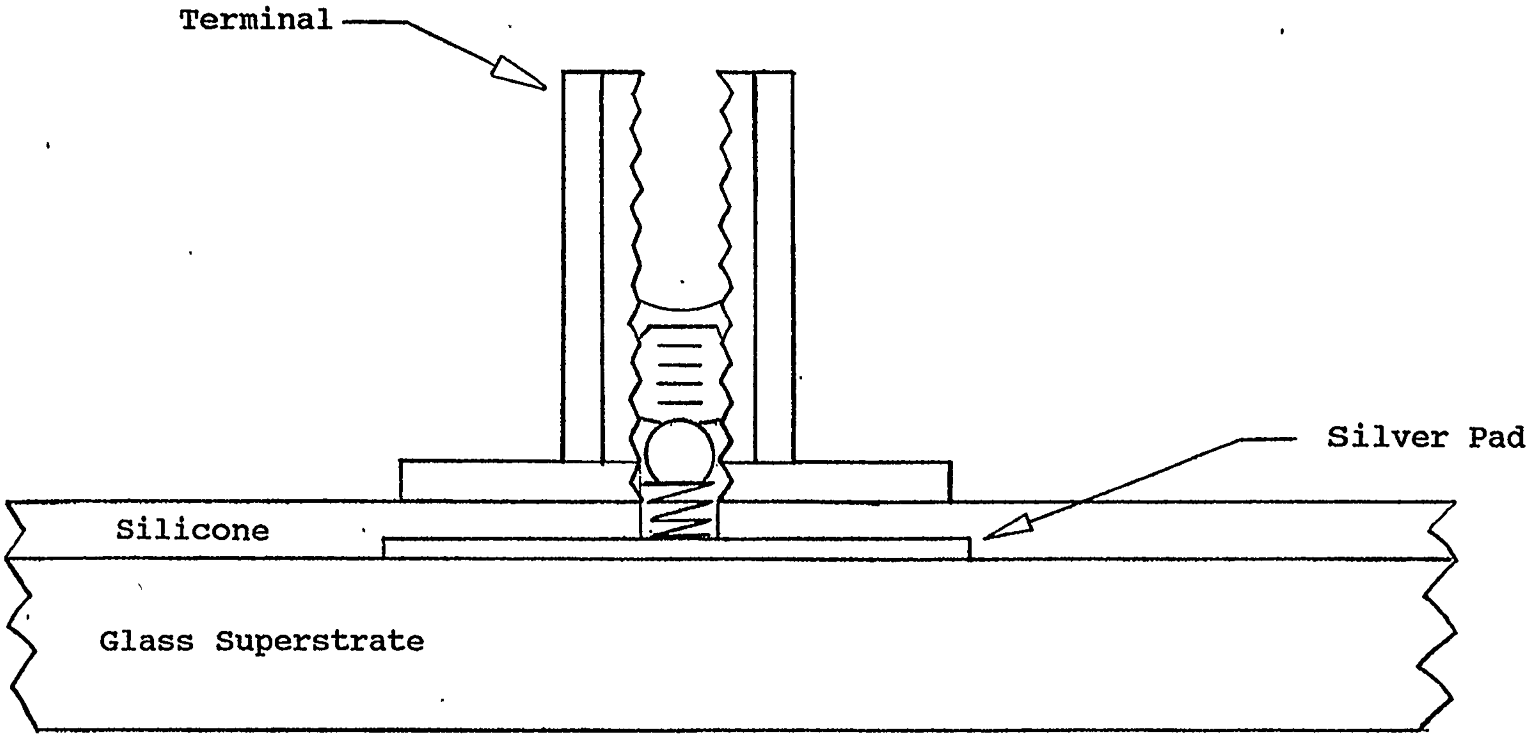
UTILITY POWER GROUP

SCALE: None
APPROVED BY:
DRAWN BY LDV
DATE: 7-14-93
REVISED

Termination System #1

Figure 1

DRAWING NUMBER
TS 71493 B



UTILITY POWER GROUP

SCALE: None
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DRAWN BY LDV
REVISED

Termination System #6

Figure 2

DRAWING NUMBER
TS71493A

8½ X 11 PRINTED ON NO. 1000H CLEARPRINT ●

Vias or openings are created through the silicone within the termination systems over the current-collection pads of the PV plate using a proprietary process.

Terminal contacts are inserted into the termination systems and potted to isolate from the environment.

The result is the termination/encapsulation system represented by Figure 2. There are 30% fewer steps for this procedure and all are easily automated. There is no soldering involved, which eliminates the production of hazardous waste products.

Encapsulant Characteristics

The encapsulation materials have been evaluated in terms of their:

1. Substrate adhesion
2. Scratch resistance
3. Chemical resistance
4. Water penetration resistance
5. Compatibility with module fabrication techniques
6. Air quality concerns
7. Cost
8. Safe application
9. Application speed

UPG has investigated a wide variety of encapsulation materials and has determined that the materials judged to be the most attractive as substitute encapsulation materials are the silicone products.

Substrate Adhesion:
These silicone materials are generally described as structural adhesives. The primerless silicone adhesive is a flowable silicone elastomer that develops a strong, self-priming adhesive bond to many substrates when properly applied and cured. The adhesive, when heated, cures to a strong, flexible elastomer that is ideally suited for adhesive applications.

Scratch Resistance:
The candidates for advanced substitute encapsulation materials all showed a weakness in the scratch resistance test as outlined in the NREL/TR-213-3624 qualification test procedure when compared to the glass/EVA/glass package. The 1/8" thick tempered or raw glass used as the back sheet in the glass/EVA/glass package holds up quite well to the scratch resistance test because the glass is thick and hard. None of the thin (less than 0.025") coatings used as candidate encapsulation materials (polyurethanes, epoxies, silicones, or plastic copolymers) can hold up to the same level of abuse as the back glass in the glass/EVA/glass

package. Moreover, the silicone materials displayed particularly poor performance in that regard. UPG was able to modify the silicone to decrease its susceptibility to being cut. The modification of the encapsulation material consisted of adding a component to the silicone after the application of the encapsulation material to the module. The material found to be the best additive are glass beads in a size range of 0.001" - 0.002" (Figures 3 and 4). Glass beads are chemically stable and mechanically robust. They have the hardness of glass which allows the encapsulation material to pass the Surface-Cut Susceptibility Test and have smooth surfaces which will not scratch the thin-films under the encapsulant. The glass beads are added to the uncured silicone by passing the module under a curtain of beads. The amount of beads applied to the silicone is determined by the speed of the module through the curtain and the flow of the glass bead curtain.

ADVANCED ENCAPSULATION MATERIAL

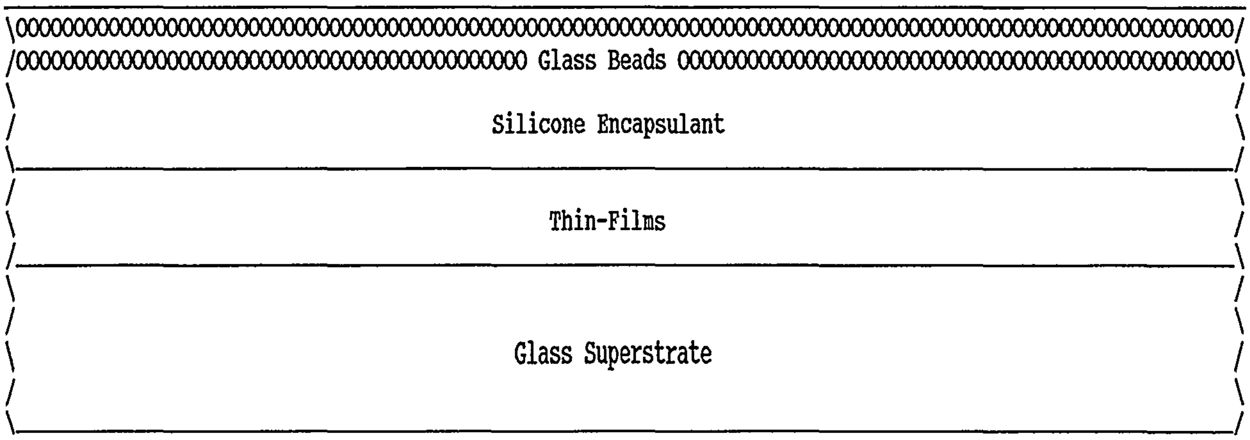


Figure 3. The Advanced Encapsulation Material composed of the silicone structural adhesive with the addition of the glass beads for enhanced mechanical strength.

Chemical Resistance:
The cured silicone adhesive is capable of being submerged in a hot solution of sodium hydroxide for periods in excess of one hour without any sign of chemical attack. This silicone rubber has extended resistance to weather, sunlight, moisture, radiation, oxidation, and ozone.

Water Penetration Resistance:
The silicone adhesive cures to a flexible rubber that demonstrates superior resistance to liquid water or water vapor penetration.

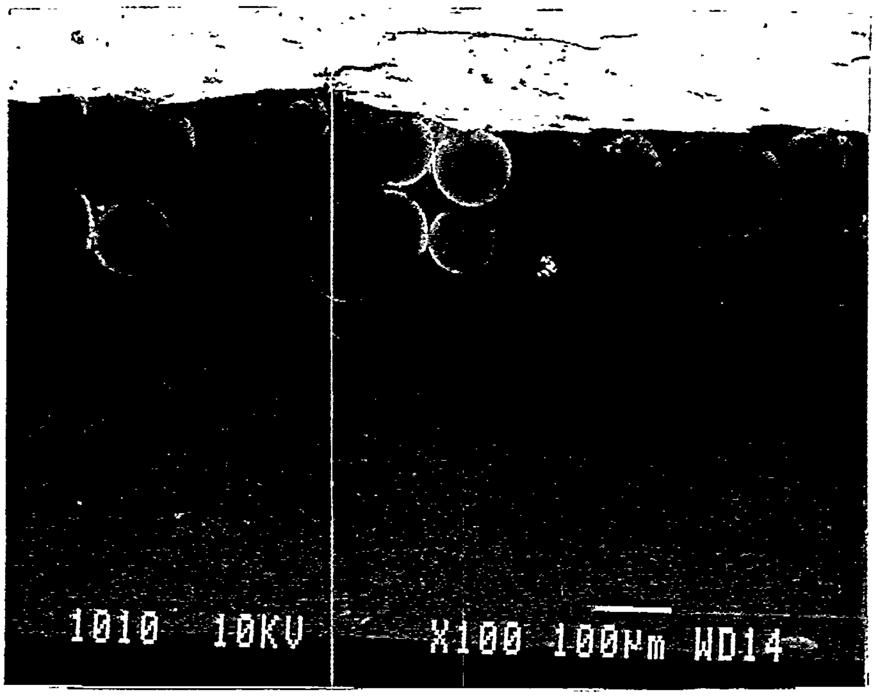


Figure 4. SEM photo illustrating glass beads embedded in the silicone adhesive. Notice that while the glass beads are fully submerged in the silicone encapsulant, there is no tendency to drift down through the silicone to come in contact with the thin-films.

Compatibility with Module Fabrication Techniques:
The application, and more importantly, the curing of the silicone adhesive on the PV module has not demonstrated any incompatibilities with the processing of the PV module.

Air Quality Environmental Concerns:
The primerless silicone material includes no solvents or cure by-products.

Cost:
At the thicknesses being applied as an encapsulant candidate material (12 mils), the cost of the modified silicone remains within the goal of this project, approximately $0.70/sq.ft.

Safe Application:
Toxicity studies of primerless silicone adhesive formulations have shown minimal industrial handling problems. This material does contain an epoxy-functional group. As with all epoxy materials, precautions should be taken to avoid exposure to eyes or skin and inhalation of vapors. Spills of the uncured silicone can become extremely slippery. Sawdust or absorbent should be immedi-

ately applied to any liquid spill for temporary relief and the spill removed with high-flash mineral spirits or other suitable solvent.

Application Speed:
The silicone material can be applied with a roller coater at a speed that easily surpasses the rest of the manufacturing line. The roller coater is designed to operate at a speed of 10 feet per minute while the overall throughput of the manufacturing line is one module (14.5" x 13.0") every five minutes.

Superstrate Materials

As stated earlier, in order to utilize the advanced encapsulation and termination techniques, we must start with a glass superstrate that is capable of passing the Hail-Impact Test. One approach is to use a 3mm thick glass superstrate that is heat tempered prior to the deposition of the amorphous silicon, which is not capable of handling the temperatures required for tempering glass. Tempering provides enough strength to the 3mm glass to easily pass the Hail-Impact Test, while untempered or raw 3mm thick glass will fail the test.

However, utilizing tempered superstrate glass has resulted in a reduction in the conversion efficiency of the PV modules (see Figure 5). The short circuit current, the open circuit voltage, and the fill factor all decrease, resulting in an approximately 15% overall decrease in maximum power. The exact cause of this power reduction has not yet been determined, but the glass superstrate does become warped or distorted during the tempering process and this distortion could be affecting the thermal characteristics of the superstrate during the amorphous silicon deposition. The sheet resistance of the TCO remained unchanged after the tempering process. Once glass is tempered it is not possible to cut into sizes compatible with our spectrophotometer and therefore we were unable to measure the change in absorption due to tempering.

An alternative to using a tempered superstrate is the utilization of glass thicker than 3mm, capable of passing the Hail-Impact Test without having to be tempered. Although 3mm thick glass will not pass the Hail-Impact Test without being tempered, UPG has determined through Sandia National Laboratories that both 5mm and 4mm thick glass will easily pass the Hail-Impact Test without requiring heat tempering. UPG has fabricated PV modules utilizing 5mm thick superstrates and the electrical results are virtually identical to those utilizing 3mm untempered superstrates. The extra glass thickness does not reduce the short circuit current of the PV module.

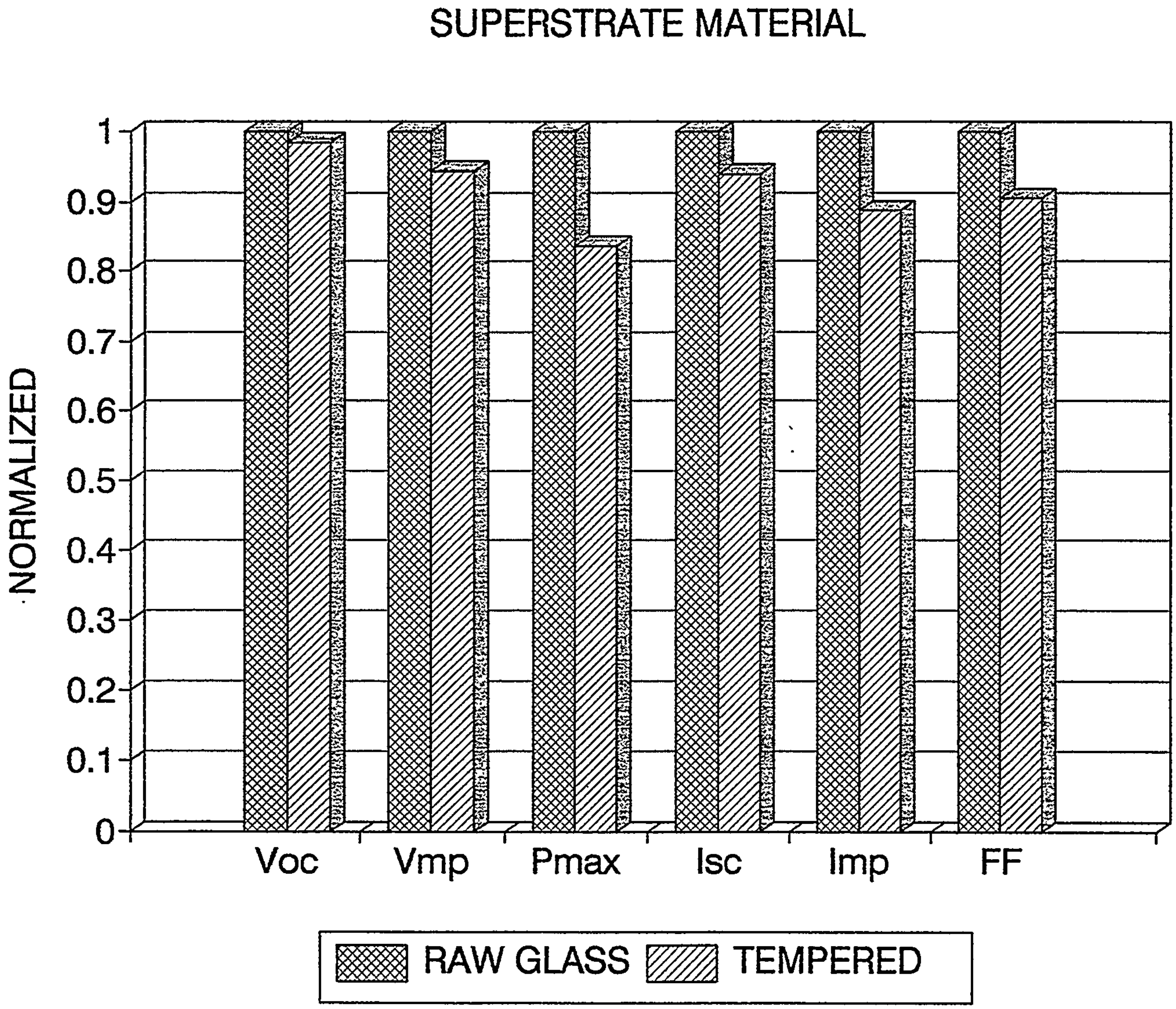

SUPERSTRATE MATERIAL
NORMALIZED
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Voc
Vmp
Pmax
Isc
Imp
FF
RAW GLASS
TEMPERED

Figure 5.

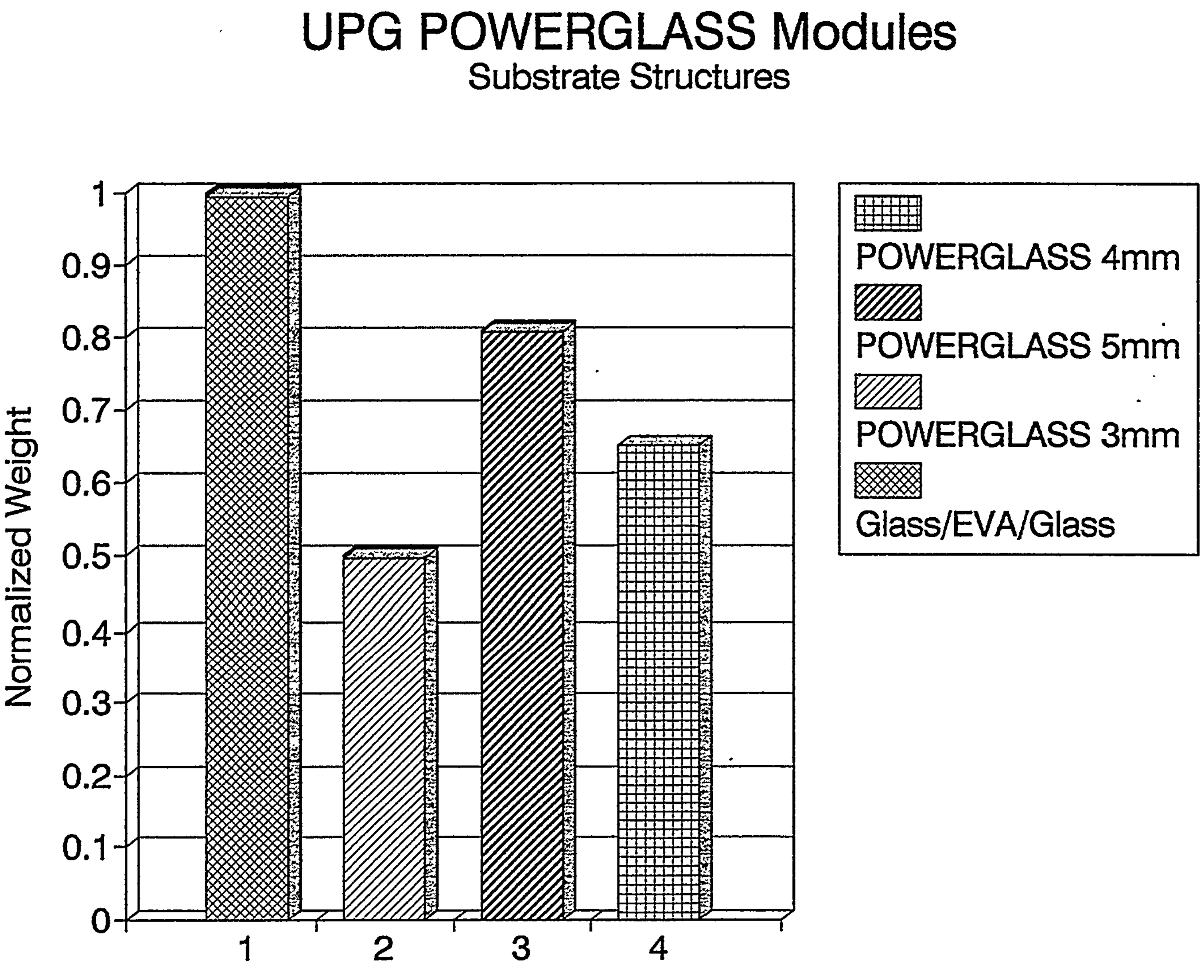

UPG POWERGLASS Modules
Substrate Structures
Normalized Weight
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1
2
3
4
POWERGLASS 4mm
POWERGLASS 5mm
POWERGLASS 3mm
Glass/EVA/Glass

Figure 6.

One of goals of the new encapsulation system was to reduce the weight of the glass/EVA/glass package which consisted of two pieces of 3mm glass laminated with EVA (see Figure 6). Eliminating the Back Glass by using a tempered front superstrate would have reduced the weight by 50%. However, a 5mm untempered superstrate would result in a 19% weight reduction, while a 4mm thick superstrate would result in a 35% weight reduction. Although a 50% weight reduction may not be attainable due to the detrimental affect of a tempered superstrate on the electrical characteristics, a 35% weight reduction utilizing an untempered 4mm thick superstrate is a significant achievement. It also eliminates the need for the glass tempering step.

Automated Encapsulation Station

After evaluating various application techniques for the encapsulation materials, the technique determined to be the most cost effective in terms of initial cost, throughput, ease of setup and operation, and minimizing waste material production is roller coating.

Roller coating operates with three rolls; the coating roll, doctor roll, and backup roll (see Figure 7).

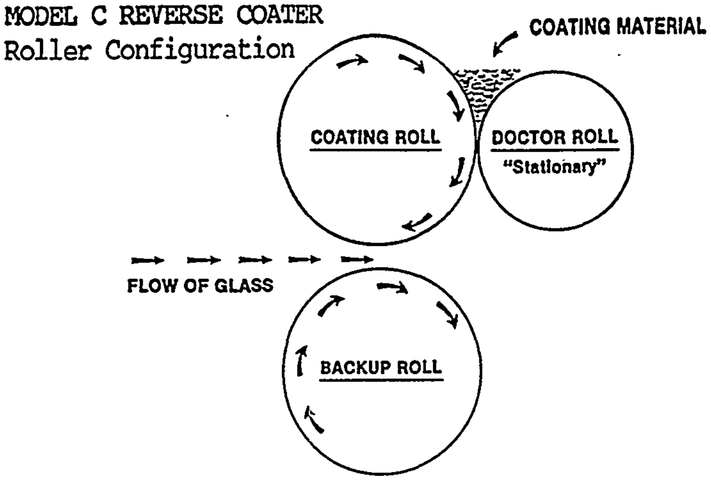


Figure 7.

