NREL/TP-411-6263 • UC Category: 270 • DE94000294

Amorphous Silicon Photovoltaic Manufacturing Technology—Phase 2A

Annual Subcontract Report 1 May 1992 – 30 April 1993

G. Duran, K. Mackamul, D. Metcalf
Utility Power Group
Chatsworth, California
A. Koniares, D. Skinner, H. Volltrauer
Advanced Photovoltaic Systems, Inc.
Princeton, New Jersey

NREL technical monitor: H. Thomas

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Operated by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC02-83CH10093

Prepared under Subcontract No. ZM-2-11040-06

February 1994

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A04

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements and Index (GRA and I); Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

Printed on recycled paper

DISCLAIMER

SUMMARY

Goal: The primary goal of this subcontract over its (3) three year duration is to significantly advance the photovoltaic manufacturing technologies, reduce module production costs, increase average module performance, and increase the production capacity existing in Utility Power Group and Advanced Photovoltaic Systems, Inc.

Approach: Utility Power Group and Advanced Photovoltaic Systems have been conducting parallel efforts in developing their manufacturing lines. Areas of focus include:

- o Encapsulation and Termination
- o Product Design
- o Process and Quality Control
- o Automation

Utility Power Group (UPG) has improved the existing UPG encapsulation system through the development of advanced encapsulation materials and processes which result in a module that does not require backing glass. In addition, UPG has developed advanced termination materials and processes. Advanced Photovoltaic Systems (APS) has performed development activities centered on the EUREKA Manufacturing line. Developments in the APS EUREKA encapsulation system have been in addition to the UPG activity on encapsulation, and offer an alternative approach to the problems of encapsulating large area thin-film modules.

TASK 1 POWERGLASS Module Encapsulation

Utility Power Group has been developing an advanced encapsulation system for its manufacturing line. Particular emphasis has been given to the simplification of the module structure to a tempered superstrate, with thin-film layers, which is protected by advanced substitute materials. This investigation included a wide-range of materials for single and multi-layer encapsulation systems designs, as well as selection of vendors to demonstrate the feasibility of superstrate glass tempering. All materials have been evaluated in terms of the level of environmental protection provided to the thin-film module, manufacturing cost reduction, and photovoltaic systems related factors. Prototype modules were then be produced for evaluation by potential and existing customers, and when required, design modifications were made. Prototype modules were then subjected to accelerated life testing. Issues addressed in product development, in addition to designing quality into the product include; considering raw material cost reduction, automation, the reliability of the product, and the weight of the product as it pertains to shipping costs.

TASK 2 POWERGLASS Module Termination

UPG has been optimizing the material(s) and process(es) utilized in the electrical termination of the POWERGLASS module. The technical approach was to design and fabricate several candidate POWERGLASS module termination configurations to be compatible with the candidate encapsulation materials and processes developed in Task 1. All termination components have been designed for use with automated insertion and assembly equipment/robotics. All designs have been analyzed in terms of manufacturing cost reduction of the current process and ease of use from the customers' viewpoint. Upon completion of design and fabrication, candidate terminals were attached to POWERGLASS modules for evaluation and testing.

TASK 3 EUREKA Module Design

Advanced Photovoltaic Systems, Inc. (APS) has been developing, by using computer aided design techniques, several power modules based on plate generated by the EUREKA manufacturing line. Evaluation of candidate designs was based upon the following criteria:

- Market Demand
- Quality
- Cost of Manufacture

The most successful designs were progressed to prototype level for a second stage of critical examination. Several iterations occurred between the design stage and prototype fabrication. Finally, full scale modules were assembled based on the best indications from the design and prototype studies. Two new products resulted from this task with clear advantages over existing manufacturing technology such as raw material cost reduction, and the weight of the product as it pertains to shipping costs. These designs still maintain the EUREKA modules' current high level of quality and reliability.

TASK 4 EUREKA Process and Quality Control

APS is engaged in an effort to reduce module production costs while maintaining quality and increasing module performance and throughput. This task is designed to advance the full automation of the EUREKA photovoltaic manufacturing system and its quality control. To perform this task, APS has:

- Increased predictability of the process;
- Identified the cause of extraneous variables;
- Evaluated the process without interrupting it.