The Coating Roll is a 4" diameter, smooth ground Nitrile covered roller. The Doctor Roll is a 2-3/4" diameter, smooth ground chrome plated steel roller. The Backup Roll is a 4" diameter, smooth ground Neoprene covered roller.

The coating material, UPG's advanced encapsulation material, is held in the trough formed by the Coating Roll and the Doctor Roll above the glass substrate. The Backup Roll is located directly below the Coating Roll. The Doctor Roll remains stationary, while the Coating Roll rotates in the opposite direction of the glass motion. This rotation acts to shear the encapsulation material against the substrate. The Backup Roll rotates in the same direction as the glass substrate motion, aiding in its transfer through the coating system. The Doctor Roll is adjustable in relationship to the Coating Roll, thereby regulating the amount of material being applied to the top surface of the glass substrate. This type of roller coating, where the Coating Roll rotates counter to the direction of glass motion, is known as Reverse Roller Coating. Reverse Coating, as well as, the durometer choice (75 Shore) and the smooth grinding of the Coating Roll are critical to this application.

A belt type conveyor will be incorporated to transport the glass through the roller coater. This powered conveyor will be driven by the same motor that drives the roller coater. The belt material was chosen to be compatible with the encapsulant material and the solvents used to clean the encapsulant from the roller coater. In addition, the belt material was chosen to provide enough adhesion to the glass substrates to prevent slippage during the coating operation. The roller coater will be capable of coating the substrate at a rate of 2"/sec., which is 6.5 seconds for the UPG POWERGLASS module or 30 seconds for the APS EUREKA module. The combination of the termination and encapsulation steps should take considerably less time than the 15 minutes per module required using the Pre-PVMaT process.

Automated Termination Station

The Automated Termination Station will consist of pick-and-place equipment designed to:

1. Position the silicone coated PV plate
2. Clasp pre-assembled terminals
3. Position the terminals over the current collection pads
4. Push the terminals down into the uncured silicone
5. Transport the PV plate to the curing oven

The Automated Termination Station will be attached to the Automated Encapsulation Station as a subsystem. This coordination is possible due to the design and development of the encapsulation and termination system process.

Module Qualification Testing

The advanced termination and encapsulation system has successfully proceeded through the module qualification testing procedure. The silicone material is unaffected by the thermal and humidity/freeze cycling. This silicone adheres very well to the glass and the modules easily pass the Wet Hi-Pot Test even after many thermal and humidity/freeze cycles. UPG continues to utilize a border along the glass where no thin-films are allowed. This serves as a barrier against electrical and material leakage. UPG developed this technique for its PVUSA modules.

The advanced termination system can easily handle over 150% of the terminal torque requirements as specified in the UL 1703 document (12 pound-inches). It is also able to handle over 25 lbs. of lateral force.

Production Costs

Table 3 is a list of the process steps UPG utilizes in the fabrication of the POWERGLASS modules.

Table 3. POWERGLASS Module Process Steps

1. Pattern Front Transparent Conductor
2. Clean
3. Screen Print Conductive Paste
4. Fire
5. Screen Print Maskant Paste
6. Bake
7. Deposit Amorphous Silicon Alloys
8. Deposit Rear Conductor
9. Anneal
10. Remove Maskant
11. Shunt Removal
12. Terminate
13. Encapsulate
14. Cure
15. Final Clean
16. Test

Figure 8 represents the Pre-PVMaT manufacturing costs broken down by process step and the three categories; materials, operating expenses, and direct labor. Process Step No.1 includes the purchase of the TCO coated glass superstrate. Process Step No.7 involves the deposition of the amorphous silicon and rear conductor thin-films. Process Step No.12 is the termination step and Process Step No.13 is the encapsulation step.

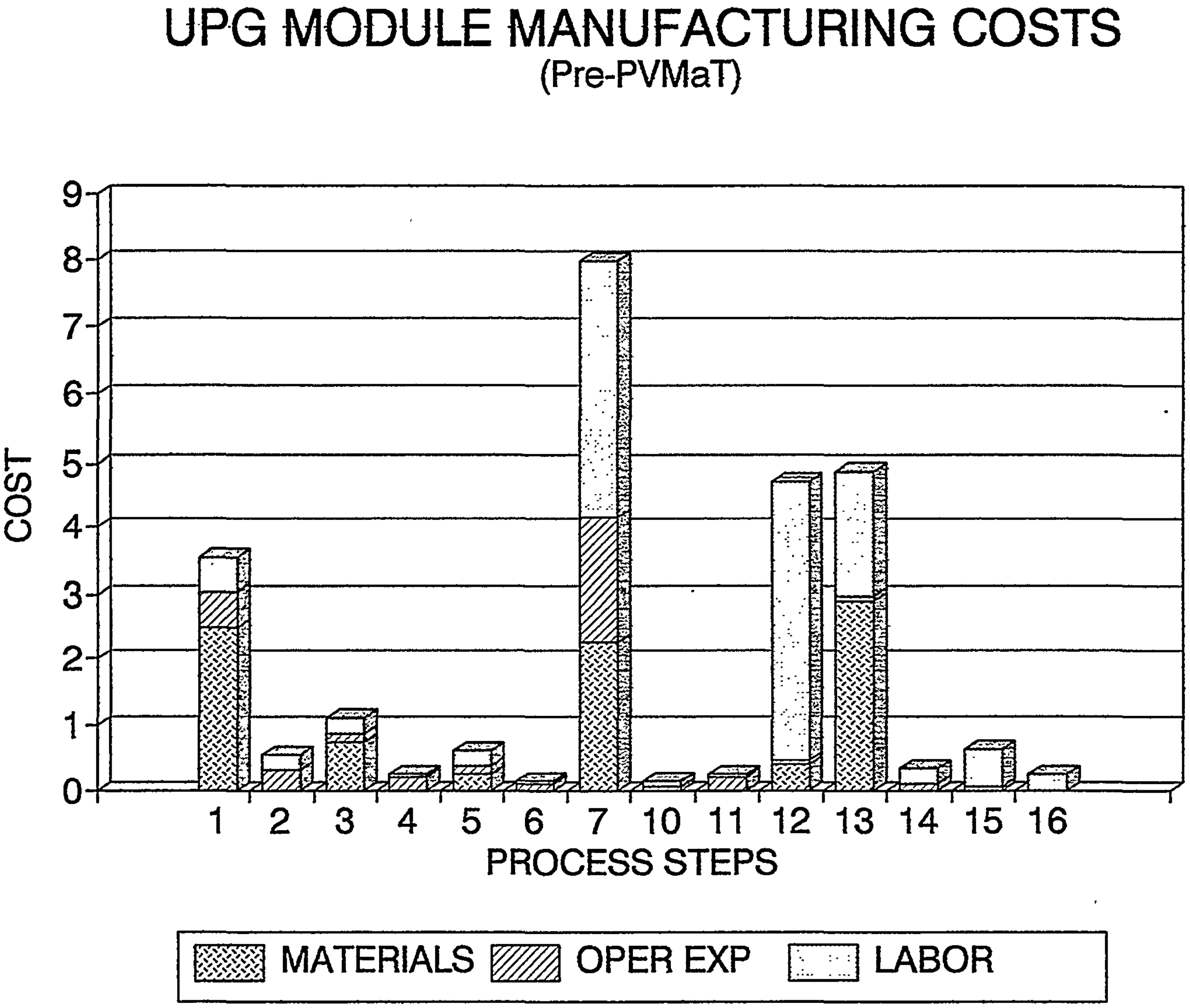

UPG MODULE MANUFACTURING COSTS
(Pre-PVMaT)
COST
0
1
2
3
4
5
6
7
8
9
1
2
3
4
5
6
7
10
11
12
13
14
15
16
PROCESS STEPS
MATERIALS
OPER EXP
LABOR

Figure 8.

Figure 9 illustrates the relative proportion of the termination and encapsulation costs to the total manufacturing costs for the Pre-PVMaT modules.

Figure 10 represents the manufacturing costs as a result of the first phase of the PVMaT Project. Notice that Steps 12 and 13 have been substantially reduced.

Figure 11 represents the manufacturing costs as a result of Phase 2 of this PVMaT Project. The costs associated with Steps 12 and 13 continue to go down.

Figure 12 represents the cost reduction goals for Phase 3 of this PVMaT effort. The Scope of Work for this subcontract did not include any effort towards cost reduction at UPG in areas other than termination and encapsulation. However, as this figure suggests, and area of cost reduction that needs to be addressed is clearly associated with the deposition of the amorphous silicon and rear conductor thin-films. Nevertheless, by addressing the cost reduction of the termination and encapsulation processes alone, Total Module Manufacturing Costs will be reduced by approximately 30% at the conclusion of Phase 3 of this PVMaT effort, as represented by Figure 13.

Figure 14 represents the progress UPG has made and the goals we expect to achieve in the cost reductions of the termination and encapsulation processes. The top bar represents the termination and encapsulation costs associated with the Pre-PVMaT module. The next bar represents the original goal established for Phase 1 of this PVMaT effort. The third bar down represents the actual costs achieved at the conclusion of Phase 1, which is significantly less than the goal. The fourth bar represents the original goal established for the Phase 2. The fifth bar represents the new goal that was established for Phase 2 at the conclusion of Phase 1. The sixth bar represents the actual costs achieved at the conclusion of Phase 2. The seventh bar represents the original goal established for Phase 3. The last bar represents the new goal that will be established for Phase 3 at the conclusion of Phase 2.

Figure 15 illustrates the termination and encapsulation cost reductions broken down by process (termination or encapsulation), phase (zero, 1, 2, and 3), and cost component (materials, operating expenses, and direct labor). Phase zero represents the Pre-PVMaT period.

UPG MODULE MANUFACTURING COSTS
(Pre-PVMaT)

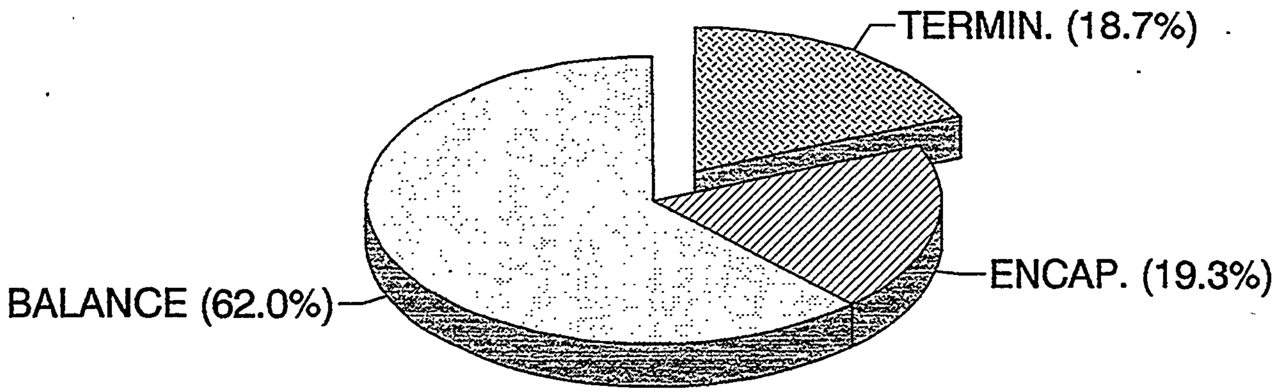


Figure 9.

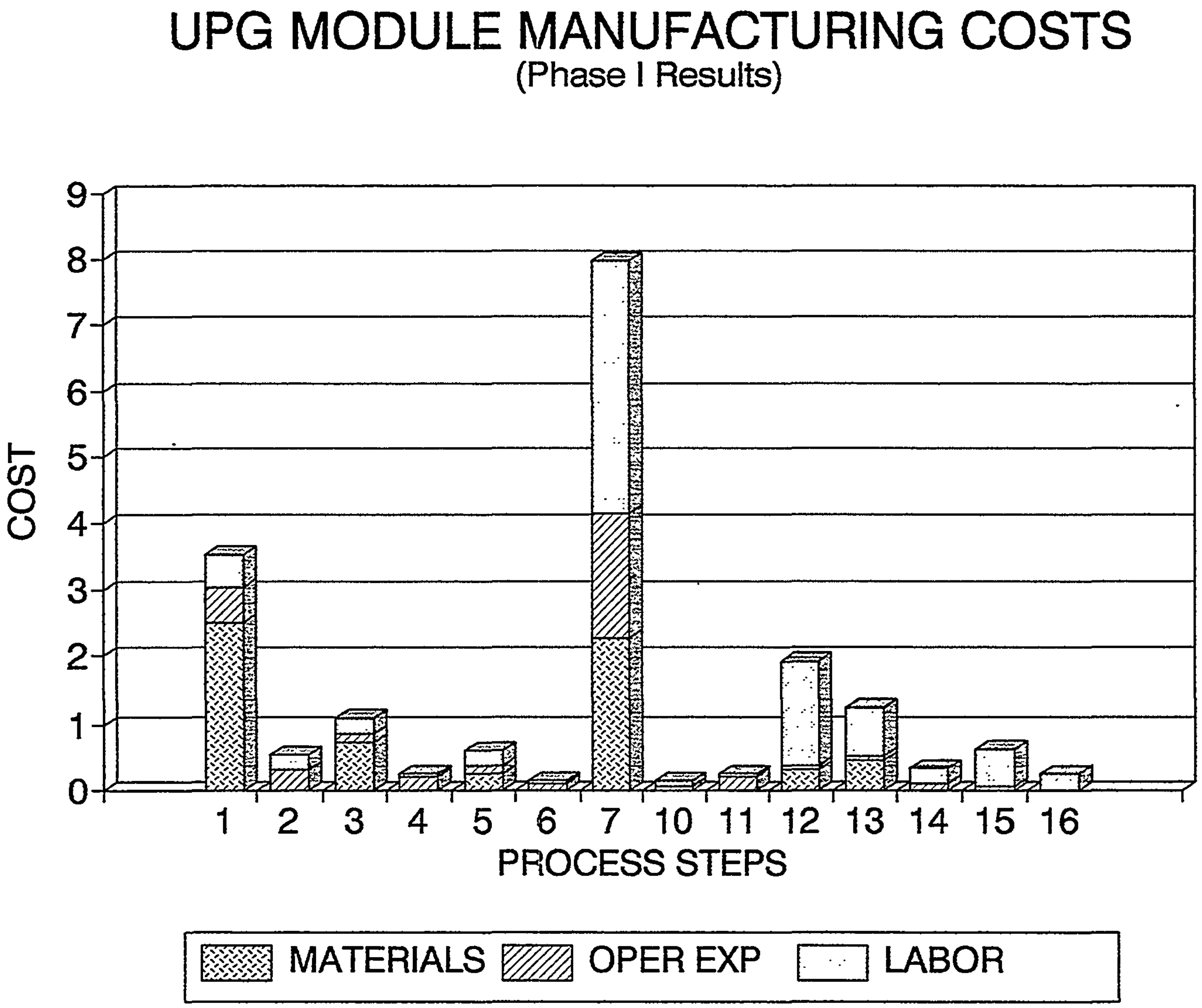
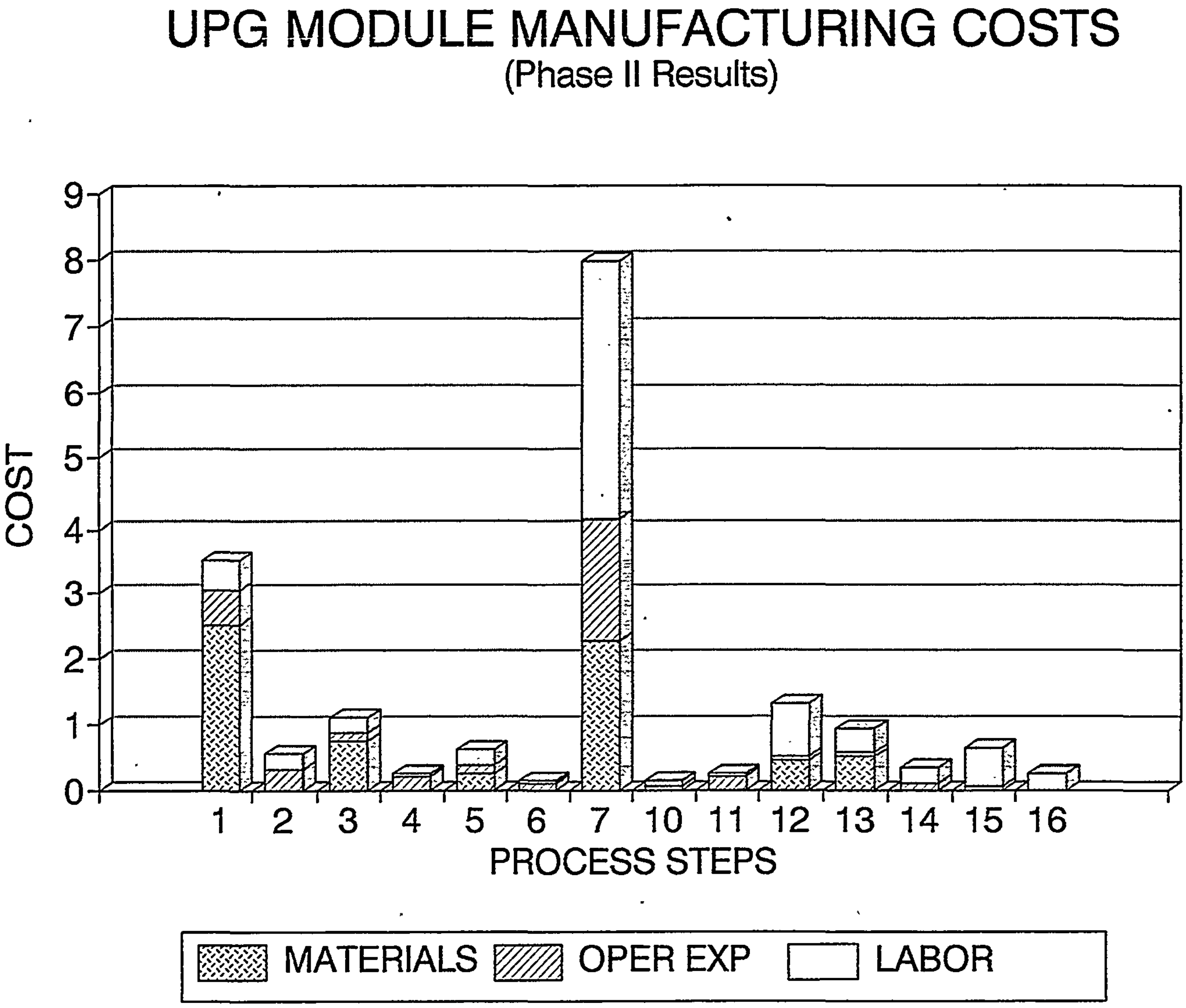

UPG MODULE MANUFACTURING COSTS
(Phase I Results)
COST
0
1
2
3
4
5
6
7
8
9
1
2
3
4
5
6
7
10
11
12
13
14
15
16
PROCESS STEPS
MATERIALS
OPER EXP
LABOR

Figure 10.


UPG MODULE MANUFACTURING COSTS
(Phase II Results)
COST
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3
4
5
6
7
8
9
1
2
3
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7
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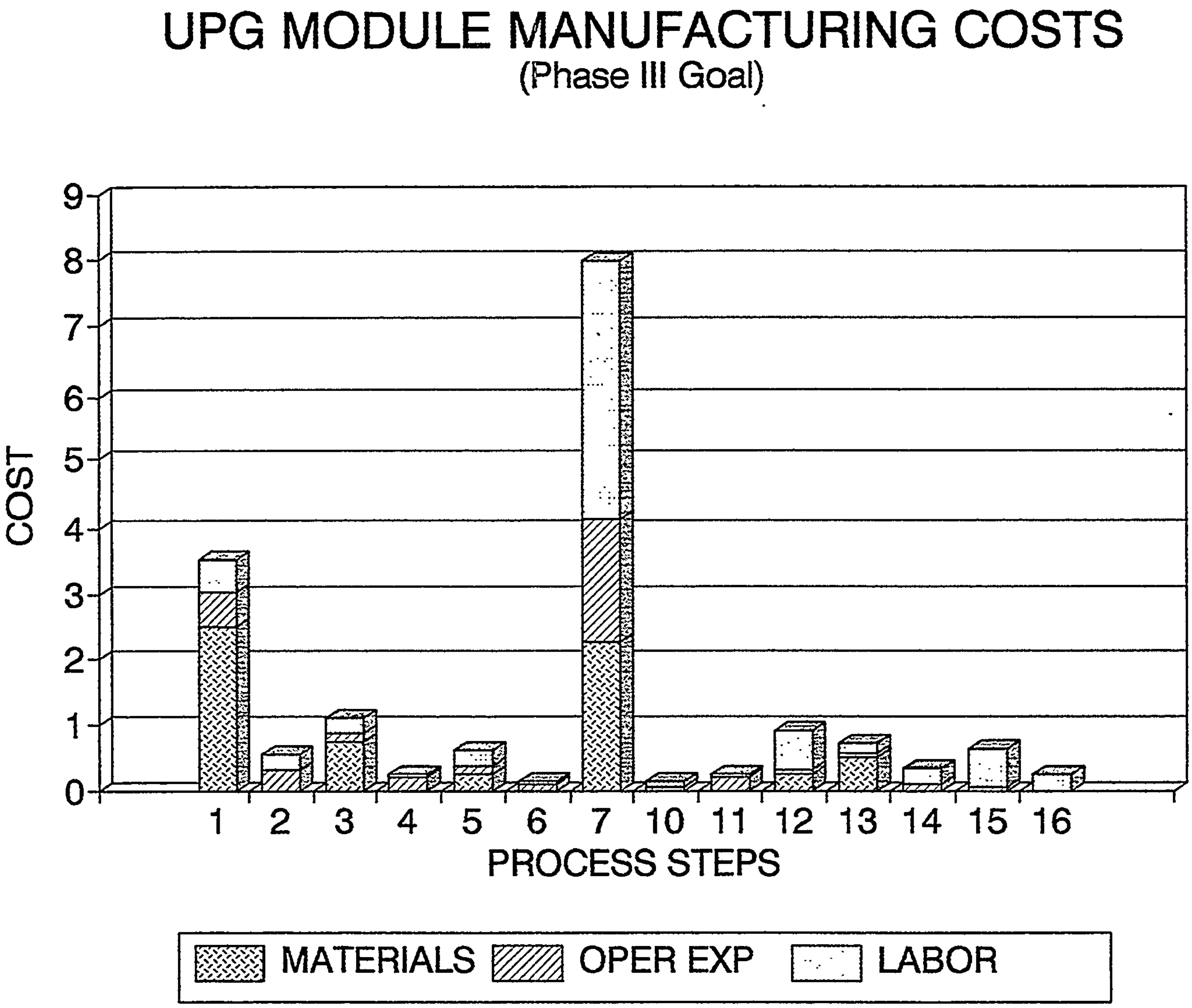
16
PROCESS STEPS
MATERIALS
OPER EXP
LABOR

Figure 11.


UPG MODULE MANUFACTURING COSTS
(Phase III Goal)
COST
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3
4
5
6
7
8
9
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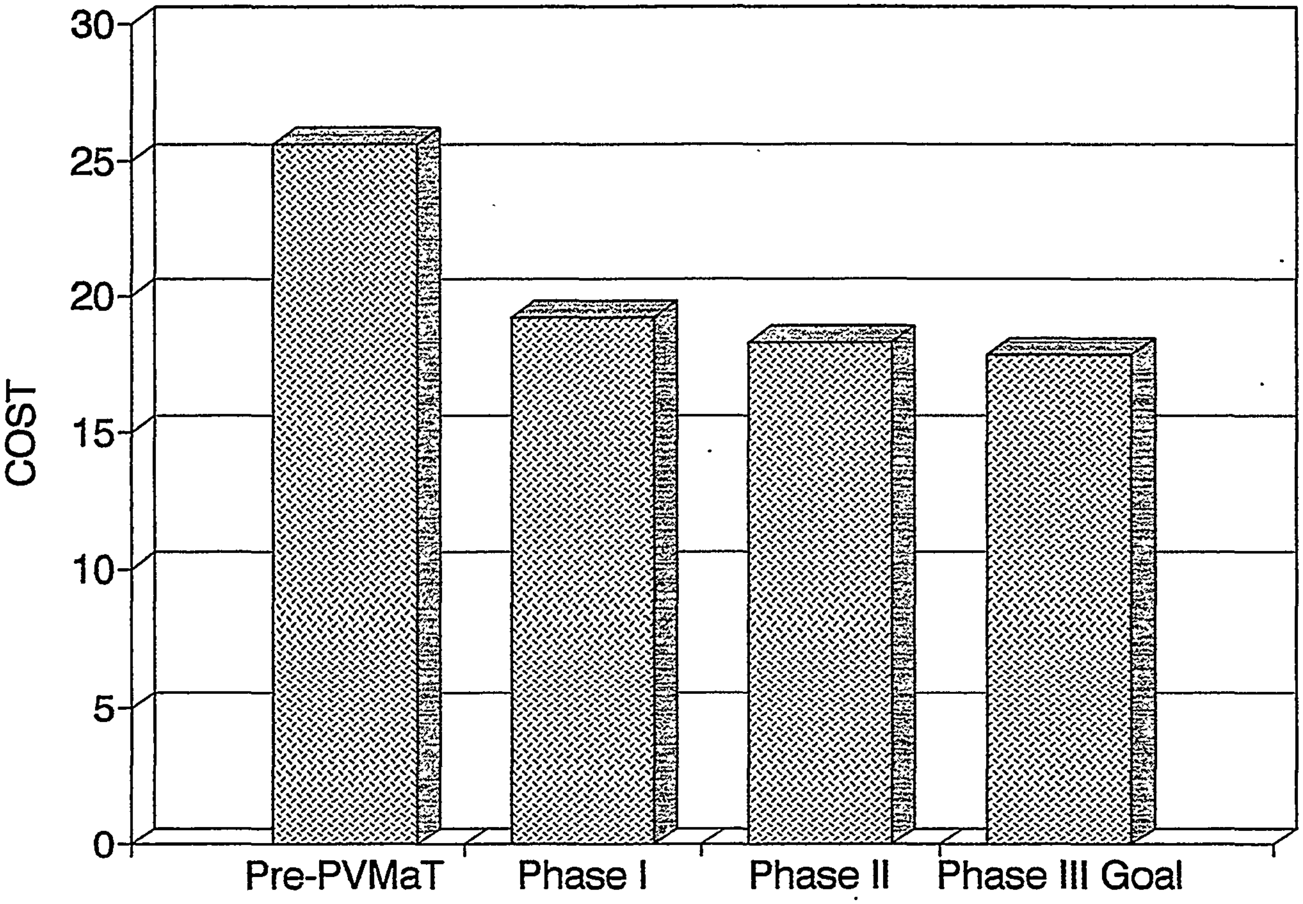
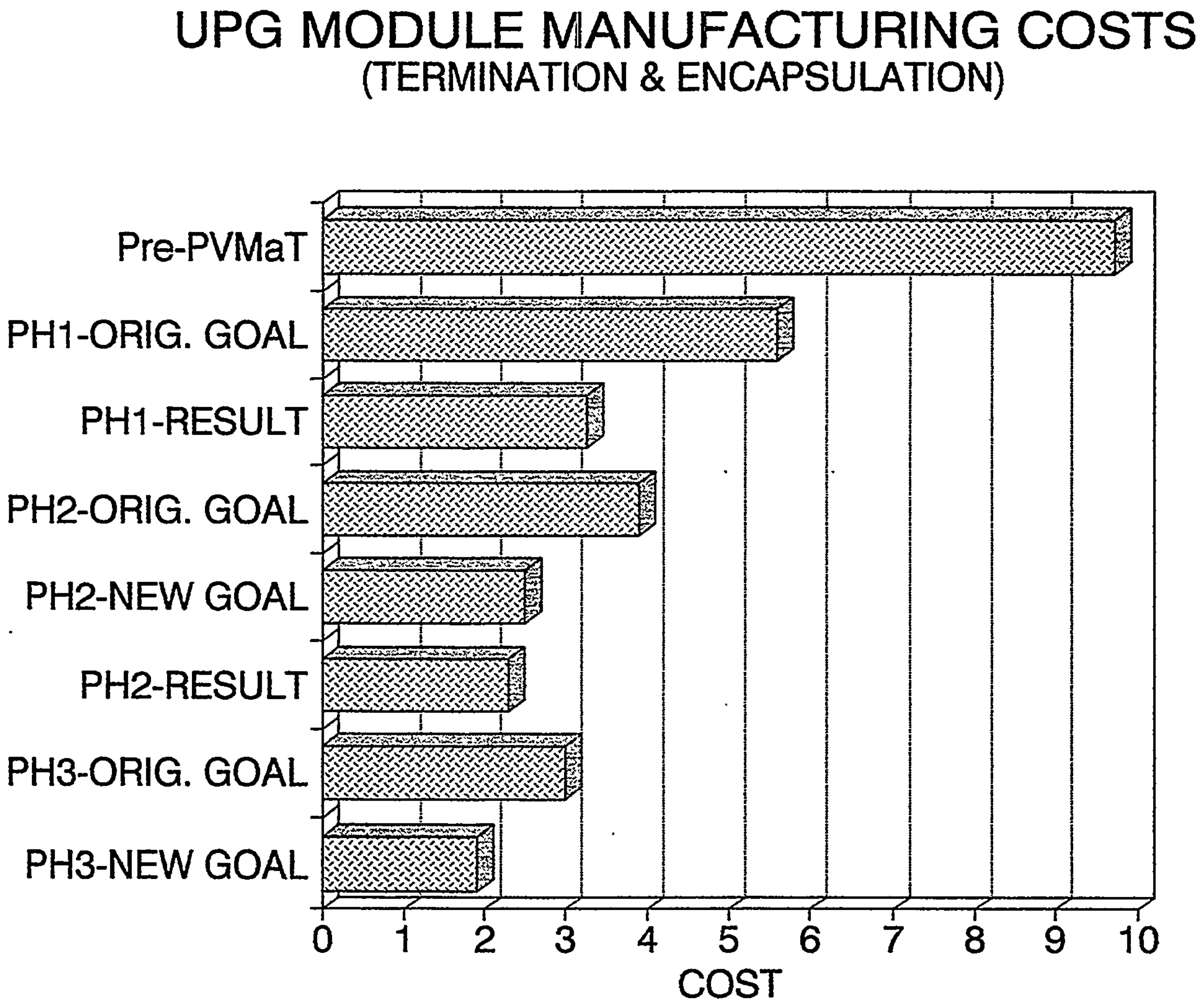
2
3
4
5
6
7
10
11
12
13
14
15
16
PROCESS STEPS
MATERIALS
OPER EXP
LABOR

Figure 12.



UPG MODULE MANUFACTURING COSTS
(Total Module Costs)

Figure 13.


UPG MODULE MANUFACTURING COSTS
(TERMINATION & ENCAPSULATION)
Pre-PVMaT
PH1-ORIG. GOAL
PH1-RESULT
PH2-ORIG. GOAL
PH2-NEW GOAL
PH2-RESULT
PH3-ORIG. GOAL
PH3-NEW GOAL
0
1
2
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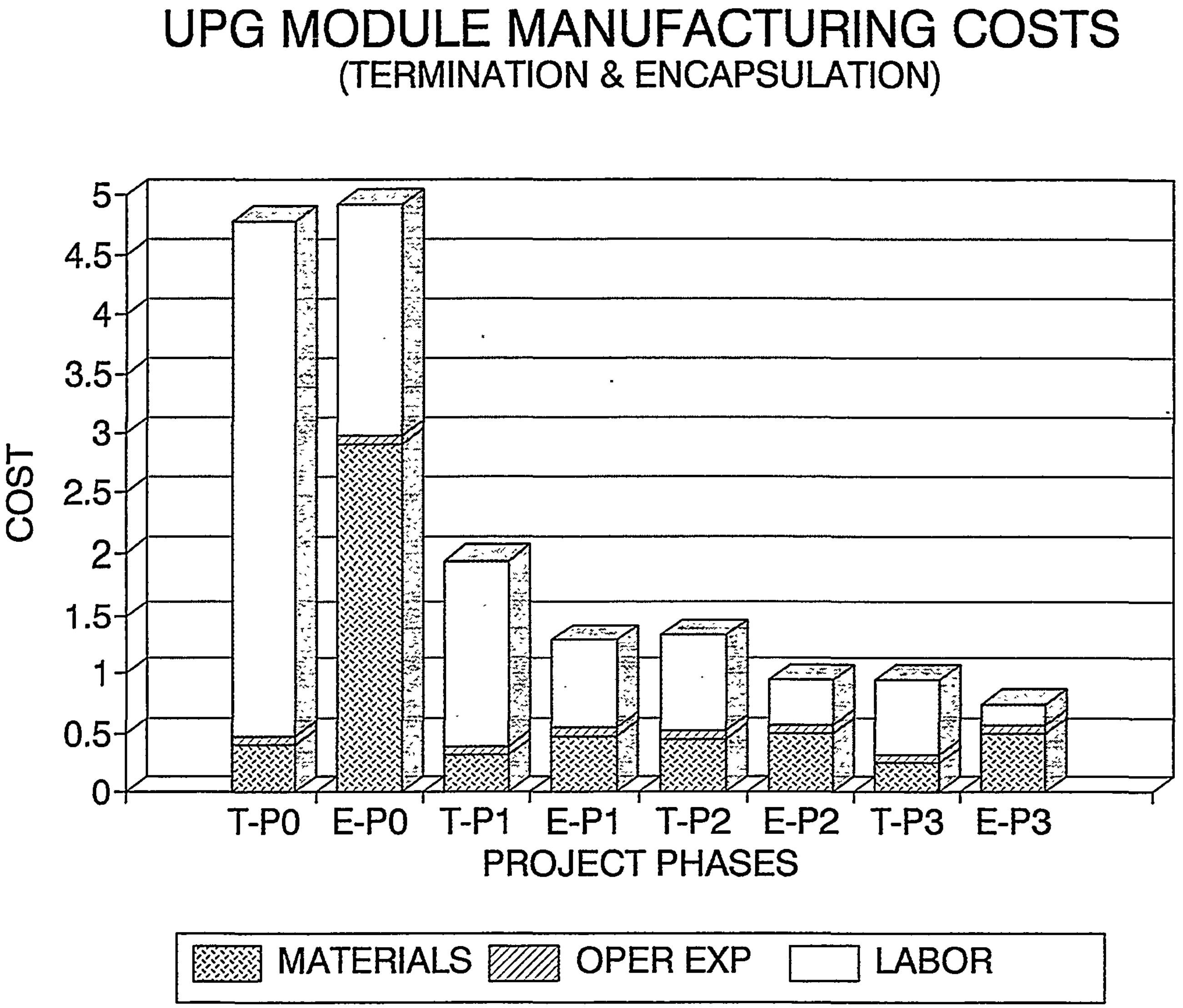
4
5
6
7
8
9
10
COST

Figure 14.


UPG MODULE MANUFACTURING COSTS
(TERMINATION & ENCAPSULATION)
COST
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0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
T-P0
E-P0
T-P1
E-P1
T-P2
E-P2
T-P3
E-P3
PROJECT PHASES
MATERIALS
OPER EXP
LABOR

Figure 15.

POWERGLASS Module Performance

Figure 16 represents the modules produced within the past year as a result of this PVMaT effort. The overall trend is a gradual increase in conversion efficiency over time. This is due to gaining a better understanding of all the manufacturing steps associated with the POWERGLASS module.

Figure 17 represents the monthly averages (20 units/month) of the unstabilized power ratings for the modules produced between January 1993 and February 1994. This dramatic increase from a nominal 5 watts per module to just over 7.5 watts per module is a result of both an increase in the unit area conversion efficiency and the tightening of the yield in the manufacturing process. Two months are missing from these data, May and November. The two missing months were devoted to maintenance and modification of the thin-film deposition equipment, during which time no new modules could be fabricated.

Figure 18 is a histogram of the PVMaT modules produced for the first quarter of 1993. Figure 19 represents the modules for the last quarter of 1993.

The stabilized power output of the Pre-PVMaT module was a nominal 4 watts per module as shown in Figure 20. During Phase I of this PVMaT effort a new module was designed and fabrication processes were developed. At the conclusion of Phase I the stabilized power output of the new POWERGLASS module was a nominal 4.6 watts. By the end of Phase II the module power output had increased to 6 watts. UPG expects the stabilized power output of the POWERGLASS module to be a nominal 6.5 watts. This increase in module power output will be a result of both an increase in conversion efficiency and in the size of the module. The Pre-PVMaT module produced 4.3 mW/cm^2 and was 12" x 12" or 930 cm^2 in total area. The new POWERGLASS module will produce 5.3 mW/cm^2 and is 13" x 14.5" or 1216 cm^2 in total area.

Production Capacity

The termination and encapsulation processes utilized in the Pre-PVMaT modules limited the throughput of the manufacturing facility to approximately four modules per hour. In Phase I of this PVMaT effort the POWERGLASS module was in the process of design and development and the throughput remained four modules per hour. During the Phase II period the encapsulation and termination process steps were sufficiently advanced to allow an increase in the throughput to approximately six per hour. With the new automated termination and encapsulation systems in place, these processes will be considerably faster, and the limiting step, the deposition of the thin-films, will allow a throughput of approximately 12 modules per hour.

On an annual basis, the throughput will increase from a Pre-PVMaT level of approximately 35,000 modules to over 105,000 modules per year for the new POWERGLASS module utilizing the automated encapsulation and termination systems.

With that increase in throughput, and the increase in module performance, the capacity of UPG's manufacturing facility will increase from approximately 140kW per year for the Pre-PVMaT modules to 680kW per year for the new POWERGLASS modules.

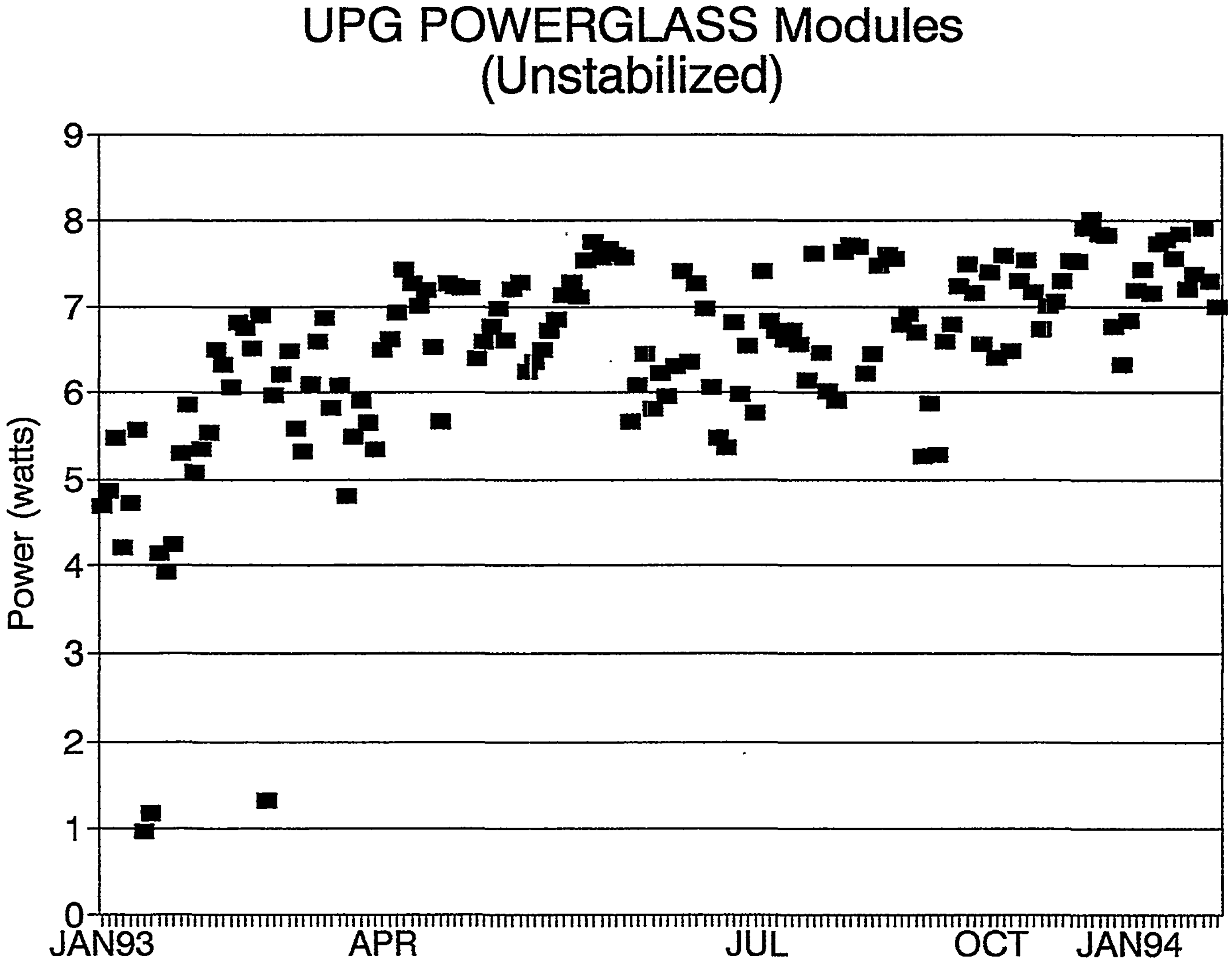


Figure 16. The modules produced within the past year as a result of this PVMaT effort.

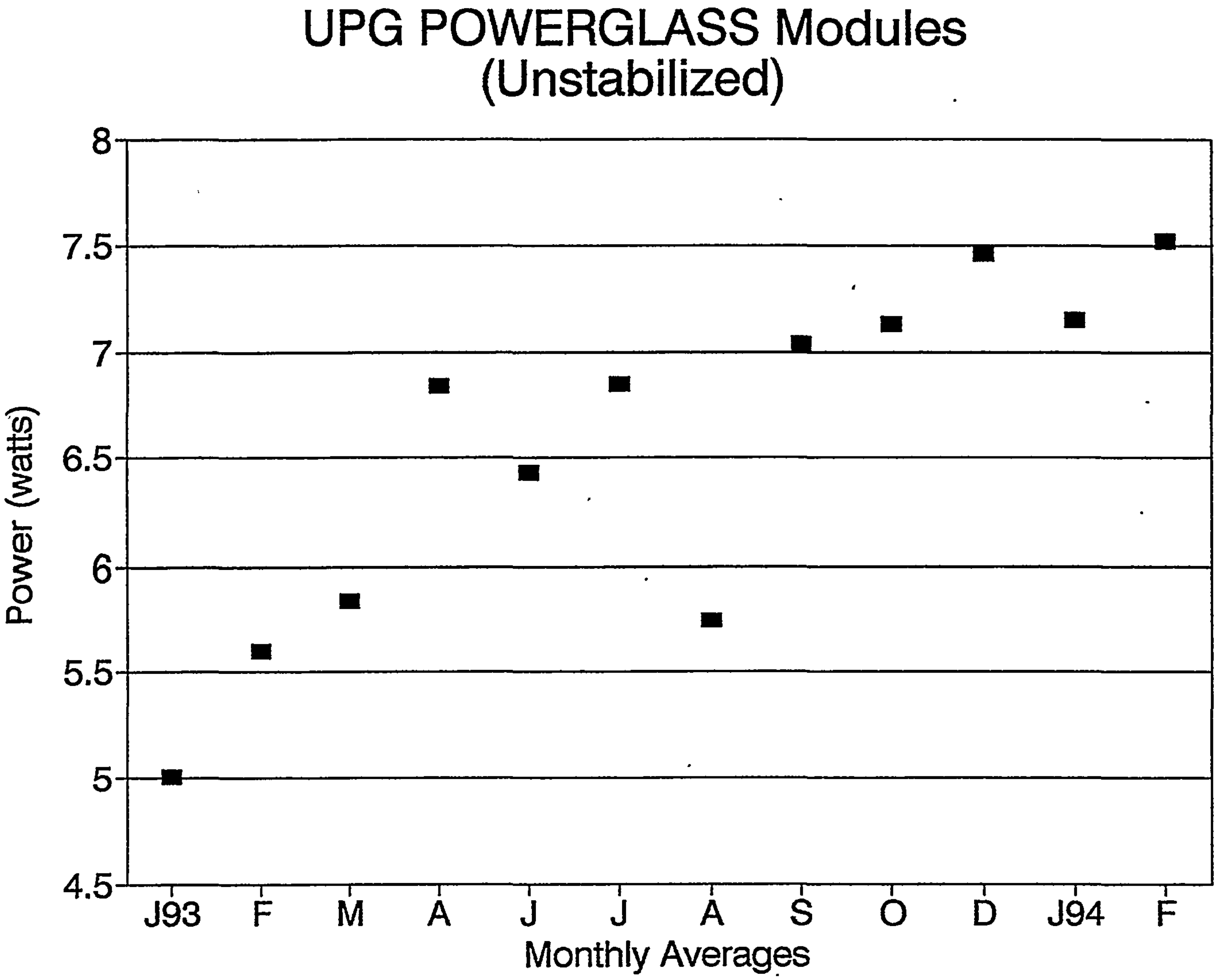


Figure 17. Monthly averages of the unstabilized power ratings for the modules produced between January 1993 and February 1994.