Through the implementation of the necessary distributed data, acquisition and control systems, coupled with the necessary manufacturing system management to link production, process and quality, the desired cost reductions coupled with enhanced product performance will be achieved. During this phase, an extensive review has been made establishing which parameters should be identified as critical control points which would greatly benefit the quality, yield and throughput of the line.

TASK 5 EUREKA Power Module Encapsulation and Termination

APS has been conducting development activities to improve the module encapsulation and termination procedure for EUREKA based product by conducting studies in the following areas:

- o Cost reduction;
- o Reduction of plate to module output loss.

During this phase of the project, emphasis has been given to cost reduction of EVA content in the laminate. APS has also been investigating methods of reducing plate to module power losses.

TASK 6 Automation in EUREKA Manufacturing Line

APS has increased and will continue to increase both the manufacturing capacity and yield of the EUREKA line. The key areas to be investigated include:

- o Throughput;
- o Reproducibility;
- o Control;
- o Automation.

During this first phase of the subcontract, emphasis has been given to the laser processing stations and key elements such as, increasing repeatability of the scribing process, increasing the active area utilization of the module, and decreasing the process cycle time.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES AND TABLES

1.0 BACKGROUND

PVUSA (Photovoltaics for Utility Scale Applications) is a national cooperative research project established to demonstrate the potential for utilities to harness the power of the sun to generate electricity. PVUSA was established to develop comparative data on the different photovoltaic technologies in utility applications.

In Phase I, PVUSA installed nominal 20kW systems based on a variety of photovoltaic technologies, called "emerging module technologies" or EMTs. Utility Power Group (UPG) participated in PVUSA by installing an EMT-1 array utilizing its tandem junction amorphous silicon module. In 1989, UPG finished producing and installing the approximately 5000 modules for this project. These modules were amorphous silicon thin-films in a glass/EVA/glass structure and have proven to be very reliable, even compared to the single-crystal and poly-crystalline silicon based PV modules deployed as EMT-1 arrays at PVUSA.

In 1992, PVUSA accepted its first large-scale photovoltaic solar-power station at Davis, CA. The PV turnkey system is a product of Advanced Photovoltaic Systems, Inc. (APS). The power station used 9600 thin-film PV modules based on amorphous silicon, each 31 x 61 inches. This array, spaced over five acres, is the world's largest thin-film PV power system.

These two systems demonstrate the availability and manufacturability of amorphous silicon PV modules for use in utility power systems. They also show that reliable thin-film amorphous silicon PV modules can be manufactured using high yield fabrication techniques.

From 1980 to 1990 worldwide photovoltaic (PV) industry sales increased from 4 megawatts to 48 megawatts, however, U.S. industry share of these sales decreased from 60% to 35%. In order for the U.S. to enhance its leadership in the market place, steps need to be taken to translate continuing R&D advances made by U.S. industry, university, and DOE laboratories, into improved module performance and production technology. Awards made under the Photovoltaic Manufacturing Technology (PVMaT) project are expected to help U.S. industry improve product quality and accelerate the scale-up of production, and result in substantial reductions in manufacturing costs.

The DOE, through its PVMaT project, intends to encourage cooperative activities with industry, and to provide tangible assistance for identifying and overcoming major technical obstacles to improving manufacturing technology.

The PVMaT project consists of three (3) phases. Phase 1 was completed in mid-1991. This problem identification phase was designed to single out and order by priority those areas in U.S. manufacturing processes where R&D was needed to achieve cost reductions in PV module production. As a result of UPG's participation in the Photovoltaic Manufacturing Technology - Phase 1 (PVMaT-1) program, the costs for producing the type of PV modules deployed at PVUSA have been itemized and classified by Process Step, Materials, Operating Expense, and Labor.

PV Module Fabrication Process Overview

Table 1 is a list of the process steps utilized by UPG to fabricate the type of modules which were deployed at PVUSA in 1989 and have since demonstrated a high degree of reliability.