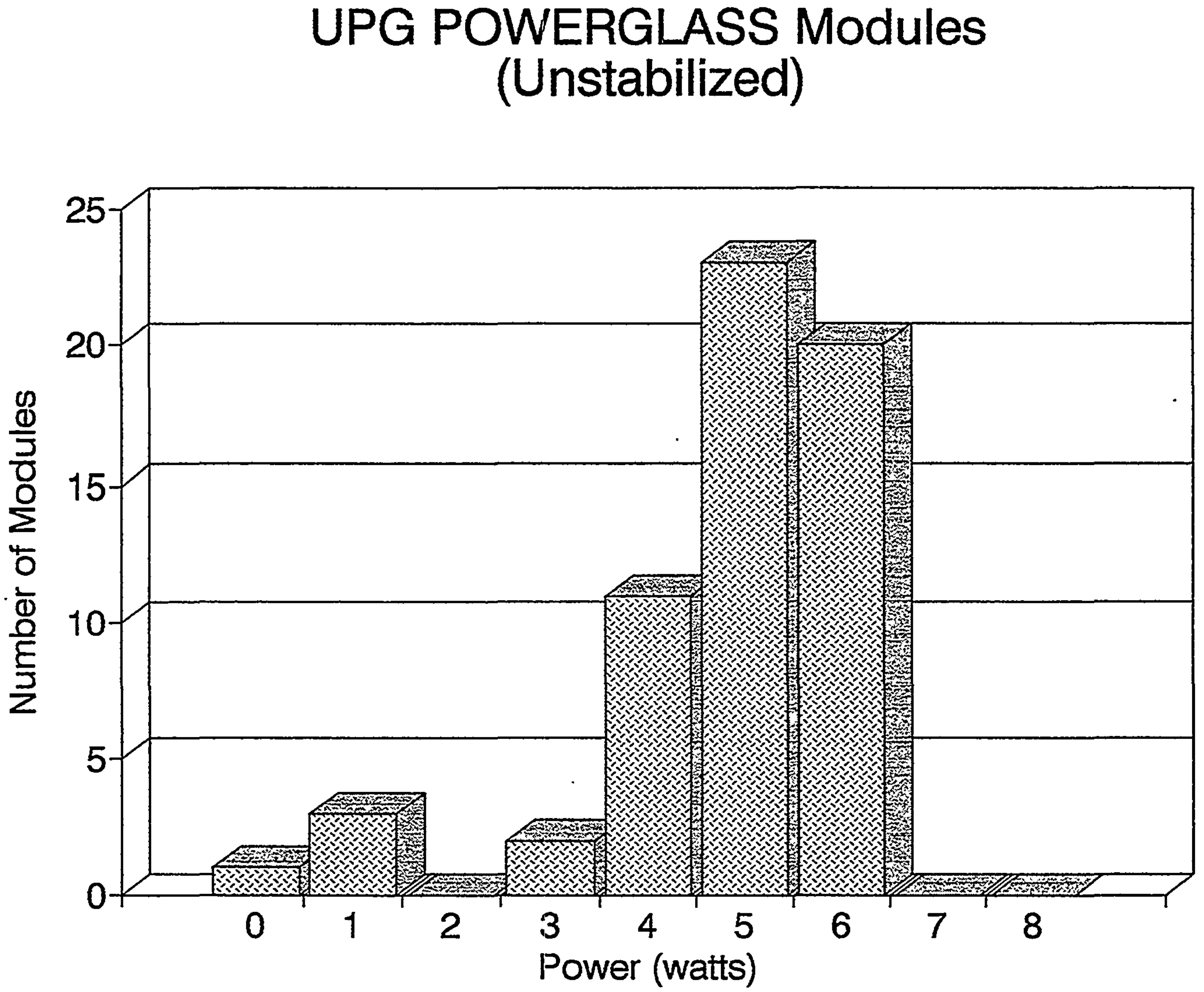


Figure 18. PVMaT modules produced for the first quarter of 1993.

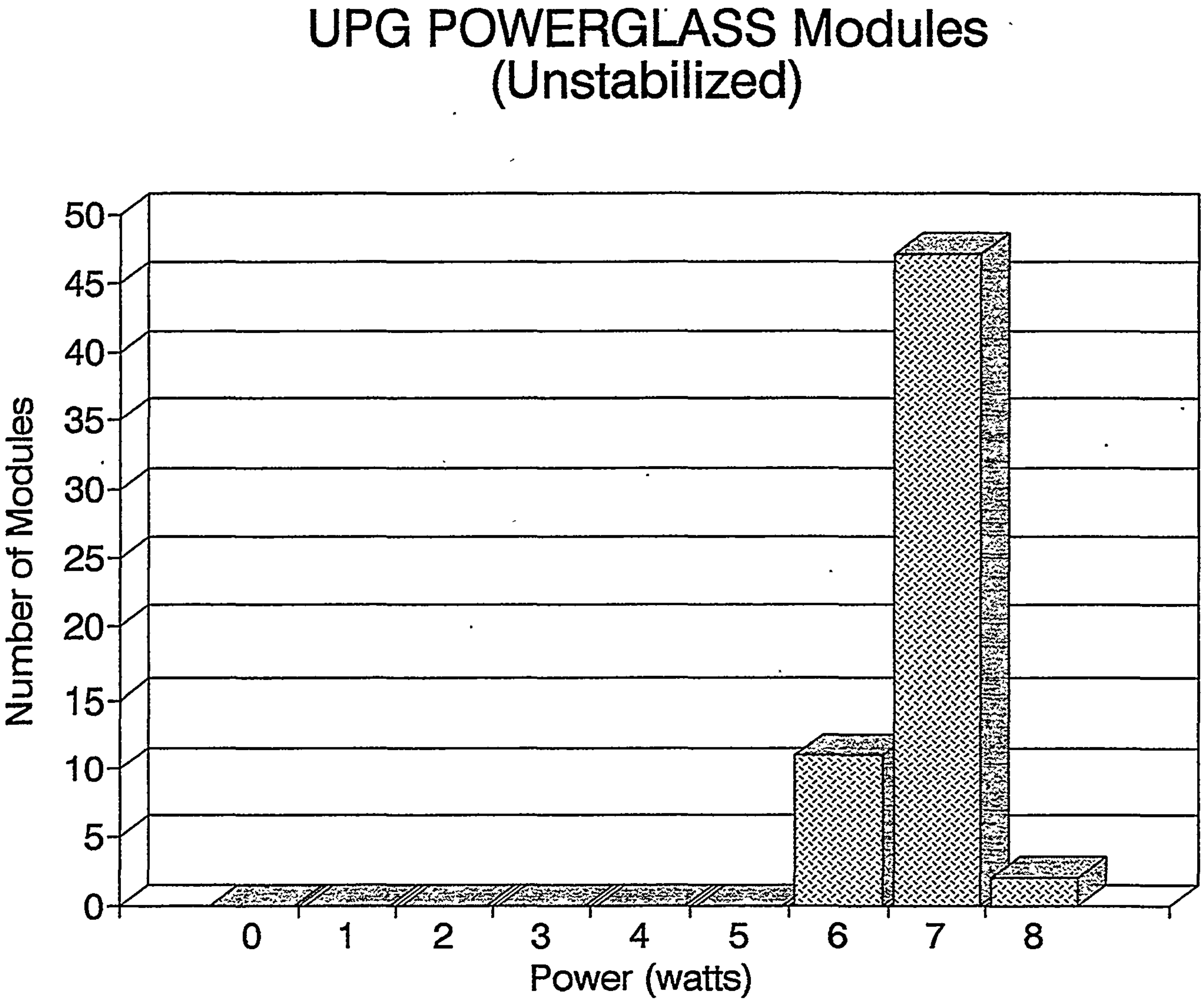


Figure 19. PVMaT modules produced for the last quarter of 1993.

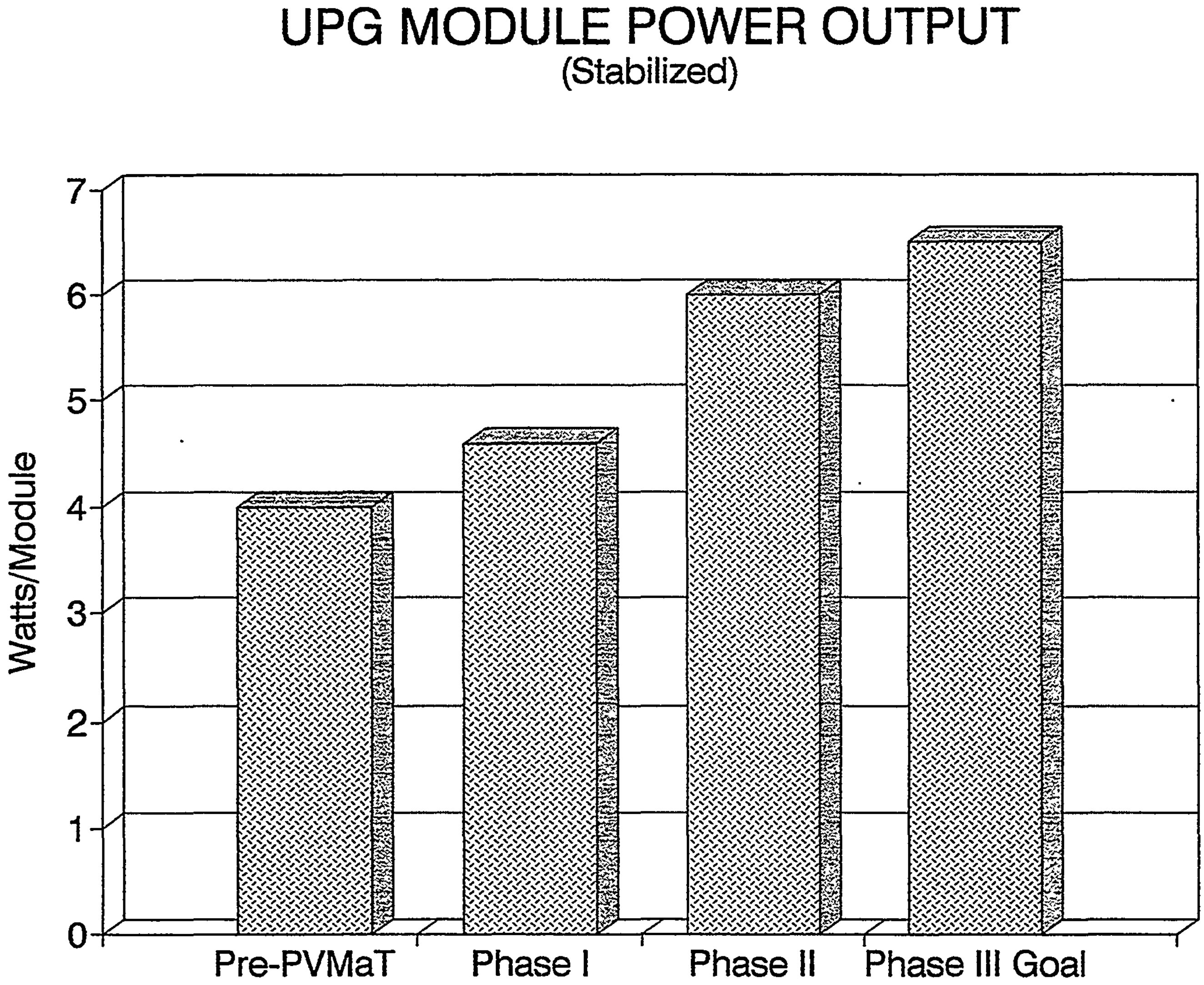


Figure 20. The power output of the POWERGLASS has steadily increased since the beginning of the PVMaT effort. UPG expects the stabilized output of the POWERGLASS module to be 6.5 watts at the conclusion of the PVMaT effort.

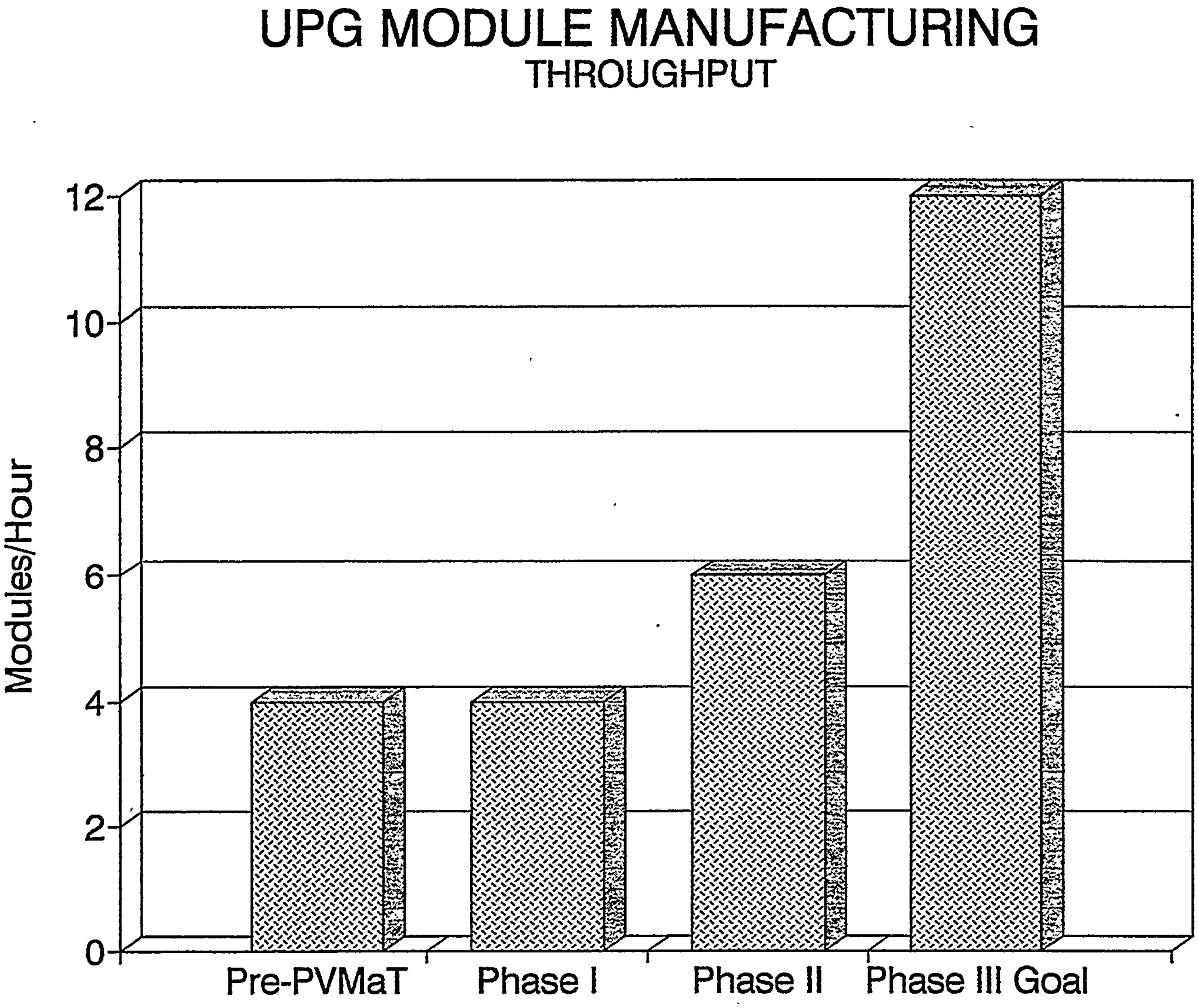


Figure 21. With the new automated termination and encapsulation systems in place the throughput of the UPG manufacturing line will increase from 4 modules per hour to 12 modules per hour.

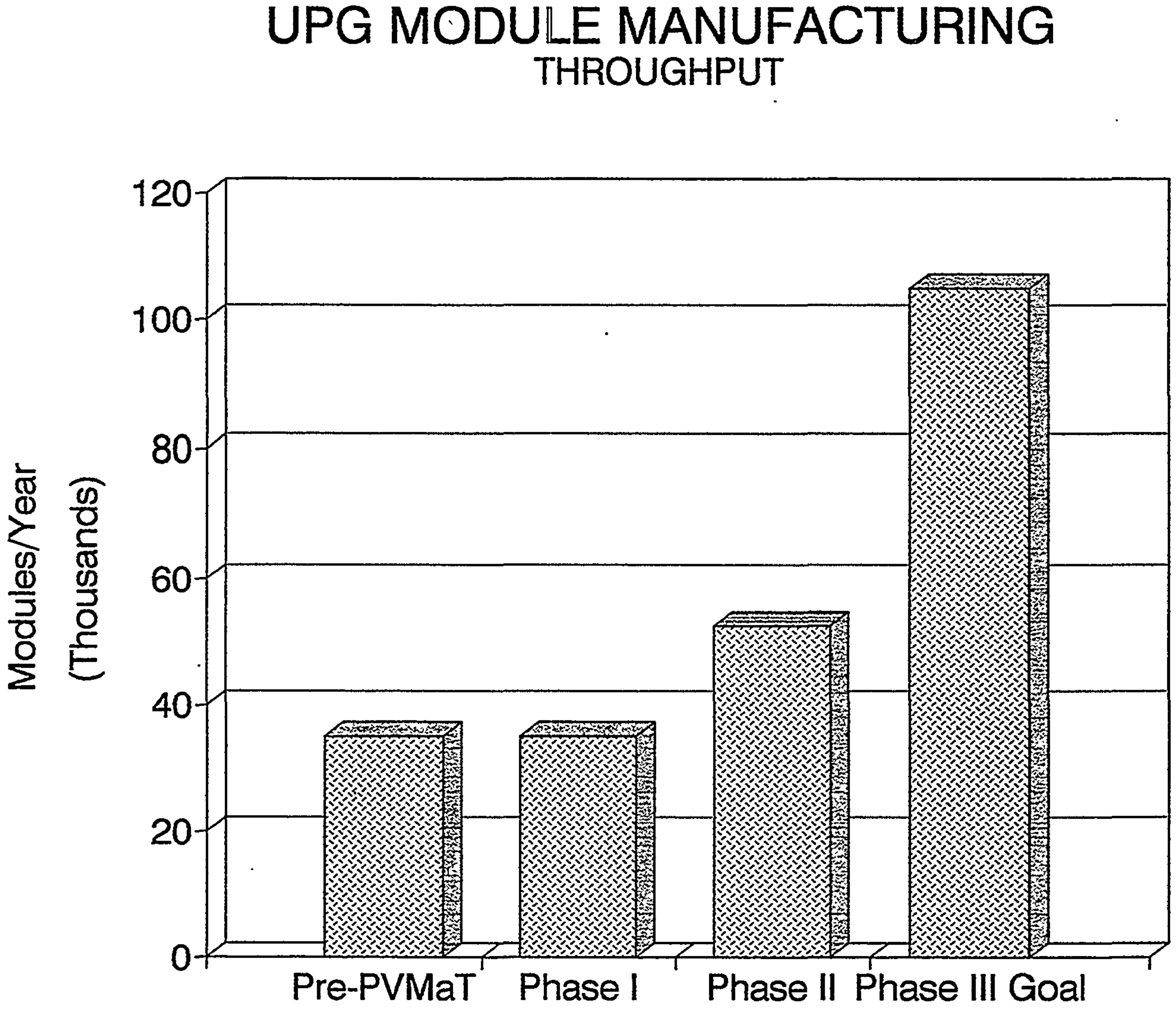


Figure 22. On an annual basis, the throughput will increase from a Pre-PVMaT level of 35,000 modules to over 105,000 modules per year by the conclusion of the PVMaT effort.

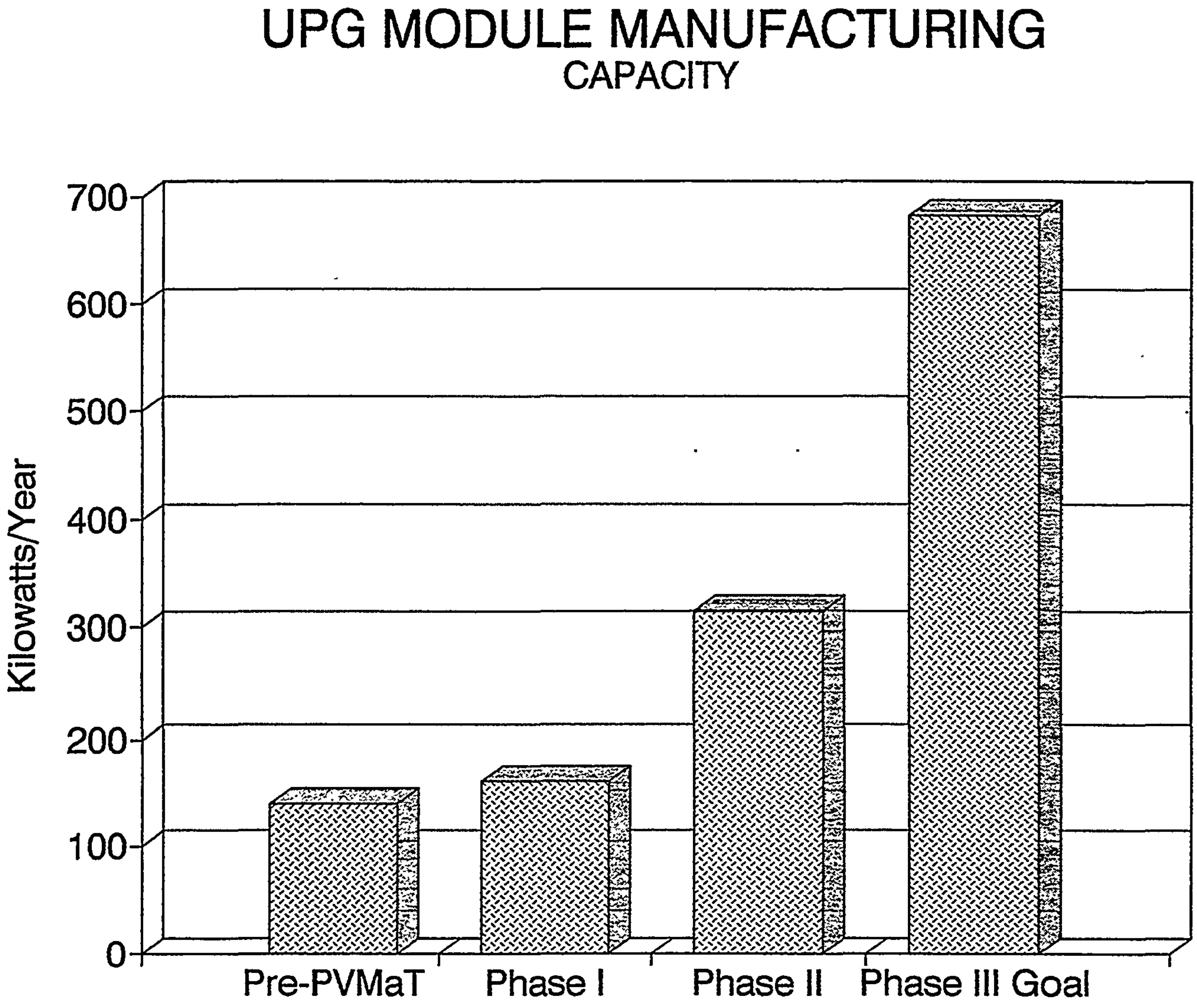


Figure 23. With the increase in throughput, and the increase in module performance, the capacity of UPG's manufacturing line will increase from 140kW per year for the Pre-PVMaT modules to 680kW per year for the new POWERGLASS modules at the conclusion of the PVMaT effort.

SUMMARY

- Significantly advance the PV manufacturing technologies

  UPG has developed and continues to optimize the advanced substitute materials and processes for thin-film module encapsulation and electrical termination of its POWERGLASS modules. The advanced termination and encapsulation have been designed to take advantage of automation techniques and will provide significant improvement in manufacturing cost reduction, yield, and reliability. The POWERGLASS module will continue to be recognized as one of the most reliable in the PV industry.

- Reduce module production costs

  UPG has obtained a cost reduction of 72% in its encapsulation process during the second phase of this project. UPG has obtained a cost reduction of 81% in its termination process. An overall cost reduction of 28% has been obtained in the total module production costs by addressing the termination and encapsulation processes alone.

- Increase average module performance

  UPG has obtained a 50% increase in its POWERGLASS module power output. This increase in module power is due to both an increase in the PV conversion efficiency and by increasing the area of the module.

- Increase production capacity

  By concentrating on the termination and encapsulation processes, UPG has increased the PV module production <u>throughput</u> by 50%. With a 50% increase in module power performance and a 50% increase in throughput, UPG has increased its PV module manufacturing <u>capacity</u> by a factor of 2.25.

Task 9 - Eureka Module Design

Objectives

The second year objectives for this task are to optimize the new Eureka power module designs and to develop a new design for architectural applications.

Market Study for New Module Designs

One new module design that was introduced during this phase of the contract is an architectural module. Market information and a design report regarding this product are presented here.

Methodology - Following an initial survey of architect, engineering, and builder respondents to identify particular applications within the building sector, a survey of the construction products manufacturers was conducted to quantify the market barriers associated with the applications. Manufacturers of balance of System components for architectural assemblies, particularly skylight and atrium manufacturers, and architectural glass product manufacturers were asked to review the technical and market issues associated with the identified niche market sectors. Specifically, meetings were held with Super Sky Products (Mequon, Wisconsin), Regal Manufacturing (Portland, Maine), and the New Products Division of Libby Owens Ford (Toledo, Ohio).

Market Overview - During the recent meeting of the American Architectural Manufacturers Association, Drucker Research (Bloomfield Hills, Michigan) reported to membership that the two emerging technologies which are likely to have the most significant impact on the building industry are Photovoltaics and Photochromics. Other energy efficient glazing technologies have matured and obtained significant market share. The PV industry has identified the building sector as an interim market opportunity obtainable in a 5 to 10 year time period which corresponds to the market maturation time frame from market introduction to acceptance in the building construction industry.

Discussions with the product manufacturers identified no significant barriers for the physical integration of the APS standard production modules into conventional glazing systems, although, the present module configuration does introduce limitations for applications.

Product Review - The architectural glass industry has evolved to provide custom glass products to the construction industry at a very minimal incremental cost over standardized production units. Due to the ability to supply custom sizes without significant cost implications, there are no standard sizes in the glass industry. Because of the economies in the manufacturing process of a:Si modules, this same flexibility can only be achieved with considerable cost implications. The APS module, while the largest thin film module in the PV industry, is also still slightly small than average architectural glass units in commercial construction.

Fenestration mechanical requirements are determined by codes for specific regions and construction systems. The module fabrication is consistent with fabrication of monolithic overhead glazing units and the strength of the APS module is adequate for a significant portion of the sloped glazing market. However, in regions where additional loading requirements are introduced such as snow loads or excessive wind loads, the APS module would not be acceptable without structural modification. This issue does not impact immediate market opportunity, as prime target regions are in southern regions with high solar insolation and no snow load consideration.

The slight opalescent rainbow discoloration which has been identified by the architects and builders as a significant barrier to the utilization of PV in a high visibility architectural application is analogous to the situation in the early introduction of other glass technologies. "Rainbows" were evident in the first generation of pyrolytic low E coatings and did limit their initial acceptance. There was some limited market opportunity in spite of the color aesthetic deficiency which permitted early introduction of the technology while the manufacturing process matured. Similar technologies require approximately ten years for full market acceptance. It can be expected that the current APS product is suitable for market introduction.

Light transmittance is an inherent part of the definition of fenestration products. Products which have no light transmission are defined as cladding panels and comprise a significant portion of the building envelope. Cladding panes, specifically spandrel panels in curtain wall construction, had previously been identified as a suitable application by the architect and builder respondents. However, for a cladding material, it is required that the product have no visible light transmission. In principle, the existing low level light transmission is easily removed to produce a completely opaque panel for this application. However, because the vertical orientation of the module in a curtain wall application does not yield high energy conversion performance, curtain wall applications do not represent the most viable market opportunity.

The highest value and most viable applications for the APS module has been determined to be in sloped glazing configurations such as atriums and skylights. These applications require white light transmission. Product suppliers have indicated application for modules with light transmission as low as 8% which may be more accomplishable as a near term objective than the 15% target. However, the market for 8% transmission glass is limited and will not lead to broad product distribution and a 15% white light transmission has been confirmed as the objective for an architectural product. Most architects will also accept reasonable spectral non-uniformity in the light coloration and pattern.

New Products

Two new module designs were developed. One was a higher output version of the EP50; it was developed as a 55 W module in the APS Trenton facility and introduced as a 60 W module when production commenced in the new APS facility in Fairfield, California. The other new product design is a semitransparent module intended for architectural applications.

Higher Output Module (EP55/EP60) - The main feature of this new design is its 60 W stabilized output compared to the 50 W output of the EP50. Towards that end, a 55 W module was developed in the APS Trenton development facility. The difference between this intermediate module and the 60 W module is the addition of ZnO to the back contact which the sputtering system in the Fairfield facility is equipped to add prior to aluminum coating.

The changes made to the EP50 to obtain the 10% higher output were:

- thinner p-layer (about 70% of previous)
- thinner i-layer (about 70% of previous)
- an extra cell and 5/8" additional cell width
- higher haze tin oxide
- improved uniformity

Of these changes, the thinner i-layer is the most critical, as it will add in excess of 5% to the stabilized output of the modules. The other changes will add about 2% each.

In order to be able to add a cell, the edge bonded foil width was reduced from 0.375" to 0.30". This module also incorporates other encapsulation improvements which deal with cost reductions and increases in throughput, and are discussed below under Task 11.

Performance of EP55/EP60 module - With production just having begun in the Fairfield facility, only limited information on stabilized output is available. This information consists of light soaked I-V measurements (600 hours at approximately V_{mp} and 50^{o} C), for modules whose silicon was deposited in the Trenton facility and whose aluminum was sputtered either in the Trenton facility (EP55) or in the Fairfield facility together with ZnO

(EP60). A much larger data base is available for light soaked diagnostic plates, 10cm by 30cm sections of full plates that contain 5cm wide interconnected cells and 3mm diameter free standing devices. Measurements made on diagnostic devices are limited to 16 hour light soaking. Extrapolations are then made of the linear decay of efficiency with log time. This is believed a worst case situation because longer-term light soaking generally shows a trend toward saturation.

Table 4 shows measured as-made electrical parameters and stabilized output estimated from diagnostic measurements (EP50 and EP55 processed in Trenton and EP 60 processed in Fairfield) and measured parameters for two full size modules silicon deposited in Trenton and sputtered in Fairfield (fourth entry in table).

Semitransparent module - The other new design is a transparent module for architectural applications. The goal was to achieve 20% cleared area with good visual uniformity. This goal was met and two prototype modules were submitted to NREL as a deliverable.

Much of the effort towards developing these modules overlaps other tasks and will be discussed under those headings. Thus uniformity is discussed under process and quality control (Task 10), and details of cost reductions in encapsulation are discussed under Eureka Encapsulation and Termination (Task 11).

Table 4. I-V Parameters of APS Modules

	As-made				Light soaked			
Type	Voc	Isc	FF	Power	Voc	Isc	FF	Power
EP50	55.6	1862	68.4	70.9	54.5	1761	53.4	51.2
EP55	56.9	1867	66.6	70.8	56.8	1788	55.8	55.3
EP60	55.5	2016	66.6	74.6	54.4	1968	55.8	58.2
EP60					55.7	1870	56.9	59.3

Several means of achieving the transparency have been tried, and sandblasting chosen. Other methods tried were:

Lasering - Multiple laser scribing was carried to the point of making a small area (1'x1') sample. For this module, the aluminum scribe was repeated 28 times to achieve a 10% open area. This together with a 1/4" clear border resulted in approximately 18% open area; the relative contribution of the border area will be less for larger modules. One advantage of lasering is the power lost is very close to the active area lost, while with some of the other techniques being considered, more output has to be sacrificed. A more powerful laser than that used for aluminum scribing may make this approach less time consuming but at this time, lasering is not deemed a good choice.

Masking - Brief testing suggested that masking prior to either silicon or aluminum deposition is possible; both have been done for other purposes. To determine the feasibility of this approach, a mask consisting of eight 0.5" diameter cylinders of teflon was placed between two opposing plates in a box carrier. Different lengths of teflon cylinders were used in order to vary the gap between the glass and the teflon pieces and determine the largest gap that will show a good demarcation line between deposit and no deposit. Examining the resultant plates indicated that to get sufficiently good resolution, the mask has to be in closer proximity to the glass than could be reliably achieved with automatic loading of box carriers. For this reason this approach was not chosen.

Sandblasting - This was the fall back position. It was tested most extensively and adopted as the method of choice. Initially small test samples were made. In full size Eureka plates it was determined that the shorting which the production sandblaster causes also occurred with the portable sandblaster used for the bulk film removal. Measurements indicate that shorting occurs up to about 1/8" from the edges of the sandblast areas; these are isolated from the active area of the panel by a laser isolation scribe. The laser isolation scribe also introduces shorts, but these shorts have much higher resistances than those resulting from sandblasting and therefore cause only a small power loss in the standard modules. Allowing an additional 1/16" for safety would result in a nearly 40% larger power loss than the gain in transparent area if 1" wide cleared strips were used. This large loss is unacceptable and therefore to adopt sandblasting, either the sandblasting damage has to be more localized or larger cleared regions have to be employed. Both were done. Masking the panel prior to sandblasting minimizes the amount of area lost and limits the damage to within 1/32" of the sandblast region.

The layout chosen for the prototype semitransparent module is shown in Figure 24. Other than the cleared area and a lower power output, the module is identical to the EP55 and the drawings submitted for that product apply. The main difference in I-V parameters of the semitransparent module is the output current loss due to the area loss. There is also a loss in FF which results from the shorting introduced by the laser isolation of the sandblast region. This shorting has little effect on full size standard modules, where approximately 1 A is generated per isolation line. For the semitransparent module only about 0.2 A is generated per each scribe line and the current shunted into the shorts is large enough to reduce the fill factors noticeably. The isolation process has not been optimized for these multiple isolated plates, and some improvement in performance can be expected when this process is optimized.

For the small sample available, the following performance comparison can be made between the semitransparent modules (ST45) and the standard EP55 module. The EP55 numbers are taken from the above table, and the degradation of the ST45 is taken to be the same as that of the EP55 (only non-light soaked data are available for the semitransparent modules at this time).

Table 5. Semitransparent Module Parameters

	Voc V	Isc mA	FF %	Power W
EP55	56.8	1788	55.8	55.3
ST45	56.7	1620	51.9	46.4

The current is somewhat higher than predicted, while the FF is lower than it is for the EP55, probably for the reasons given above.

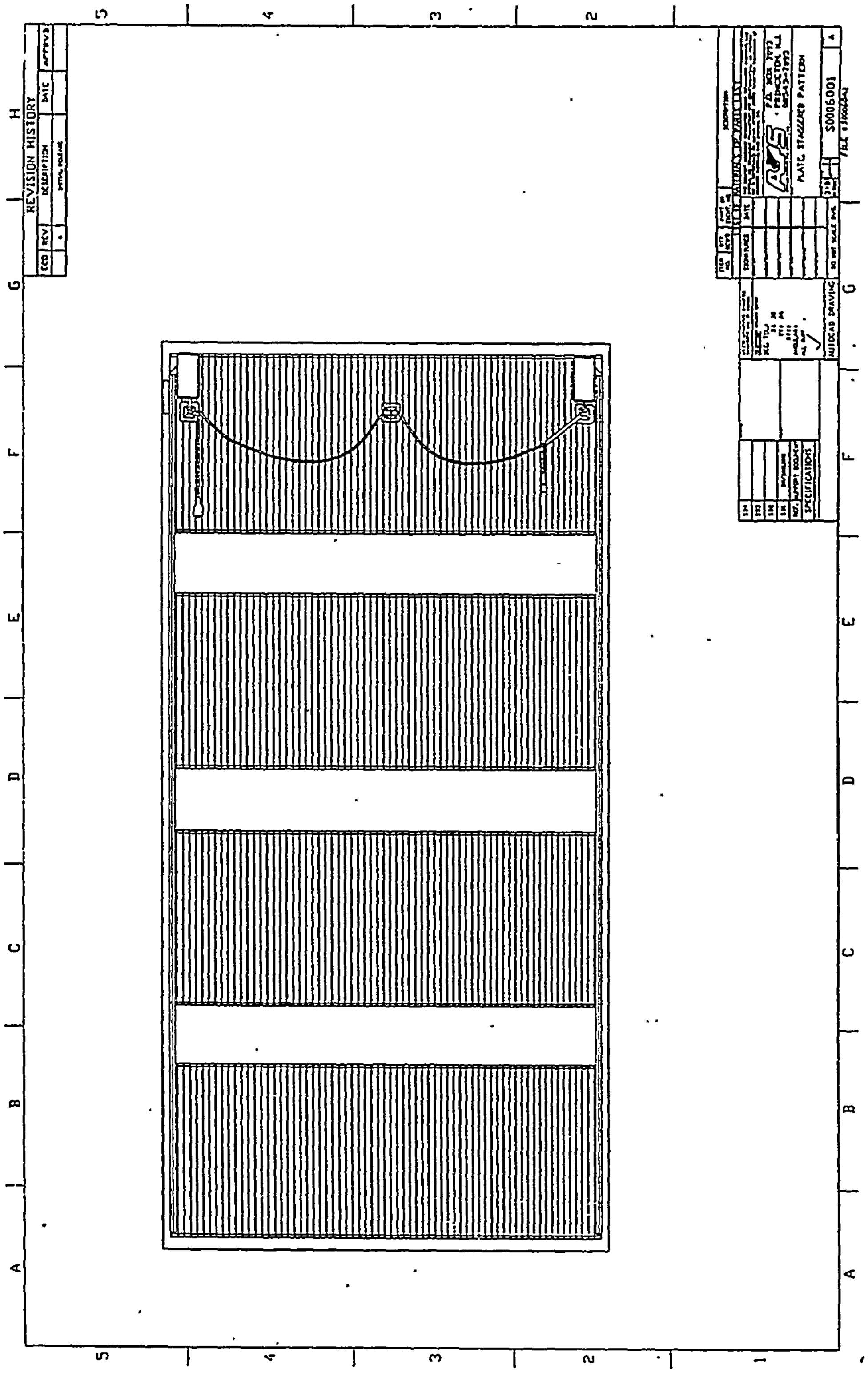


Fig 24 Layout of Semitransparent Module

Task 10 - Eureka Process and Quality Control

Objective

The objectives of this task are to establish a high degree of process and quality control within the Eureka manufacturing system in order to improve quality, yield, and throughput of the line and to introduce SPC into the Fairfield facility.

Several somewhat interrelated items fall into the area of process and quality control. Thus, in addition to the critical control parameters specifically identified, several other topics are separately discussed; these are uniformity, RGA measurements, flow calibration, testing of product, and product tracking.

Review of Critical Control Points

The goal was to determine the influence of critical control points on quality, yield, and throughput, with actual control to be achieved later. Since APS was nearing operation of its new facility when this effort began, tight control of many of these critical areas has been put in place, although more stringent controls may be implemented at a later date. Five control points were studied in some detail. They are; deposition base pressure, flow rates during deposition, pressure during deposition, laminator temperature and edge isolation quality. The influence of the deposition control points on product quality and deposition rate was studied. While deposition rates (thickness measurements) are not a measure of quality, they can provide detailed and almost real-time feedback on the extent of control of the deposition process.

Deposition Base Pressure - A graph was presented in the first Annual Report that showed the influence of base pressure on plate quality (FF); this graph is repeated as Figure 25. While these data are as-made results and not light soaked, testing of product having a range of quality strongly suggests that light soaked results would behave similarly. The influence of base pressure on throughput can be inferred from the pumpdown characteristics of the deposition system. Clearly a more stringent pumpdown requirement will result in a longer pumpdown, and hence, lower throughput. To counteract this, steps have been taken to reduce the pumpdown time and make it consistent with the overall throughput requirements of the factory.

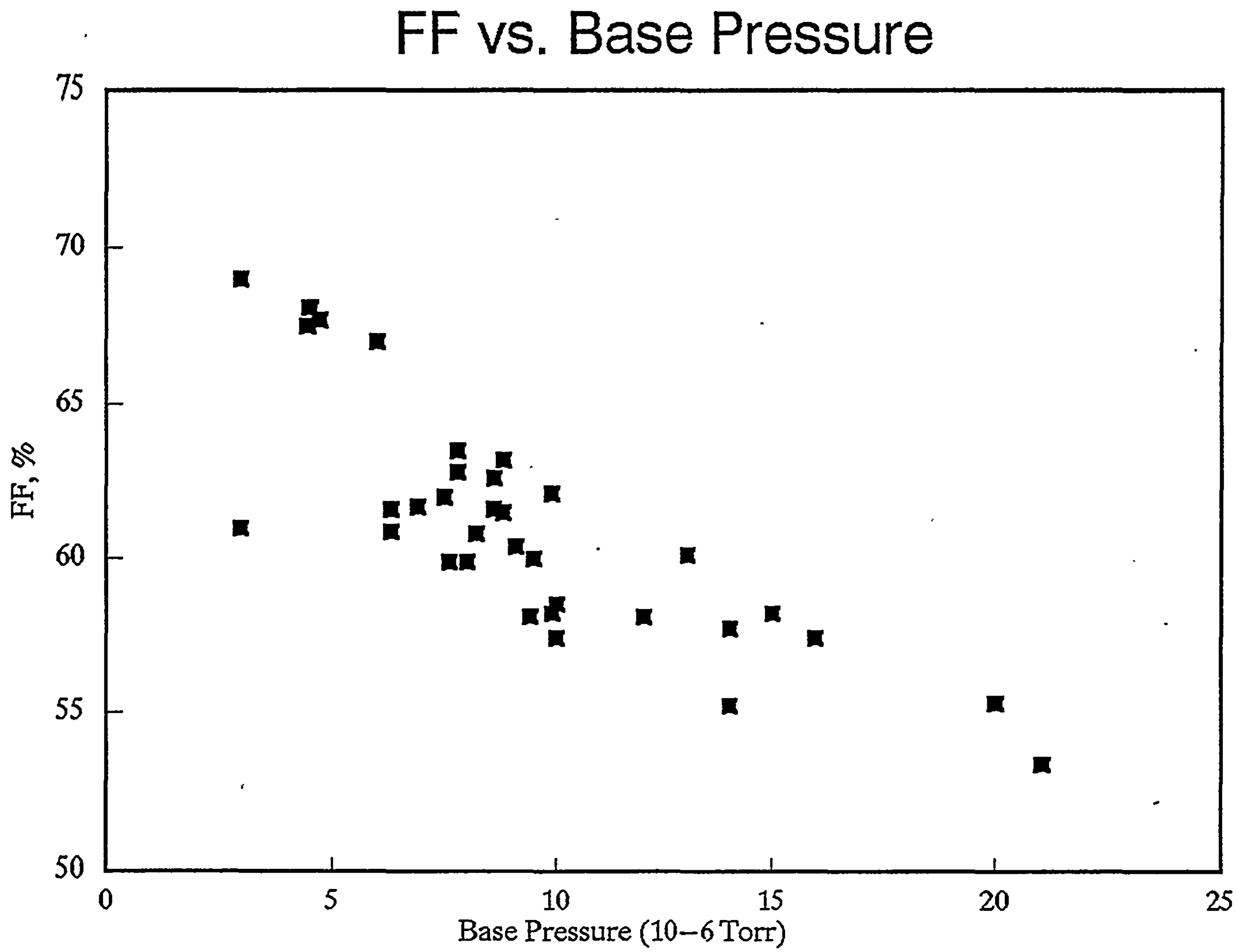


Fig. 25. Fill Factor vs. Base Pressure

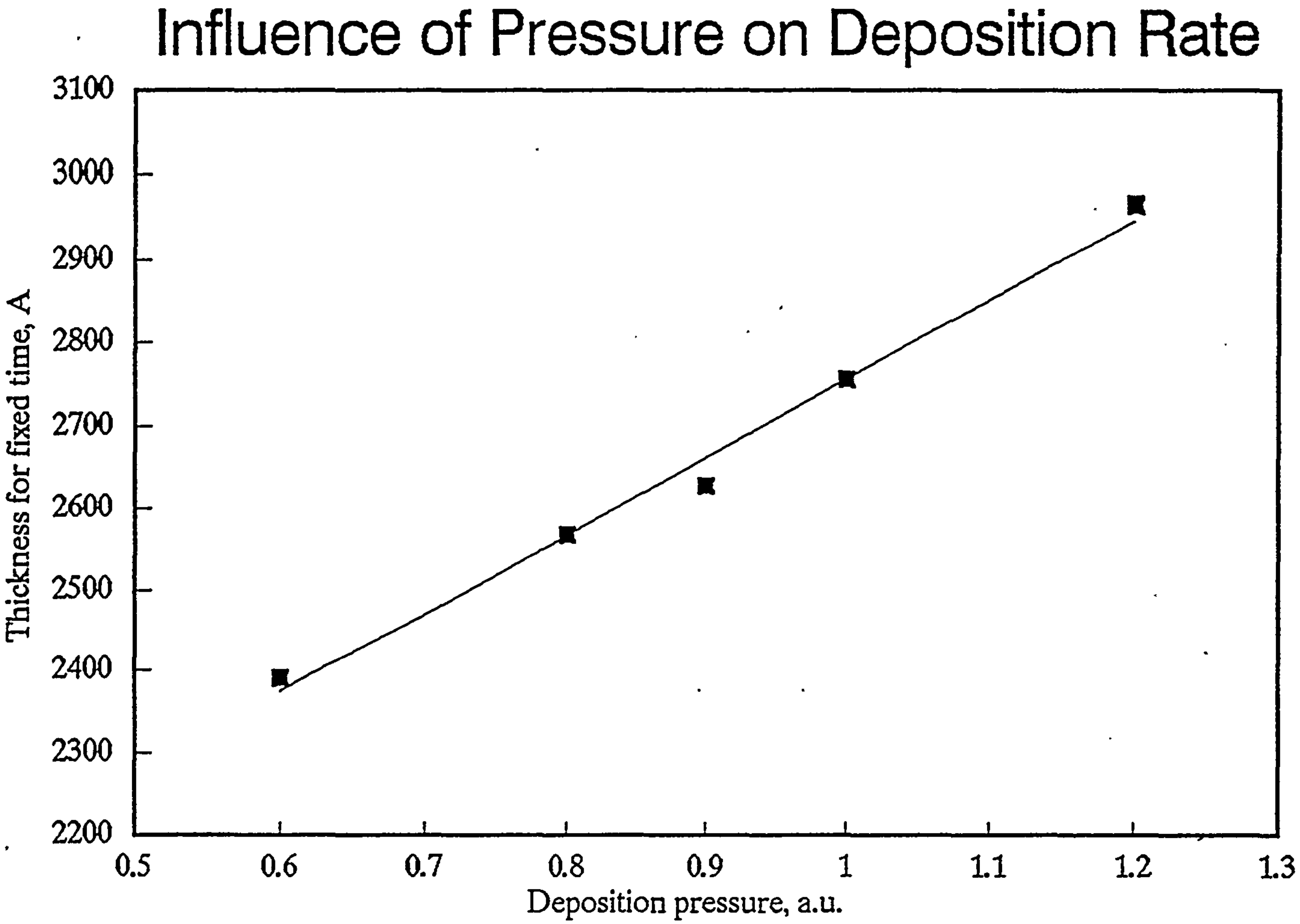
Deposition Pressures - The influence of deposition pressure on deposition rate (thickness) is shown in Figure 26. These data were obtained from three separate deposition runs and illustrate the scatter from run to run. It should also be noted that the thickness measurements are more correct relative to each other than absolutely.