Table 1. PV Module Fabrication Process

Number	Process Step
1.	Pattern Front Transparent Conductor
2.	Clean
3.	Screen Print Conductive Paste
4.	Fire
5.	Screen Print Maskant Paste
6.	Bake
7.	Deposit a:Si
8.	Pattern Semiconductor Material
9.	Deposit Back Metal
10.	Anneal
11.	Remove Maskant
12.	Encapasulate
13.	Terminate
14.	Cure
15.	Final Clean
16.	Test

Figures 1a and 1b illustrate the PV module fabrication process sequence used by UPG as of the start of PVMaT Phase 2A.

Currently, and for the modules produced for PVUSA, UPG purchases glass that has a transparent conductive oxide deposited on one surface. Most of the major glass companies, both foreign and domestic, produce tin oxide coated glass for various applications. American Float Glass (AFG), Ford Glass, Libbey-Owens-Ford (LOF), and PPG Industries produce the product domestically, while Asahi Glass and Nippon Sheet Glass (NSG) produce it in Japan. UPG is currently conducting research to deposit advanced transparent conductive oxides (TCOs) on glass and other substrates for use as the front electrode in thin-film solar cells, but, production modules produced by UPG utilize commercially available tin oxide coated glass.

The first process step is the patterning of the TCO. This patterning consists of the isolation between cells and the formation of a border or region along the edge of the glass which will ensure that there will be acceptably low levels of current leakage during the Wet Hi-Pot Test.

The glass is then washed in an aqueous solution to remove any debris from the TCO patterning step.

Next, the busbars and bridge conductors are screen printed using a silver/glass frit paste and fired at elevated temperatures to insure good adhesion and electrical contact.

This is followed by screenprinting a maskant to define the cell area and ensure that no thin-films will be deposited along the edge of the glass. This maskant is baked out to remove any volatile organics which could interfere with the thin-film deposition.

The substrate is then placed in the vacuum chamber where the remaining thin-films are deposited.

Once out of the vacuum chamber, the maskant is removed from the substrate resulting in a working PV module.

The silver/glass frit paste that was printed and fired onto the glass substrate to form busbars for current collection, also provides solder locations for tin-plated copper ribbon. This four mil (0.004") thick ribbon is soldered to the busbar and threaded or fed through a hole in the EVA and back tempered glass which make up the lamination/encapsulation package. After the module has been laminated to the back glass with EVA, the ribbon is soldered to a terminal that in turn is attached to the back tempered glass sheet. This terminal is then protected with a silicone tube or boot to provide electrical isolation and a means of potting to seal the terminal from the effects of weathering.

Although this proved to be quite reliable and produced a very robust termination/encapsulation system, the cost of this procedure was a significant fraction of the total module manufacturing cost.

UPG Module Manufacturing Costs

The UPG PV modules produced for and deployed at PVUSA are to be considered as Pre-PVMaT modules. While producing this sizable quantity of modules, accurate manufacturing costs were obtained.

Figure 2 shows the costs of the fabrication process steps listed in Table 1. The costs of each process step have been further broken down into three components; materials, operating expenses, and labor. Steps 7 and 8 have been grouped together because these two process steps occur sequentially in the same in-line fabrication system as essentially a single step. Notice that steps 11 and 12 (Termination and Encapsulation) are two significant cost factors.

Combined as a single cost element in Figure 3, these two steps represent the largest cost component of the PV module fabrication process.

Figure 4 shows that the Termination and Encapsulation steps combined make up approximately 38% of the UPG module manufacturing costs, therefore, an effective way to reduce the module manufacturing costs is to focus on these two process steps.

PVMaT Project Goals

The main goal of a successful three-year effort by the UPG/APS team is to increase module manufacturing yield over the current level by 35% while decreasing the direct cost by about 25%.

In order to achieve this reduction in total direct costs, the termination and encapsulation direct costs will have to be decreased by about 65%. The termination and encapsulation cost reduction goal for Phase 1 of this project was initially set at about 40%, however, UPG has been able to reduce the cost of termination and encapsulation by almost 65% in Phase 1 alone (Figure 5). UPG has good reason to project that the termination and encapsulation cost reduction over the three-year effort will approach 80% (Figures 6 & 7), resulting in a total direct cost reduction of 30% (Figure 8). This will result in termination and encapsulation costs representing only 10-11% of the total direct costs versus 38% prior to the PVMaT effort (Figure 9).

Figure 1A

PV Module Fabrication Process

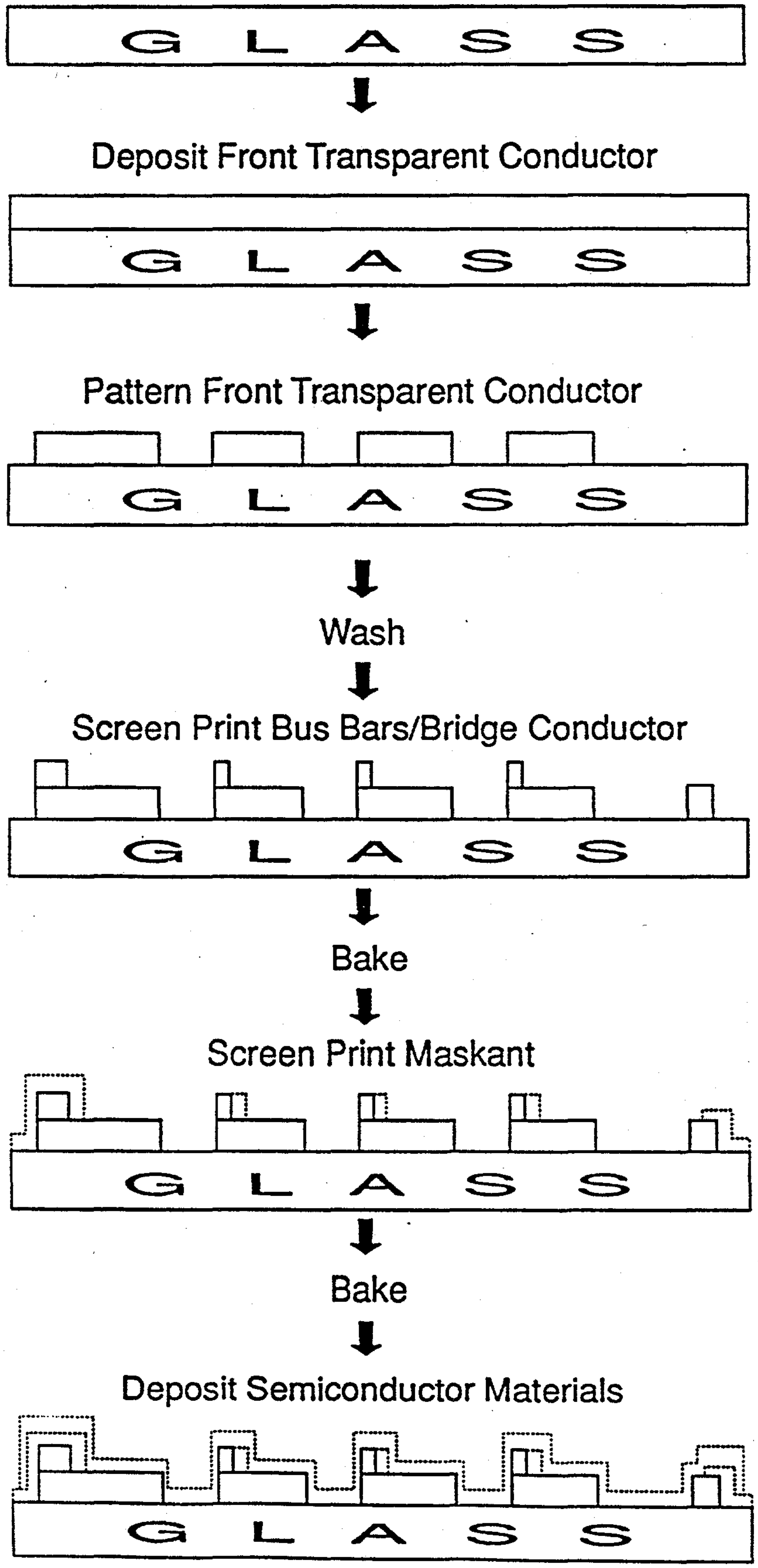


Figure 1B

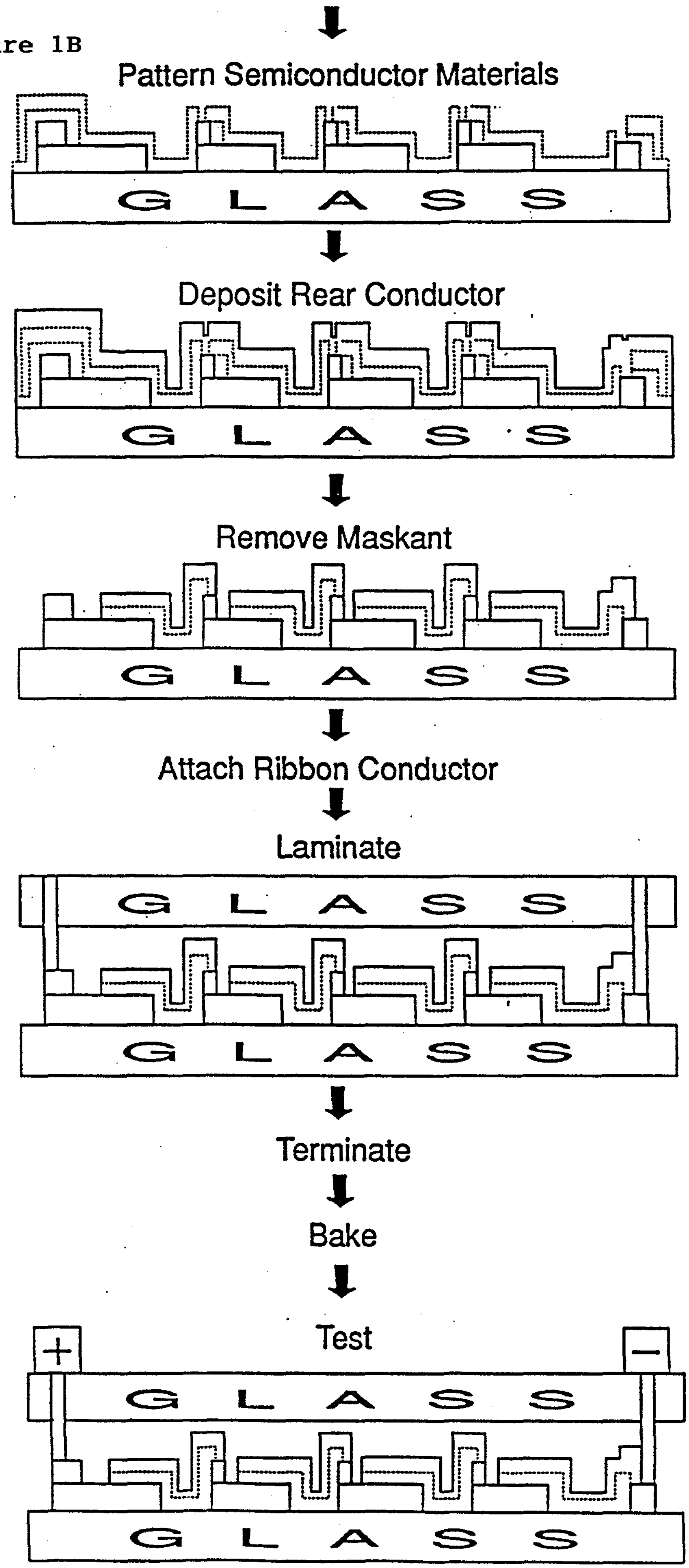

Pattern Semiconductor Materials
GLASS
Deposit Rear Conductor
GLASS
Remove Maskant
GLASS
Attach Ribbon Conductor
Laminate
GLASS
GLASS
Terminate
Bake
Test
+
−
GLASS
GLASS

Figure 2. Costs of the process steps for the Pre-PVMaT modules based on the list of steps in Table 1 and further broken down into three components; materials, operating expense, and labor.