Flow Rates - The influence of flow rates on deposition rates has been determined. Changes in flow rate without changes in composition have only a small effect on deposition rate. The effect is well within the variation in thickness from plate to plate. Uniformity changes are more easily detected and composition changes will result in changes in uniformity (this is further discussed under uniformity).

Edge Isolation Quality - Two potential problems with sandblasting are that film removal is not complete, and that damage due to sandblasting extends into the active area of the plate. With the recent reduction of space between the sandblasted region and the edge isolation line (to isolate the active area from the sandblast region) from 1/2" to 3/16", the second problem becomes even more important. The extent of shunting is not only influenced by the distance from the sandblast region (which is fixed), but more importantly be the quality of the sandblasting.

Figure 27 shows the influence of shorting on power output. Plates that have not been shuntbusted lose several percent of power as a result of shorts (typically from aluminum scribing); shuntbusting should add no measurable shorts, but has on occasion resulted in more than 10% higher loss and short term yield losses near 50%. To control this step, a low light level open circuit voltage measurement ($LLLV_{oc}$) is made after sandblasting (and just recently during the plate I-V measurement before sandblasting). The basic assumption made in using these measurements is that the light intensity is low enough so that the V_{oc} for each cell is equal to the product of cell shunt resistance and current. This will be the case if both cell resistance and light intensity are sufficiently low. If the light intensity is set to typically result in an I_{sc} of I, and the minimum $LLLV_{oc}$ allowed is V, then the power loss that this corresponds to can be calculated. Thus, V/I corresponds to an effective resistance, R, of the shunts, and at the maximum power point, a current, V_{mp}/R, will be lost to the shunts. Since the maximum power current is I_{mp}, the fraction $(V_{mp}/R)/I_{mp}$ (or $V_{mp}*I)/I_{mp}*V)$) is an estimate of the power lost.

For the EP50, typical values are 38 V for V_{mp}, and 1300 ma for I_{mp}. The light intensity is set to give an I of 5 ma and the cutoff V was chosen to be 4 V. Thus, the maximum power that is allowed to be lost in sandblasting is about 3%. If the $LLLV_{oc}$ of a plate is less than 4 V after sandblasting, the plate is passed



measurements are averages for several plates each
thicknesses are normalized to a given deposition time

Fig. 26. Effect of Deposition Pressure on Deposition Rate

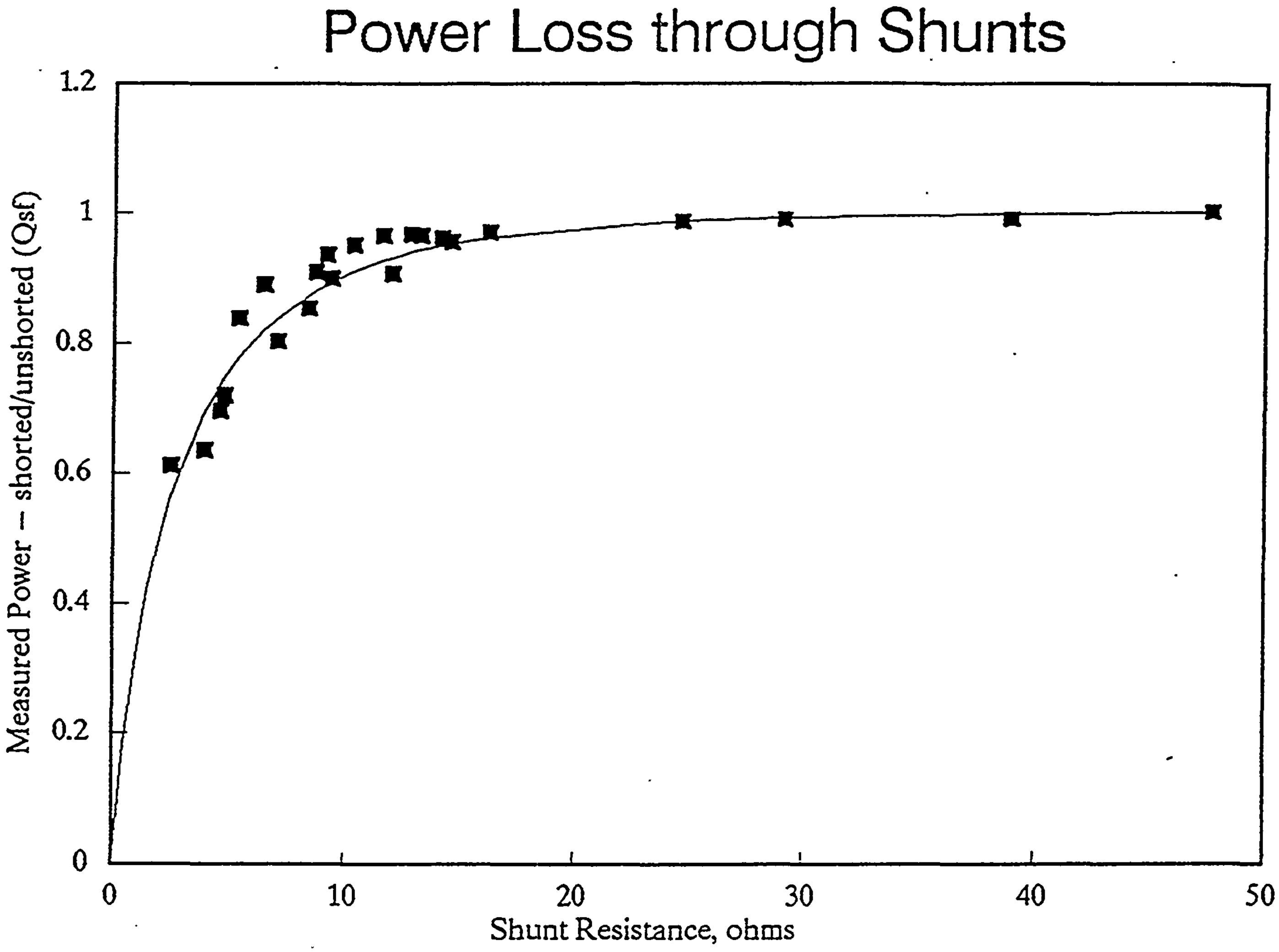


Fig. 27. Power Loss caused by Electrical Shorts

through the sandblaster a second time. If the voltage drops as a result of the second pass, then the sandblasting is halted and the problem corrected. These steps together with visual inspection for incomplete sandblasting are considered sufficient for monitoring and controlling the sandblasting procedure.

By adding a $LLLV_{OC}$ measurement at the plate I-V station, a comparison of before and after sandblasting $LLLV_{OC}$ can be made and corrective action can then be based on these measurements rather than on a second sandblasting and V_{OC} measurement. This second measurement will make it easier to immediately deal with plates whose $LLLV_{OC}$ is less than 4 V even after shuntbusting, which happens occasionally. In the Fairfield facility, all measurements will be centrally collected and used to control the process. Thus, automatic comparisons of the two $LLLV_{OC}$ measurements and actions based on them are planned.

Laminator Temperature - With the introduction of the split cure and its short heating cycle in the laminator, control of the laminator temperature becomes more important. If the laminator platen temperature is too low, incomplete cure results, while too high a temperature causes bubbles to form. These observations, though qualitative, were convincing enough so that early in the program it was decide to have tight control of the platen temperature and its uniformity in the laminators installed in the Fairfield facility. Towards this end, the heating elements for the platen have been divided into four zones, each separately controlled. Four additional thermocouples are placed on the platen to further define temperature uniformity. These additional controls and monitoring steps are believed to provide the necessary temperature control of the lamination step.

Yield at the Critical Control Points

The APS manufacturing line began production runs in April of 1994 at the nominal rate of one run per day. A new product, the EP60 was introduced in Fairfield. One component of the increased output over that available in the APS development line in Trenton is a higher quality tin-oxide (haze about 6% compared to 3 to 4% haze of the tin oxide used earlier). In part because a lower haze tin-oxide is also being used together with the higher quality tin-oxide, a product mix of 50, 55 and 60W PV plates is allowed for.

Deposition - For deposition, three critical control points were investigated. For these three critical control points a combined yield of 91.3% (.97 cubed) would have to be exceeded to meet the milestone stipulated. For the last five runs processed in April (one week of runs), the results shown in Table 6 were obtained. The 17.5% plate loss is mainly the result of RF problems where entire RF sections (four plates each section) did not fire. These problems are cable related and are being addressed.

Table 6. Thin Plate Line Yields

	Count	Percentage Yields Plate	Electrical	Cumulative Electrical
Plates in	240	100		
Plates out	198	82.5		
"60 W" plate	64	26.7	32.3	32.3
"55 W" plates	116	45.8	58.6	90.9
"50 W" plates	13	5.4	6.6	97.5
Rejects	5	2.1	2.5	100

Encapsulation

For the encapsulation line two control points were studied. The edge isolation quality is monitored separately via the low light level voltage measurement. For a one week period, the quantity processed was 81 pieces, and of these, only 1 failed this test.

The second control point in the encapsulation line is the lamination platen temperature. Failure at that point manifests itself in delamination or other reason for rejection. For the same batch of 81 plates, rejection at lamination was 2 plates, again within the 97% yield level.

As will be shown in a discussion of costs, the overall yield for a one week period was 65%. The remaining yield losses are best explained by a learning curve. The control points chosen were meant to address the difficult issues, fine tuning of the remainder of the line should bring overall yields to acceptable levels in the 80% range.

This concludes the discussion of critical control points and the milestones associated with this task. The following are separate issues that were deemed important and which received significant attention.

Uniformity

The main reasons for improving the uniformity of the silicon deposit are appearance and internal matching of I-V parameters. For architectural applications, it is believed that the uniformity of the modules delivered to PVUSA needs to be improved upon. The primary reasons for this is a very thin deposit in one corner of most plates that existed when this program began (see Figure 28 and the explanation below). While this comprises only a small area of the plate, it can be very visible, more so for thinner average thicknesses of plates. This thin spot may be as little as 1/3 the thickness of the thickest region of the plate. Electrically, its influence is not very great unless the silicon is thin enough to make laser scribing difficult. With the need to reduce i-layer thickness for improved stabilized output, the non-uniformity becomes an important issue. In order to achieve the stabilized 60 W power output, module i-layers thicknesses were considerably reduced. This reduction was only possible with the improved uniformity that resulted from the work done in this program.

The two main causes of non-uniformity are the RF connection to the powered electrode (which causes a decrease in thickness) and chemistry. Because silane is consumed during the deposition, the gas phase composition varies from top to bottom of the box carrier (the direction of gas flow) and this is reflected in a change in deposition rate, it being higher at the bottom than at the top (contrary to what might be expected).

In order to judge progress in improving the uniformity, two tools are being used. First, an optical thickness monitor is part of the silicon laser station; it measures light transmission at 25 points on each plate and stores these measurements for later analysis. Secondly, a digital still camera has been acquired which is used to photograph every plate that is processed. The photograph is taken through a 580 nm filter to better define the thickness variations. Images obtained with this setup typically show fringes of equal thickness that are separated by about 600 nm. The actual darkness of the image is not very significant since it is a function of light intensity and exposure time.

Figure 28 shows an image of a plate made with the standard box carrier and under standard conditions. This is typical of what is obtained under these conditions, although only slight variations in thickness, as would typically be obtained from plate to plate and run to run can alter the details of the image.

The first approach at eliminating the gross variation seen in the lower left hand corner was to increase the size of the box carrier, thus allowing the glass plate to be removed from the region of thinnest deposit. The result of this change is shown in Figure 29 which is a plate made in a larger box carrier but with otherwise the same conditions as the plate in Figure 28. As can be seen, the closely spaced fringes of thin deposit have disappeared. An unexpected result of this box carrier was a much thicker deposit in the opposite corner of many plates.

Fig. 28. PV Plate Deposited in Standard Box Carrier

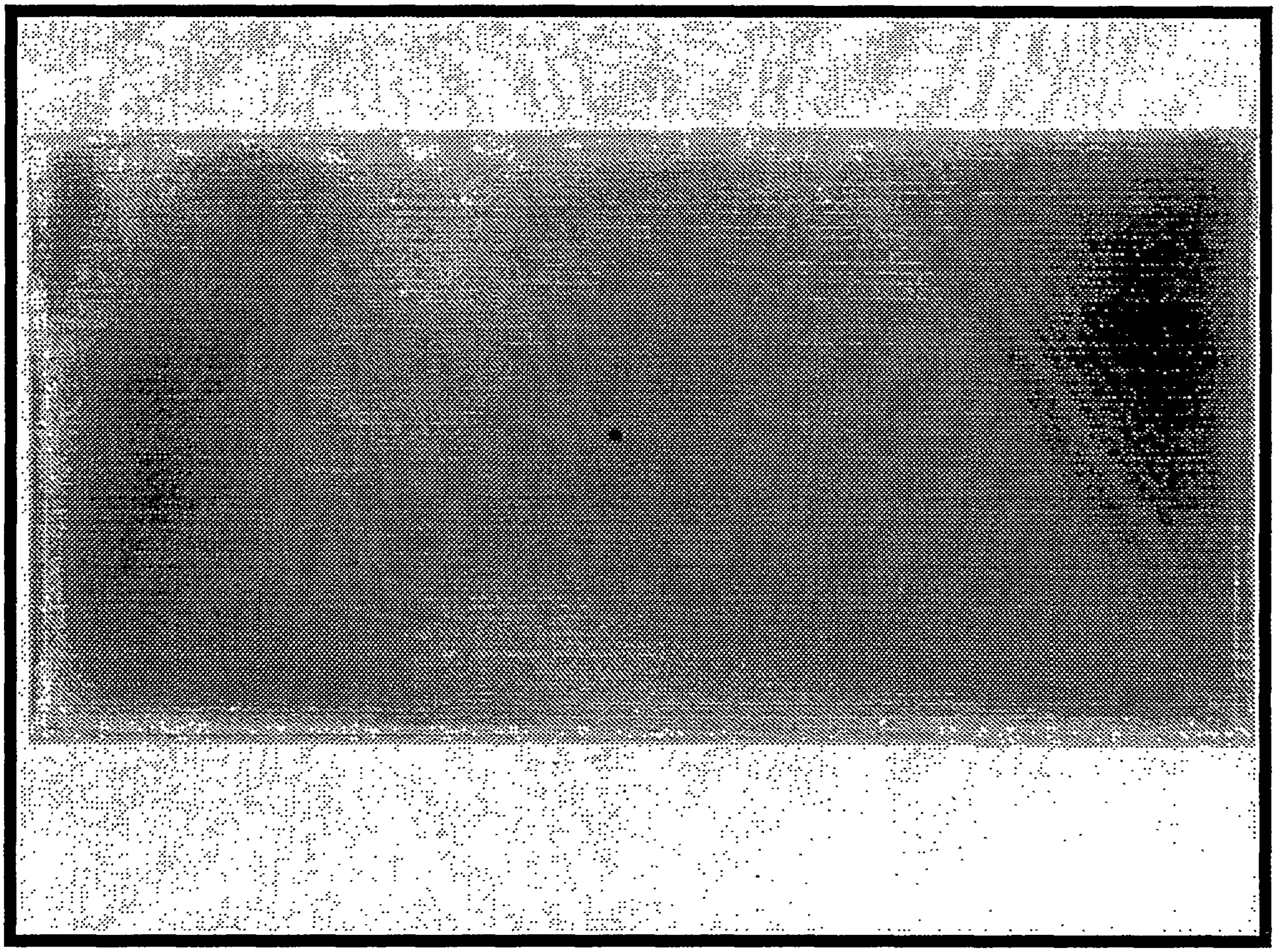


Fig. 29. PV Plate Deposited in Modified Box Carrier

For some plates, this thickness would double over a very small region of the plate. Increasing the flow rates of deposition gases in order to reduce the residence time to compensate for the larger volume of this box carrier, helped the situation, although the thickness is still somewhat greater in that corner than would be expected. Figure 30 shows an image of a plate made with 20% higher than normal flow rates in the box carrier. Similar to adjusting the flow rates, reduced pressures also tend to improve the uniformity of deposit. Thus the standard deviation of the 25 thickness measurements decreased from 16% to 12% (a 25% reduction) when the deposition pressure was decreased from 100% to 50% while maintaining the standard flow rates.

Another approach to reducing non-uniformity is to make the RF effect counter the chemistry effect. By making the RF feed point at the bottom of the box carrier rather than the front, the general increase in thickness from top to bottom resulting from chemistry should in part be offset by the decrease due to the RF effect. This has been tried in a small box carrier with the results shown in Figure 31. Only a small region of thinner deposit is seen at the bottom of the plate. To eliminate this small area of thinner deposit additional modifications have been made to the box carrier. These are along the lines of the larger box carrier in that the RF connection point is removed from the discharge region. In this case, a 3.5 cm extension to the electrodes has been added. A box carrier with this modification is nearing completion.

It should be added that thinner deposits are much more noticeable to the naked eye than are thicker deposits because as the deposit gets thicker, the appearance becomes darker and variations become less apparent. The images obtained with the digital camera are made under conditions that enhance uniformity variations; the visual appearance of the panels made with the larger box carrier are quite good. The larger box carriers described above are currently in use in the APS Fairfield facility.

Residual Gas Analysis Measurements

A residual gas analysis (RGA) instrument (Transpector from Leybold Inficon, Syracuse, NY) has been in use for several months. Two applications have been identified and tried for this instrument (and are foreseen in the APS Fairfield facility). One is the standard application of a residual gas analyzer, to determine the quality of vacuum prevailing in a pumped down deposition chamber. This will not only detect some leaks, but will also identify any abnormal or unusual outgassing that may be occurring. The second use is to monitor the deposition process itself. In analyzing background gases, the species of greatest magnitude is, as expected, water. Low levels of other species are also present, but to very much smaller extents. Thus, signals at mass 28 and 44,