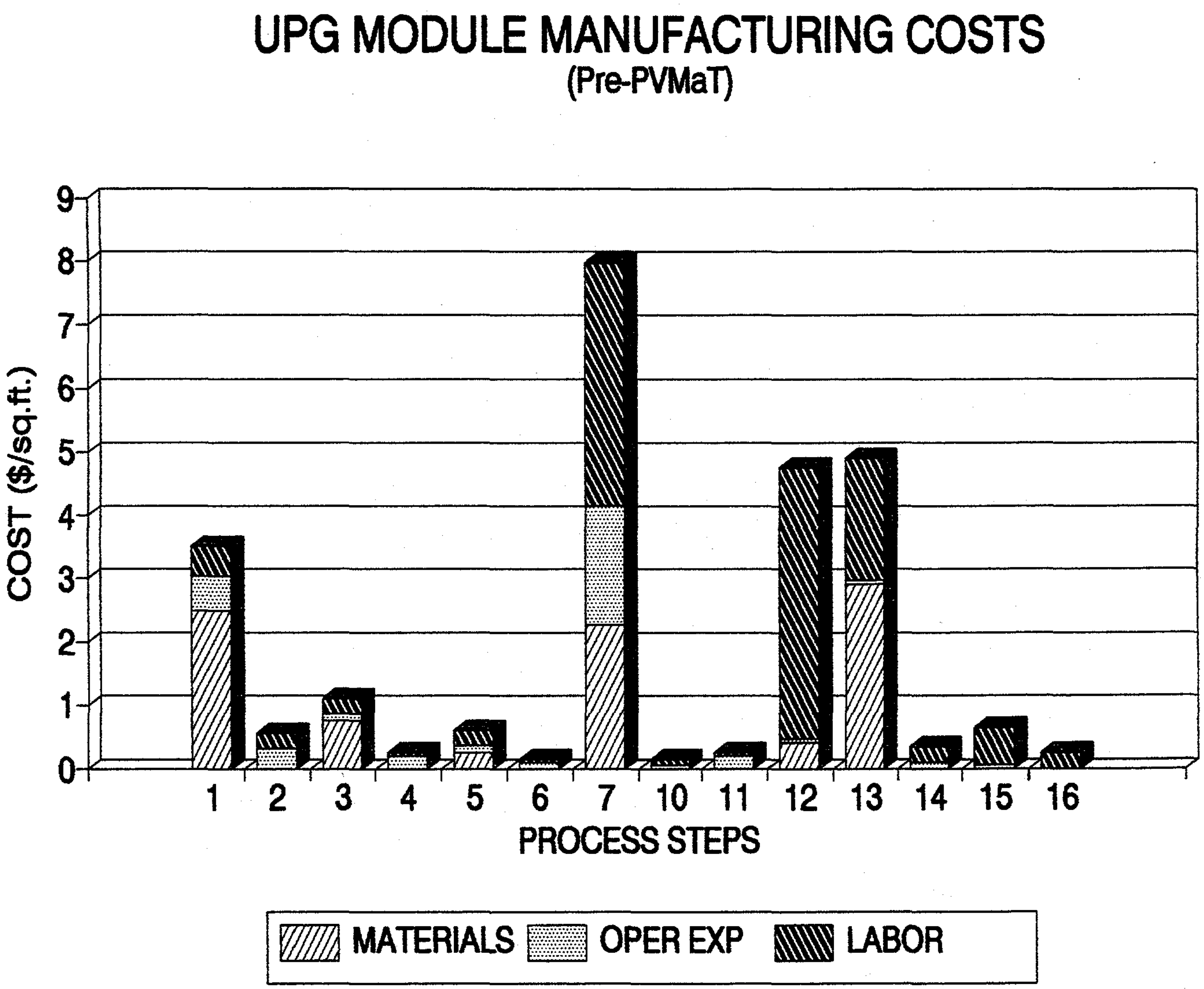


Figure 3. Costs of the process steps for the Pre-PVMaT modules based on the list of steps in Table 1. The costs of process steps 11 and 12 have been combined to show the magnitude these two steps have on the total manufacturing cost.