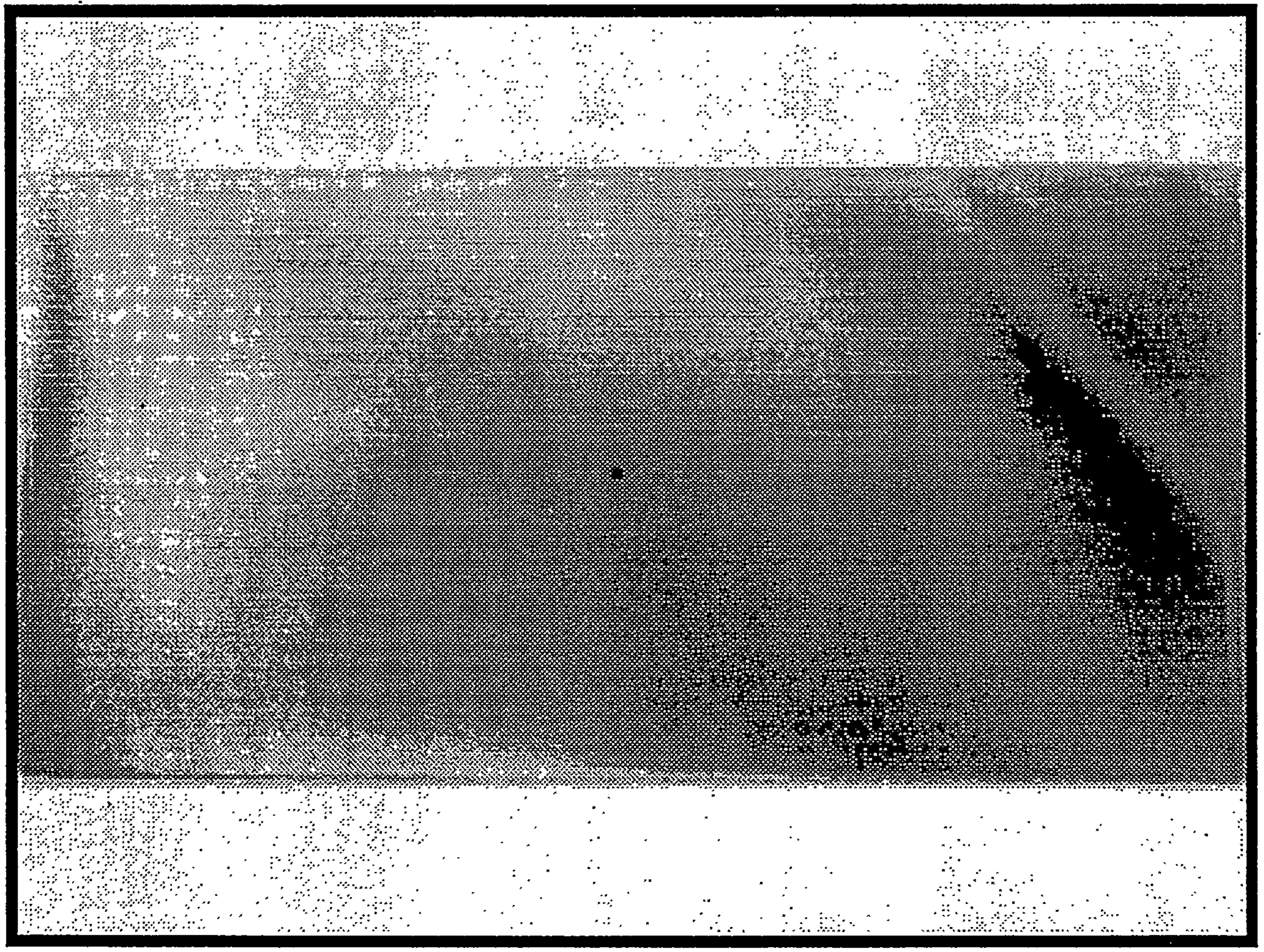


Fig. 30. PV Plate Deposited in Modified Box Carrier with Higher Flows

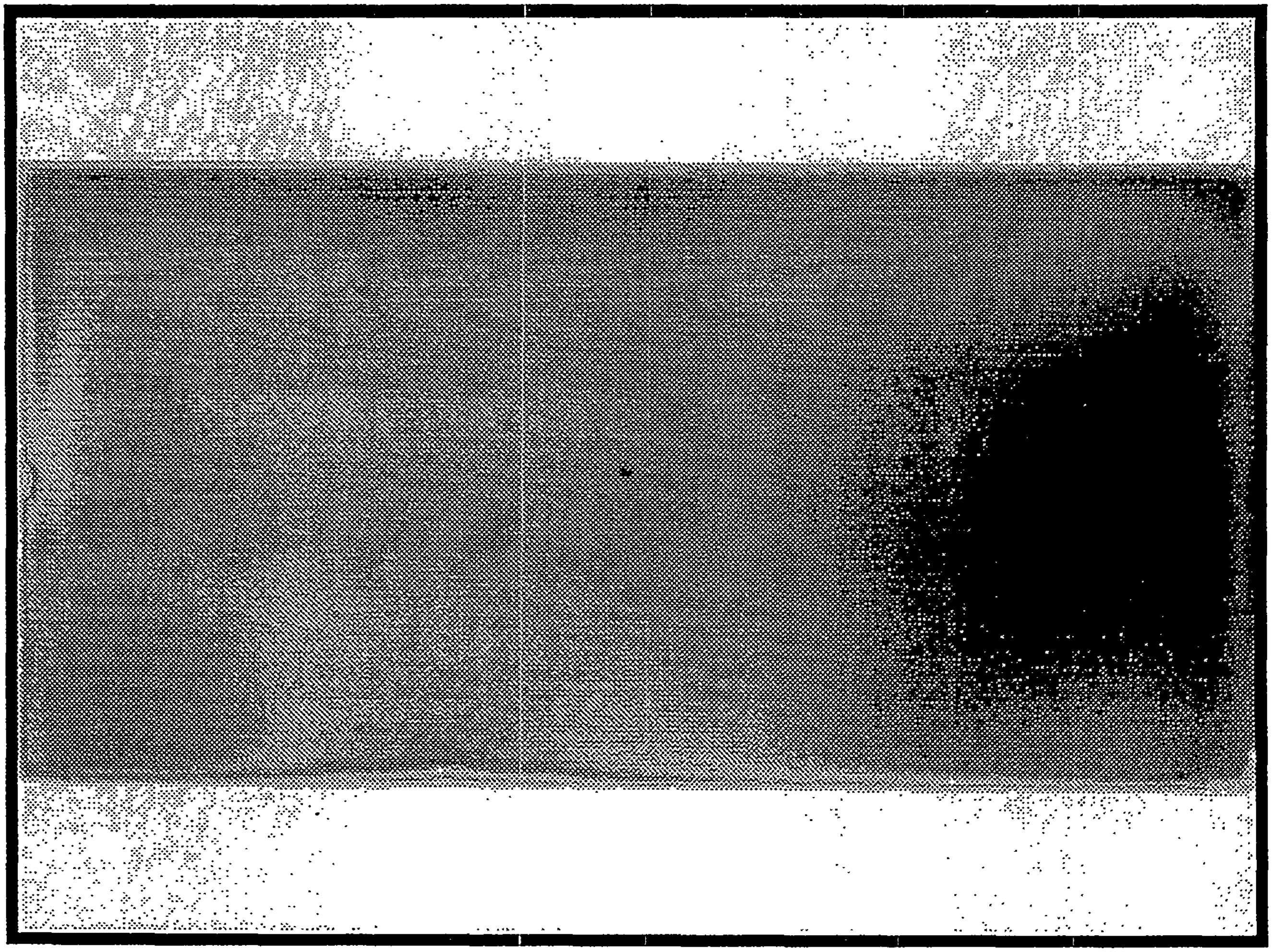


Fig. 31. PV Plate Deposited in Standard Box Carrier with Bottom RF Connection

which could be CO and CO_2, are detected as are others. The RGA can track 12 species in the trend mode; this will likely be the preferred detection mode once the species to be tracked have been identified. Among the candidate species are water at 18, nitrogen at 28, silane at 30, disilane at 60, trisilane at 90, a silicon carbon cross species at 45, and others.

One way of monitoring the process which has been investigated is to measure the concentration of silane and of the higher silanes that are produced during the discharge (as well as concentrations of dopants). Without a calibration of the RGA for the gases measured, partial pressures to within a given (but unknown) constant factor can be determined. For the same deposition conditions, the same signals should be obtained and thus a form of process control is possible. The specific RGA being used has a mass range of 1 to 200 amu although the highest mass that has been useful is for trisilane in the 90 amu range. Silanes higher than trisilane have not been detected. Typically disilane (monitored at 58 and 60 amu) will have a signal roughly 1% that of silane and trisilane (at 84, 86, 87, 88, and 90 amu) will be about 1% of the disilane. For mass calibration purposes a mixture of inert gases is introduced into the chamber on a periodic basis; this mixture contains He, N_2, Ar, Kr, and Xe. The extent to which process monitoring can be carried, will to some extent, depend on the stability of the instrument. Changes in cracking pattern of trisilane have been observed and suggest that at the low concentrations that this species is at, the stability of the RGA may not be sufficient to monitor it. Related to uniformity, consumption rates of silane in various diluents were determined (these are considered proprietary information). Mixtures tested were silane in He, Ar, and H_2. In these mixed gases it was found that the silane consumption rates as a percentage of the silane concentration increased as the silane was diluted. Over the range of interest (±50% of normal), the effect was smallest for hydrogen dilution and roughly equal for argon and helium. In all cases, the uncertainty in flow rates (see below) would contribute less than 1% variation in consumption rate.

Flow Calibration

Since deposition gases are mixtures (more correctly solutions), flow rates are more important than if pre-mixed gases were used. To better define and control the composition of these deposition gases, a flow calibration station was assembled. The technique involves filling a nearly empty vessel with the gas of interest with the set flow to be calibrated and measuring the time required for the pressure to rise to a predetermined level. To allow a wider range of flows to be handled, the vessel used consists of two roughly 6 liter chambers connected by a valve. The volumes of the chambers were determined from both their geometry and filling them with water and weighing the water used.

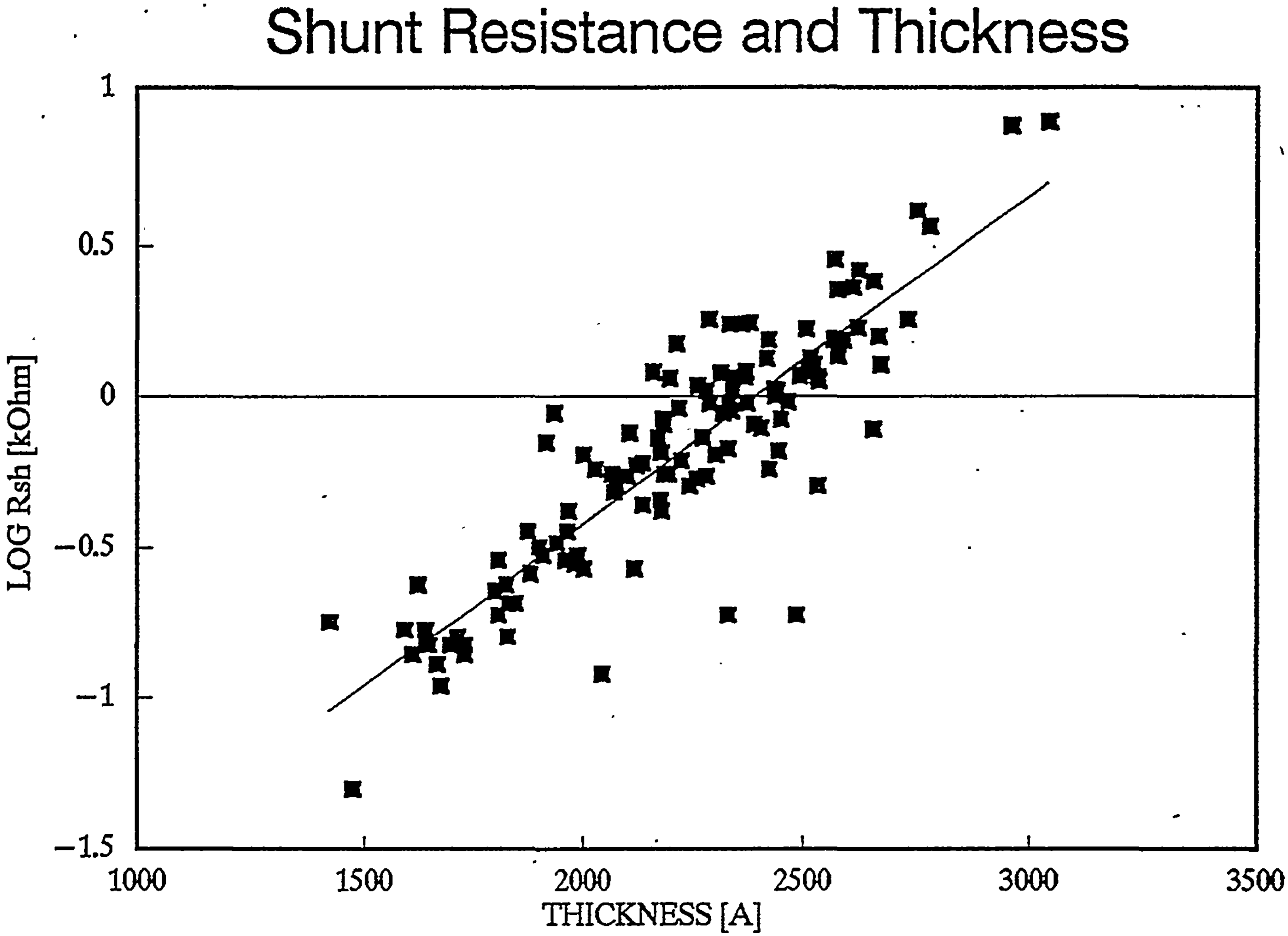
From several volume determinations, it is believed that the volumes are known to be within 0.2%. To calibrate a flow meter or controller, the chamber(s) is evacuated, the flow is set and the time is measured that is required for the pressure in the chamber to increase from a starting low pressure near zero, to a final high pressure near atmospheric. A 1000 Torr pressure gauge is used to detect both starting and stopping pressures. The valving and pressure readout have been connected to the deposition system computer for more precise control and measurement. To test the system, the lower pressure set point was varied from 100 to 500 mTorr. These changes had no systematic effect on flow determination for a given set point. The entire set of flow controllers was then checked; it was determined that two controllers (H_2 and CH_4) were off between 15 and 20%, two (Ar and PH_3 mixture) were off between 5 and 10%, and the others (P-mixture and silane) less than 2%. The rather large discrepancies are likely the result of erroneous internal adjustments of the flow meters rather than faulty flow meters.

For additional calibrations, the scatter in deviation of measured flows compared to set-points was typically 2% with the exception of the methane flow controller, which have varied by more than 10% in the group of four measurements. The discrepancy was traced to an unstable zero point in the controller.

Lasering

One of the contributing factors to increasing the output of the APS module to 60 W is a significant reduction of the i-layer thickness. Thinner silicon can however result in lower quality aluminum scribing. This aluminum scribing difficulty is more serious than it first appeared. It seems to be reasonably well defined characteristic of the scribing of the aluminum and is very thickness dependent.

Since the determination of QSF values (the percentage power output not lost due to shunting) involves the measurement of shunt resistances (R_{sh}) of individual cells, and 67 cells are active on a PV plate, thousands of such cells are measured with each batch. When small, 4" x 12" "diagnostic" plates are cut up for detailed measurements, these shunt resistances are also measured as are thicknesses at over 100 positions on the plate. The diagnostic measurements exhibit a very strong correlation of shunt resistance with thickness. Figure 32 shows log (Rsh) vs. silicon thickness for one plate. The very good correlation suggests that the shorting is not a random process, but rather a reasonably well defined phenomenon. The type of relationship shown in Figure 32 is often seen although the details vary with sample, laser beam used, and time.



FITT −2.58 + .00108 * (TH)

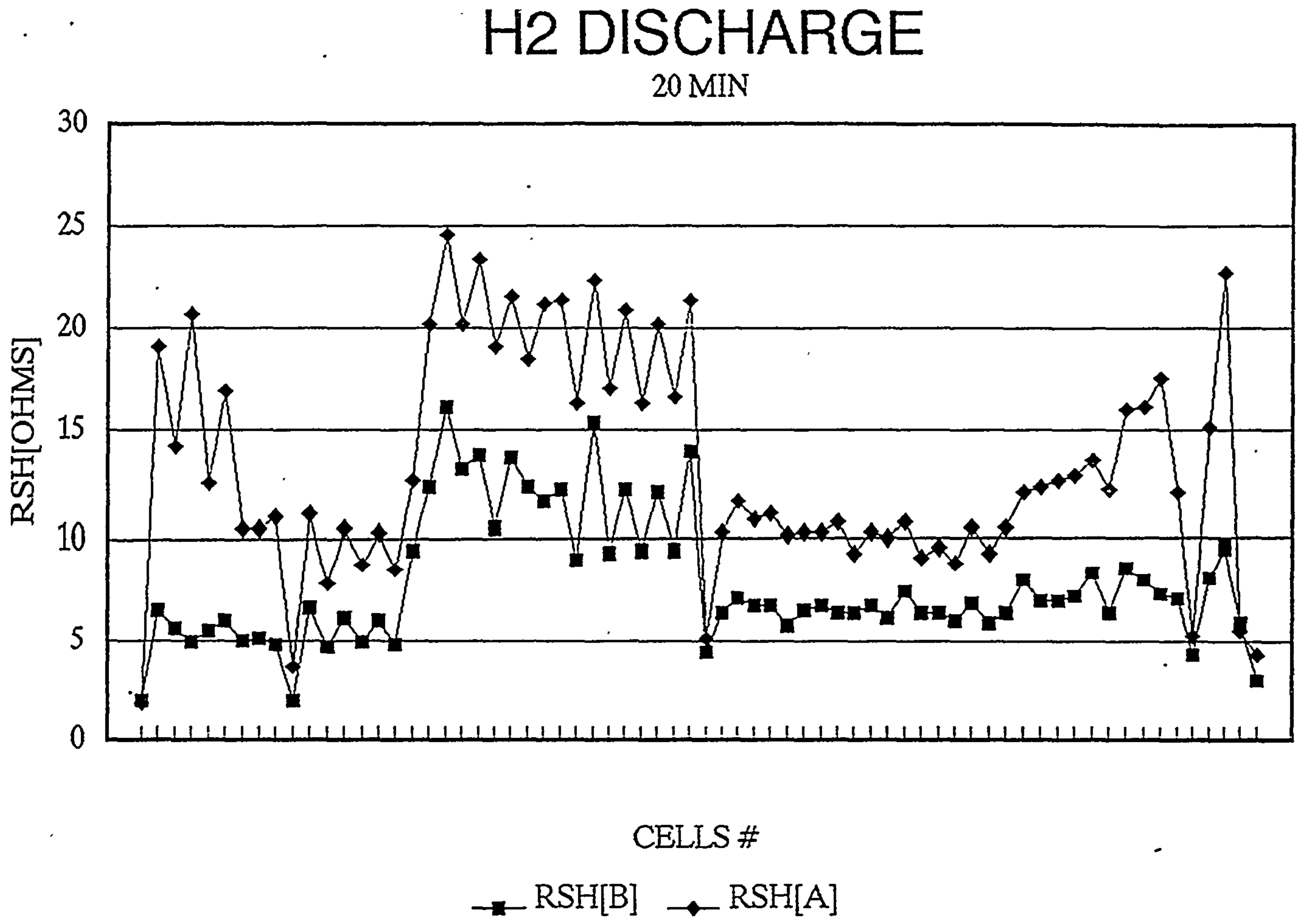
Fig. 32. Relationship of Silicon Thickness and Shunt Resistance

In order to attempt to understand this problem, several tests have been carried out. Some of the shorted plates have been subjected to a hydrogen discharge after aluminum scribing. The discharge is similar to that for deposition except that the pressure is approximately doubled. The result of such discharges is typically an increase of about 50% in shunt resistance which, depending on the starting point, can add several watts to a panel. Figure 33 shows resistances of a poorly scribed panel before and after a 20 minute hydrogen discharge.

By varying the "p-layer" large changes in shunting have also been observed. Leaving out the boron produces many essentially non-shorted cells (these are rare otherwise), although many low resistance cells remain and the effect on QSF is small. Leaving out carbon in the p-layer has no dramatic effect on shunting. Thinner p-layers also reduce the shunting. Some control over shunting is possible by varying the laser scribing conditions. Halving the scribing speeds, for example, can double the shunt resistances. Judging the effect of processing changes is difficult to determine because repeatability of the lasering is not very good; a ± 20% change in hunt resistance can easily occur when scribing is repeated a second or third time.

The same type of lasering difficulties are also being experienced at the Fairfield facility. There, the influence of the back contact on scribing quality is given some attention. It appears that the addition of the zinc oxide (not available in Trenton) improves the back contact lasering and the thickness of the aluminum also plays a role. Tentatively a zinc oxide layer thickness of approximately 1800 angstroms and about 3000 angstroms of aluminum appear to give the best scribing results, with QSFs in the nineties. Ultimately, details of the back contact also have to be consistent with PV performance.

Measurements of "diagnostic" plates revealed numerous cases of significantly higher than expected contact resistances between the tin-oxide and aluminum. For some cells, these resistances appeared to reduce fill factors by as much as ten to twenty percent. In order to be able to gain some information in the factory to determine whether or not contact resistances are a problem, I-V measurements have been made at lowered light intensity in the I-V tester. The idea behind these measurements is that if the contact resistances are high enough to reduce power output by reducing fill factor, then at lower intensity fill factors should increase. Fill factors will increase, however, even if there is no contact resistance because of the tin-oxide sheet resistance which will become less important at the lower intensity. The increase at lower light intensity due to the tin-oxide sheet resistance will apply to all the plates, and can be used as a baseline; any plates that have a much higher increase would then be suspected of having some cells with a significantly higher contact resistance.



RSH[B] Before H2 discharge RSH[A] After H2 discharge
pd113h2–pd129 plate 11

Fig. 33. Effect of Hydrogen Discharge on Shunt Resistance

Data Analysis and Report Format

A two page draft "Run Summary Report" format has been generated. This report has as input the data collected for a run and summarizes these data and draws conclusions from them. It includes the following items.

One page contains the I-V measurements for each plate, the power QSF value for the plate, low light level V_{oc} (LLL V_{oc}) measurements, R_s, which is the slope of the I-V curve at V_{oc} (a series resistance type number) and thickness (thickness and LLL V_{oc} are not yet available in the Fairfield facility).

I-V parameters for each plate are corrected for light intensity and temperature. The R_s value as well as an R_{sh} resistance (the slope at I_{sc}) are determined by the software and stored in the run file, but the R_s number is more useful to print out since the shunting is already indicated by QSF numbers.

The low light level V_{oc} measurement provides information that is in large part shunt determined, i.e., like the QSF determination. It may prove useful in those instances when it disagrees with the QSF numbers. The LLL V_{oc} measurements are currently made as part of the I-V measurements in the Trenton facility, but the light source has not yet been installed in the Fairfield testers.

The second page summarizes the silicon deposition and lasering process and points out potential problems. Both silicon deposition and lasering are done by more than one component of each system; these components can perform differently and therefore need to be tracked. Thus, there are two deposition systems in each of which several box carriers can be used. Lasering is done with two lasers, and four beams for each laser. The following summary is obtained.

Average QSF corrected I-V parameters and silicon thickness for each RF section.
Average power QSF values for each laser beam and each laser.
Average QSF corrected I-V parameters and thicknesses for the run and best plate.

An "items to watch" section identifies any values that are out of line, i.e. a given laser beam not performing or an RF section producing low quality product.

Finally, a troubleshooting section (this is being worked on) suggest reasons for nonconforming values, i.e., possibly a p-layer was lost on an RF section, a plate might have a crossed scribe, etc. This will be done with look-up tables where a given number that is out of the range of what is deemed acceptable will result in a list of reasons to be reviewed. Each of these reasons will likely have effects on other parameters that are tracked, and these will be looked for. Ultimately those reasons that are not excluded will be listed.

Product Tracking

A bar coding technique is being tested for plate and module tracking throughout the process. A material and adhesive have been identified that might be used on plates and applied after plates are unloaded from the box carrier. Pre-numbered tags will be used for this application. In addition to tagging product, box carriers will also be tagged to allow automatic association of preheat and deposition data with a given run. A bar code reader has been acquired and is being evaluated. The test in progress is meant to determine if there are any detrimental effects from passing these small 1/4" by 2" tags through the sputtering system. Currently, all plates are identified by hand scribing a number near one edge of the plate.

Fairfield Facility Processing Status

Silicon Deposition - For the same process conditions, the deposition system in Fairfield produces a lower deposition rate than does the system in Trenton. The reason for this is not known, but the RF system is suspected. Modifications to the matching networks used in Fairfield have been made, and are being tested to determine whether the reason for the lower deposition rates could be differences between the matching networks in use in Trenton and those used in Fairfield; no conclusions have been drawn yet. To determine whether other differences in film deposition exist, individual p, i and n-layers have been deposited on plain glass; sections of glass with i- and n-layers have been sent to New Jersey for analysis to determine if their properties are in the ranges expected.

Sputtering - For a small stretch of runs, significantly lower than usual currents were obtained from the PV plates. Figure 34 shows measured average Isc values for several runs as well as a fitted (linear regression fit to p- and i-layer deposition times) line through these points.

Since an aluminum target had been changed in the sputtering system just prior to the time the current drop was experienced, that system was suspected of causing the problem. The target that was put in the system had stainless steel components in it and these were thought to be responsible for the lower currents. To verify this assumption, films were sputtered on plain glass and analyzed, not only from films sputtered from the target in question, but from the other two aluminum targets as well.

Analysis of these films showed their reflectance to vary considerably. One of the targets deposited films that were similar to those obtained in the Trenton sputtering system. Films from the other two targets, however, had reflectance between 5 and 15% lower. These reflectance measurements were initially made using a portable instrument constructed for that purpose. It consists of a high intensity red LED and a silicon detector mounted in a block of phenolic such that their axis are at about 45 degrees relative to each other. Laboratory measurements using a spectrophotometer confirmed these results and showed that the lowered reflectance was broadband over the 400 to 700 nm range measured. Chemical analysis of the samples confirmed the suspicion that the aluminum was contaminated with iron.

A related difficulty has been the RF cables that deliver power from the matching networks to the box carrier. The requirements of low impedance, high temperatures and high vacuum requirements makes these a complicated matter. The difficulty has been the bends required to connect the points inside the chamber. A roughly 1.5" repositioning of the box carrier inside the deposition chamber has helped alleviate the problem, but work is ongoing to improve cabling.

24-Oct-94 Page. 1
EMF
Summary Report Run: PD143

PLATE	VOC	ISC	FF	PW	VM	IM	RS	LLLVoc	THICK	QSFPW
1	57.3	1.973	54.4	61.6	43.7	1.408	9.1	3.1	3642	96.8
2	55.2	1.924	50.3	53.4	38.5	1.385	8.5	3.7	3572	96.8
3	56.8	1.997	56.9	64.5	41.9	1.540	11.1	1.6	3756	96.8
4	57.7	2.015	57.4	66.7	43.5	1.534	12.5	3.4	3672	96.8
5	56.4	2.019	61.1	69.6	44.0	1.580	4.2	0.0	3844	97.0
6	56.1	2.043	61.5	70.5	42.5	1.659	7.3	3.9	3914	97.3
7	56.7	2.045	62.7	72.8	43.2	1.685	10.9	5.6	4183	98.9
8	56.4	2.052	61.2	70.8	42.8	1.655	10.1	0.0	4045	96.0
9	no fire									
10										
11										
12										
13	56.8	2.063	62.7	73.6	43.2	1.702	4.6	3.4	4277	97.5
14	57.2	2.061	62.3	73.5	44.0	1.668	11.3	0.0	4254	99.2
15	56.9	2.077	62.4	73.7	43.4	1.700	10.8	4.1	4223	97.6
16	56.7	2.071	62.1	72.9	43.4	1.681	7.3	3.4	4220	97.1
17	no fire									
18										
19										
20										
21	57.4	2.070	58.9	69.9	42.4	1.648	14.6	0.0	4367	98.7
22	56.2	2.086	64.4	75.5	43.5	1.735	2.4	3.5	4384	99.3
23	57.1	2.088	61.1	72.8	42.6	1.708	4.8	4.8	4424	98.0
24	57.4	2.082	61.5	73.5	43.2	1.701	6.5	5.1	4453	99.2
25	57.6	2.093	61.3	73.9	42.7	1.729	6.6	5.0	4724	98.2
26	57.5	2.104	60.7	73.5	43.6	1.686	14.3	4.4	4702	97.6
27	57.3	2.084	60.2	71.9	43.2	1.664	6.8	4.3	4674	97.8
28	57.2	2.115	59.6	72.2	43.3	1.668	10.9	8.2	4780	96.4
29	56.9	2.089	64.1	76.2	43.8	1.738	8.0	7.3	4357	97.4
30	57.1	2.093	59.2	70.7	41.6	1.698	4.9	3.7	4243	98.0
31	57.4	2.087	61.8	74.1	43.1	1.717	10.1	8.7	4243	96.7
32	57.5	2.091	61.4	73.7	43.6	1.693	5.6	6.3	4380	95.7
33	57.5	2.084	62.2	74.5	43.4	1.718	6.8	8.4	4353	97.5
34	57.3	2.075	61.3	73.0	44.3	1.647	13.4	0.0	4268	97.9
35	56.9	2.083	61.1	72.4	44.5	1.628	5.6	5.8	4411	98.5
36	56.8	2.054	60.0	70.1	43.3	1.618	12.0	0.0	4459	98.0
37	56.4	2.036	60.4	69.4	43.1	1.610	7.1	0.0	4130	97.9
38	55.8	2.037	58.0	66.0	41.5	1.591	10.2	0.0	4028	73.8
39	56.3	2.044	62.1	71.4	43.2	1.655	10.9	0.0	4166	96.1
40	laser alignment								4189	
41	57.5	2.155	59.8	74.0	40.9	1.809	9.1	11.4	4709	98.3
42	57.2	2.136	60.1	73.4	42.2	1.741	9.9	0.0	4759	99.4
43	57.0	2.124	59.9	72.6	42.4	1.710	7.3	0.0	4749	97.4
44	48.2	2.022	55.3	53.9	32.6	1.652	17.2	7.3	4606	91.3
45	no fire									
46										
47										
48										
AVG	56.7	2.065	60.3	70.6	42.6	1.656	8.9	3.6	4282	96.8
STD	1.55	0.0444	2.73	5.16	2.03	0.0848	3.27	3.06	314	4.17
RUN STD	57.29	1.736	70.4	70.1	45.5	1.538	8.8			

Fig. 34. Page 1 of Deposition Run Analysis Report

RUN PD143 Page.2
Dep. date: 18-Feb-94
Chamber: 2
Box Carrier: A
Measured Date: 22-Feb-94

IV Measurements corrected by QSF

SECTION	VOC	ISC	FF	PW	VM	IM	RS	LLLVoc	Thick
1	57.2	1.977	56.2	63.7	41.9	1.467	10.3	3.0	3660
2	56.7	2.040	63.1	73.0	43.1	1.645	8.1	2.4	3996
3									
4	57.1	2.068	63.6	75.2	43.5	1.688	8.5	2.7	4244
5									
6	57.1	2.081	62.1	73.9	42.9	1.698	7.1	3.4	4407
7	57.6	2.099	61.9	74.8	43.2	1.687	9.7	5.5	4720
8	57.5	2.090	63.3	76.1	43.0	1.711	7.2	6.5	4306
9	57.3	2.074	62.3	74.0	43.9	1.653	9.5	3.6	4373
10	58.1	2.039	66.9	79.5	42.6	1.619	9.4	0.0	4128
11	55.5	2.109	60.5	71.0	39.5	1.728	10.9	4.7	4706
12									
AVG	57.1	2.064	62.2	73.5	42.6	1.655	8.9	3.5	4282
STD	0.69	0.0381	2.70	4.09	1.22	0.0740	1.25	1.79	314

AVG Ratios

ELC E/O	1.002	0.992	0.998	1.007	0.988	1.006	0.885	0.698	0.982
GND E/O	0.990	0.973	0.983	1.002	0.963	0.965	1.353	0.854	1.010
GLASS TYPE	0								
AHA/BHA	na								
AHA/BHA STD	na								

REGRESSIONS

	CONST	SLOPE	R2
VOC/THK	52.79	0.001	0.35
ISC/THK	1.64	0.0001	0.71
FF/THK	73.39	-0.002	0.19
VOC/ISC	39.01	8.755	0.37
LLLVoc/QSF	77.74	-0.743	0.17

Averages per AL-laser beams

	AL-Laser 1		AL-Laser 2		AL-Laser 3		AL-Laser 4	
Beams	1	2	3	4	5	6	7	8
Beam power	110	121	104	109	109	102	75	107
Pulse width	60		61		54		52	
QSF	87.6	96.3	98.0	98.3	97.9	96.5	97.9	97.7

Electrical Yield :

	Overall Plates	%	Corrected Plates	%
60 (>= 75)	2	5.71	12	34.29
55 (>= 68)	27	77.14	20	57.14
50 (>= 64)	3	8.57	1	2.86
< 64	3	8.57	2	5.71

Fig. 35. Page 2 of Deposition Run Analysis Report

Task 11 - Eureka Encapsulation and Termination

Objectives

Two objectives of this task are to reduce encapsulation costs and increase module power through redesign of the cell layout.

Cost Analysis

Production in the new APS facility in Fairfield, California has only recently begun and is at a low throughput. In addition, yields at this early stage of production are low. Nevertheless, the cost reduction goals are already within reach.

For five consecutive runs made in the deposition system, and 81 modules (from previous runs, because of the time lag between thin film processing and encapsulation) encapsulated, the yields and direct costs per watt shown in Table 7 were realized; corresponding pre-PVMaT costs are shown in parenthesis.

The thin film processing losses (at 85% yield) are mainly due to RF problems, not to low electrical yields. The reason for the low encapsulation yields (78%) is partly inexperience of new operators. Some of the operators have just recently been added and are undergoing training. The total direct cost reduction is 11% compared to the 10% goal of this project, and the encapsulation labor cost saving is 24% compared to the 50% goal.

Table 7. Fairfield Facility Direct Costs

	Pieces In	Pieces Out	Yield %	Labor Cost $/Wp	Material Cost $/Wp
Thin Film	240	204	85	.30(.31)	.46(.68)
Encapsulation	81	63	78	.44(.58)	.66(.53)
Total Cost				.74(.89)	1.12(1.21)

Note: Pre-PVMaT costs are shown in parenthesis

Split Cure Process

While the cost targets are not quite achieved, very significant progress was made in the encapsulation area with the development of the split cure process. Laminating a module at the Trenton line required 10 minutes, plus one minute for loading and unloading of the laminator. To achieve the necessary throughput in the

Fairfield facility, it will be necessary to reduce this cycle time to six minutes. A short term goal for the Trenton line was to achieve an eight minute cycle, which, through equipment improvements and optimization, would result in the six minutes in Fairfield. From a series of tests designed to reduce the eleven minutes required for one cycle, it became apparent that fine tuning would not result in the required reduction in cycle time. The focus was therefore shifted to developing a split cure process, in which only part of the EVA cure would occur in the laminator and the rest in a separate oven.

The initial means of determining the success of a given test was by appearance and the lack of bubbles. When a procedure had been arrived at that looked promising, gel content measurements were made on eight modules. Samples were divided into five categories:

1. Standard cure of a 9 minute cycle.

2. 3.5 minute first stage split cure followed by a 10 and 15 minute post-cure in laminator with no pressure applied.

3. 3.5 minute first stage split cure followed by a one hour high temperature post-cure without letting the sample cool during transfer to the oven.

4. 3.5 minute first stage split cure followed by a one hour high temperature post-cure, letting the sample cool before transfer to the oven.

5. 3.5 minute first stage split cure only.

The first stage split cure is done at reduced laminator pressure but at the same temperature set point as before. In all but the case in which only the 3.5 min. first stage cure is done, the gel contents averaged in the range of 87% to 92%. With only the first stage split cure gel contents of about 90% were obtained in the center of the laminate and were less than 30 at the edges.

An important part of the thin film processing sequence is a heat aging as the final step before I-V measurement. Since the split cure includes an extended heating period, tests were carried out to determine whether the heating done for the EVA cure could also be sufficient for replacing the normal heat aging. The result of this testing was positive and it was decided to adopt the split cure process subject to passing environmental testing.

Samples were prepared for testing the split cure process as well as additional changes that were deemed desirable. Thus, a thinner EVA was used, 12 mil instead of the 18 mil previously used. The narrower foil mentioned under Task 9 was used, and a tab replaced the wire loop that had previously been welded to the foil. Modules made with these changes were subjected to 10 humidity/freeze (HF) cycles and 200 thermal cycles. A second set together with some older modules was sent through 1000 hour damp heat test. One of the four samples subjected to the cycle test had a small chip in the glass prior to the test, and this developed into a 1" crack during the test. The other three passed the tests. The set of samples that were exposed to the 1000 hour damp heat test have passed the subsequent leakage test. One of the older variety modules showed signs of water penetration. This failure was traced to poor adhesion of one of the boots. Some early modules made with the split cure, but using 18 mil EVA, were exposed to 50 thermal, 20 HF, and another 150 thermal tests. They were visually unchanged.

The split cure has several important advantages over the previously used process. These are:

- The throughput of the lamination process is doubled.
- The lower laminator pressure during the split cure avoids EVA being squeezed out from between the two pieces of glass, and a much cleaner module results almost eliminating cleaning costs.
- The 12 mil EVA is less expensive and more can be put on a roll, thus reducing down time for changing rolls.
- The cost of a heat age furnace and one laminator is avoided.
- Space is freed up.
- The elimination of a step avoids the yield loses at that step.

Estimates of the cost savings associated with the new process incorporating the split cure are the following:

Material	- $0.053/sq.ft.
Labor	- $0.37
Electricity	- $0.17
Yield-thin film	- $0.029
Yield-encapsulation	- $0.083

The split cure process has been transferred to the Fairfield facility where it is currently being used for encapsulation.

New Junction Cover

The currently used in-line molded junction cover (boot) is a great improvement over the previously used rubber boot and was developed because the process of applying it could be more easily automated. Nevertheless, a simpler design and one that replaced the wire harness (wires and connectors terminating in the junction cover) was deemed desirable and an effort was undertaken to develop such a process. Conceptually, the junction cover would consist of a rectangular enclosure and cover with external connectors integrally bonded to one side and supplied with internal tabs for welding to the foil through the cover glass. The enclosure will be glued to the glass with a fast cure adhesive, the tabs welded, the enclosure filled with pottant and cured. A cover for the enclosure will likely be attached to it.

At this point, prototype enclosures have been obtained and have been applied to half-size modules for testing. Early tests showed poor adhesion of pottant to the enclosure; this was remedied by better cleaning of the enclosure prior to use. Following ten humidity-freeze cycles, good adhesion of pottant to the enclosure was maintained without exception on the six test samples.

Means of bonding through the hole have been investigated. Two ways of bonding to the thin foil have been successfully tried. In one the external tab is placed underneath the foil on the PV plate. The second involves masking the silicon before sputtering. This results in no aluminum film in that area and hence no "soft" insulating material (such as tape which would interfere with bonding of an external tab to the foil) is required.

Environmental Testing of Foil Bonds - Thermal testing has been carried out on ten samples with tabs welded to the foil. Contact resistances of the welds were measured before and after 150 thermal cycles. A slight increase from 5.6 to 6.3 milliohms resulted. Since this change is close to the accuracy of the measurements and the resistances are so small, the welds are considered acceptable, although an additional longer test is being carried out to verify this.

A possible change in EP module layout has also been investigated that would replace the terminal covers in two corners of the module with one terminal cover accessing the thin films through one hole-similar to the EN modules. Benefits associated with this approach include having to make only one kind of cover glass, requiring only one hole, processing of EN and EP type modules would be very similar and not require equipment changeover.

Qualification Testing

The approach to qualification has been to adopt the test sequence that was part of our PVUSA contract. One reason for this is that we have experience with those procedures, and have test results for product that is in many ways similar to the current APS product, thus making some testing not essential at this time. The other reason for adopting the PVUSA procedure is that our large modules have unique characteristics which are not recognized by the industry in currently established standards. Thus, the fact that glass conducts electrically means that if a module is large enough, very large leakage currents can be obtained, but these are not necessarily any more detrimental to the long term survival of a module than smaller leakage currents in correspondingly smaller modules. PVUSA acknowledged this and some other characteristics that make our modules different and we were able to arrive at a reasonable test sequence.

The initial testing was designed to evaluate changes that had been made in encapsulation and to subject product encapsulated in Fairfield to the most critical tests of the sequence; PV plates for these test modules were made in the Trenton facility. Once normal production occurs in the Fairfield plant, a new test sequence will be started and all tests will be carried out. The tests omitted from current tests are the hail impact test which was passed twice before with large safety margins, and the bypass diode thermal test, for similar reasons. The tests carried out and the results of the testing are shown in Table 8.

In Table 8, TC stands for thermal cycles, HF for humidity/freeze cycles and DH for exposure to damp heat at 85^{o}C and 85% RH. The DH was not part of the PVUSA test sequence but was carried out because it appears that some form of this test will be adopted in future testing.

In addition, a module with 12 mil EVA underwent and passed static, structural integrity testing of 50 lbs/sq.ft.

Table 8. Qualification Type Testing

12 mil EVA Sample	Test	Output, W before/after	2200V leakage, ua before/after
1	50 TC+10 HF	72.4/74.8	6.5/22
2	50 TC+10 HF	73.1/74.9	7.8/14
3	200 TC	74.6/73.9	<50 ua
4	200 TC	75.0/73.9	<50 ua
5	900 hr DH	71.3/ -	
6	900 hr DH	- /70.6	

18 mil EVA Sample	Test	Output, W before/after	2200V leakage, ua before/after
1	50 TC+10 HF	70.8/72.9	14.8/7.0
2	50 TC+10 HF	71.2/69.1	15.8/13
3	200 TC	73.9/73.3	<50 ua
4	200 TC	75.4/72.7	<50 ua
5	1000 hr DH	74.3/76.8	21/200
6	1000 hr DH	69.1/68.3	20/70

Somewhat related to module testing is the testing of a shipping container. Three single module shipping containers were subjected to drop tests (as per test procedures from the National Safe Transit Association;Project 1A). The containers were dropped from a height of 12 inches.

Two of the containers were made of cardboard. Other than minimal signs of external damage in the corner, these containers passed the test; the module inside was not damages. The third container was wooden and it too protected the module with only slight damage to the container. The cardboard containers were tentatively adopted for use.

Task 12 - Automation of Eureka Manufacturing Line

Objective

The main objective of this task is to continue automation of both the thin film and the encapsulation line.

The effort on this task has concentrated on the new APS Fairfield facility where equipment has been installed, tested, and since April 1994, used to manufacture PV modules.

Status of Fairfield Line

Automation of the thin-film deposition chamber box carrier loaders for the Eureka manufacturing line was scheduled to be but was not completed in the first year of the contract. The automatic loading equipment was, however, completed in the second year, tested and shipped to the Fairfield facility in October 1993. It has since been installed, tested, and is now in use.

A program for improving the automation of glass transport processes on the Eureka manufacturing line to 90% was completed. With the program in place, APS was able to achieve a level of 88% automation.

APS had set a requirement of a 90 second process time for back contact lasering. Prior to shipping the lasering station for the back contact, its cycle time was determined to be less than 90 seconds, satisfying the requirement. However, a separate end isolation laser stage had to be installed in order to achieve this throughput. The lasering station, including the end isolation laser, as well as the other two lasering stations have been installed in the Fairfield facility and are operational. Problems with the aluminum and silicon laser were discussed in the Task 10 section, Process and Quality Control.

A goal was set to achieve an overall yield of 90% for the glass transport process systems for the APS Fairfield Eureka manufacturing line. The yield achieved during the last week of operation in April attributed to the glass transport part of the line was 93%. Yields are more fully discussed under Task 11 with costs.

Fairfield Equipment Status

Glass Preparation Line - Tests done on the glass seamer/hole driller showed that plates could be processed at a rate consistent with the throughput of cover glass preparation, i.e., 45 seconds. An additional air knife was installed on the exit section of the glass washer prior to the SnO_2 laser. Previous to the installation of the air knife, the stacked cover glass plates had a tendency to adhere to each other causing plate loading problems and yield losses at the EVA applicator line.

Deposition Systems - Both deposition systems and preheat stations are installed, although only one of the deposition systems is being used. RF matching networks and some other items need to be completed for the second deposition system to be operational.

Two types of software packages have been selected for the deposition system. The first package, which is a high level language, is the work horse. This CASE (computer aided software engineering) package contains all the logic needed for control, safety, and interlocks. The second package is a MMI (man-machine interface) which will be used for supervisory control, monitoring and data acquisition. Software for carrying out the deposition has been written and is being used. Additions to this software will be required in the future, mainly in the area of data acquisition.

Two box carriers have been constructed for the Fairfield facility. These are the larger box carriers that have undergone testing in Trenton for improved uniformity (see Task 10 above). Based on recent testing carried out on the line in Trenton, some modification to these two box carriers will be made to improve both their pump down characteristics and also to further improve uniformity. Tests carried out in Trenton to determine pump down characteristics have shown that a small box carrier modified for improved pump down reached 30% lower pressure after one hour pumping than did the standard box carrier, while the larger box carrier achieved a 65% higher pressure than the standard carrier.

RF cables had to be redesigned for the Fairfield deposition system because of the change in positioning of the matching networks. The relatively sharp bends in the cables that were necessitated by the change in geometry sometimes resulted in insulation burning through at bends in the cables which in turn often resulted in RF sections (of four plates each) with a missing layer. Several iterations of cable design with increasingly closer tolerances improved the situation, but more work will be required to make the cables and connectors as reliable as required.

Sputtering System - After installation, the sputtering system passed both mechanical testing and process acceptance testing. Measurements that were carried out included resistivity of both ZnO and aluminum, sheet resistance of both ZnO and aluminum, transmission of ZnO, and uniformity of these properties in both films. Tests for impurities were also carried out which were passed. Early testing of the sputtering system and the aluminum laser station made use of silicon deposited plates from the Trenton facility. Quality problems encountered with the system were discussed under Task 10 above.

I-V Testers - Both plate and module I-V testers are operational. Results indicate that excellent correlation exists between the testers, more so in the output than in the individual I-V parameters.

Encapsulation Line - The process acceptance test of the encapsulation line was satisfactorily completed in October, as demonstrated by the processing of 100 EP50 plates with a yield of 90%. This test, performed by production operators, established that the design capability, capacity and product quality, as defined in the documentation package, could be achieved following the prescribed manufacturing process procedures. After the qualification test, modifications were made to the equipment in order to accommodate the split cure process. Thus the two laminators in use, which had provided a laminate every 4.5 minutes, will now provide a laminate every 2.25 minutes. To accommodate this increase in throughput, a second mounting bracket/mold injection station was installed, debugged and placed on=line.

Several other modifications were made to the line as well. The laminator PLC (programmable logic controller) was reprogrammed to initiate the lamination cycle upon closure of the lid by the operator. Previously, the operator initiated the cycle by engaging the Start button, and thus, a possible source of operator error was eliminated by this change in programming. Laminator temperature uniformity was improved by controlling each platen by four individual heaters; this allowed a reduction in process time of over one minute.

Temperature time profiles were obtained for one of the boot and bracket cure ovens. Fifteen thermocouples were monitored; five each (on the four corners and the middle of the module) on the first, middle and top shelf of the fully loaded curing rack. After two hours from a cold start, temperatures ranged from 157°C to 168°C with a 165°C set point. The temperatures in the center of the middle module and a corner of the top module were both 157°C. All other temperatures were in the range 162°C to 168°C. During production, a cold rack will be introduced into a hot oven, thus reducing the time required to reach the set point temperature (since the oven will already be hot).

Several upgrades were incorporated into the foil bonder in order to improve bond alignment, bond integrity and the 90 second throughput. These upgrades included installing of an applicator guide, reducing the speed drive of the feed stock, machining the feed guide to improve alignment, defining the optimum tuning of the bonder power supply and matching the transport speed to that of the foil application.

The original injection heads for the boot (terminal cover) resulted in a marbled appearance of the cured boot. Although this appearance did not seem to affect the performance of the boot, it seemed desirable to improve it. New injector heads that more accurately dispense the two component material were installed and were found to perform well.

With these modifications the line has been operating with the production of EP50 plate shipped from Trenton facility. EP50, EP55, and EP60 modules have been produced since the thin film line has been in production.

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13. ABSTRACT *(Maximum 200 words)*

This report describes work performed by Utility Power Group (UPG) and its lower-tier subcontractor, Advanced Photovoltaic Systems, Inc. (APS), to develop their manufacturing lines. UPG focused on the automation of encapsulation and termination processes developed in Phase 1 of the subcontract. APS focused on completion of the encapsulation and module design tasks, while continuing the process and quality control and automation projects. The goal is to produce 55-W(stabilized) modules in a new facility. At its Trenton EUREKA manufacturing facility, APS (1) developed high throughput lamination procedures; (2) optimized existing module designs; (3) developed new module designs for architectural applications; (4) developed enhanced deposition parameter control; (5) designed equipment required to manufacture new EUREKA modules developed during Phase 2; (6) improved uniformity of thin-film materials deposition; and (7) improved the stabilized power output of the APS EP50 EUREKA module to 55 W. In its Fairfield EUREKA facility, APS (1) introduced the new products developed under Phase 1 into the module production line; (2) increased the extent of automation in the production line; (3) introduced statistical process control to the module production line; and (4) transferred progress made in the Trenton facility into the Fairfield facility.

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