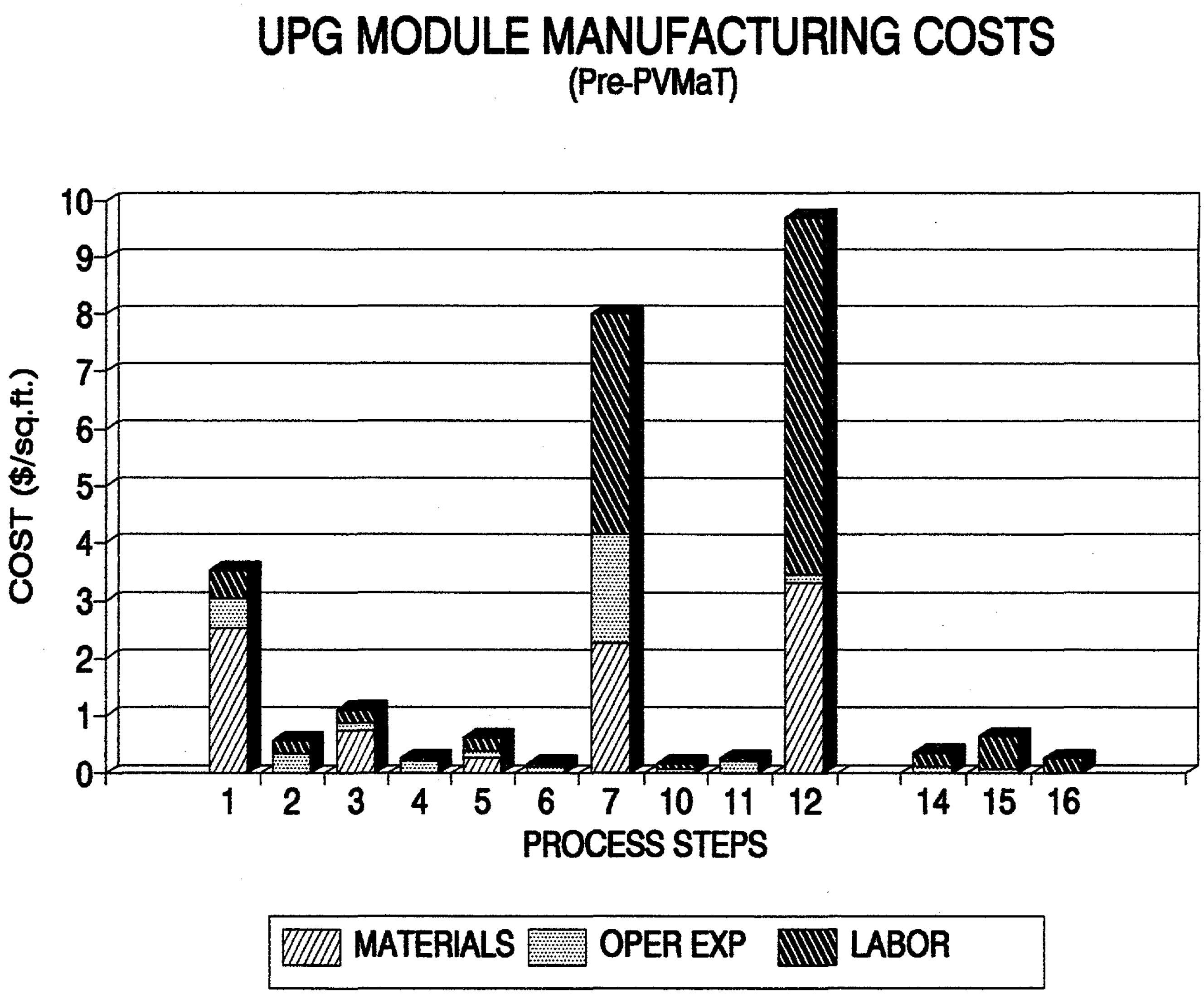


Figure 4. Ratio of the costs of termination and encapsulation process steps to the balance of the process steps for the Pre-PVMaT modules.

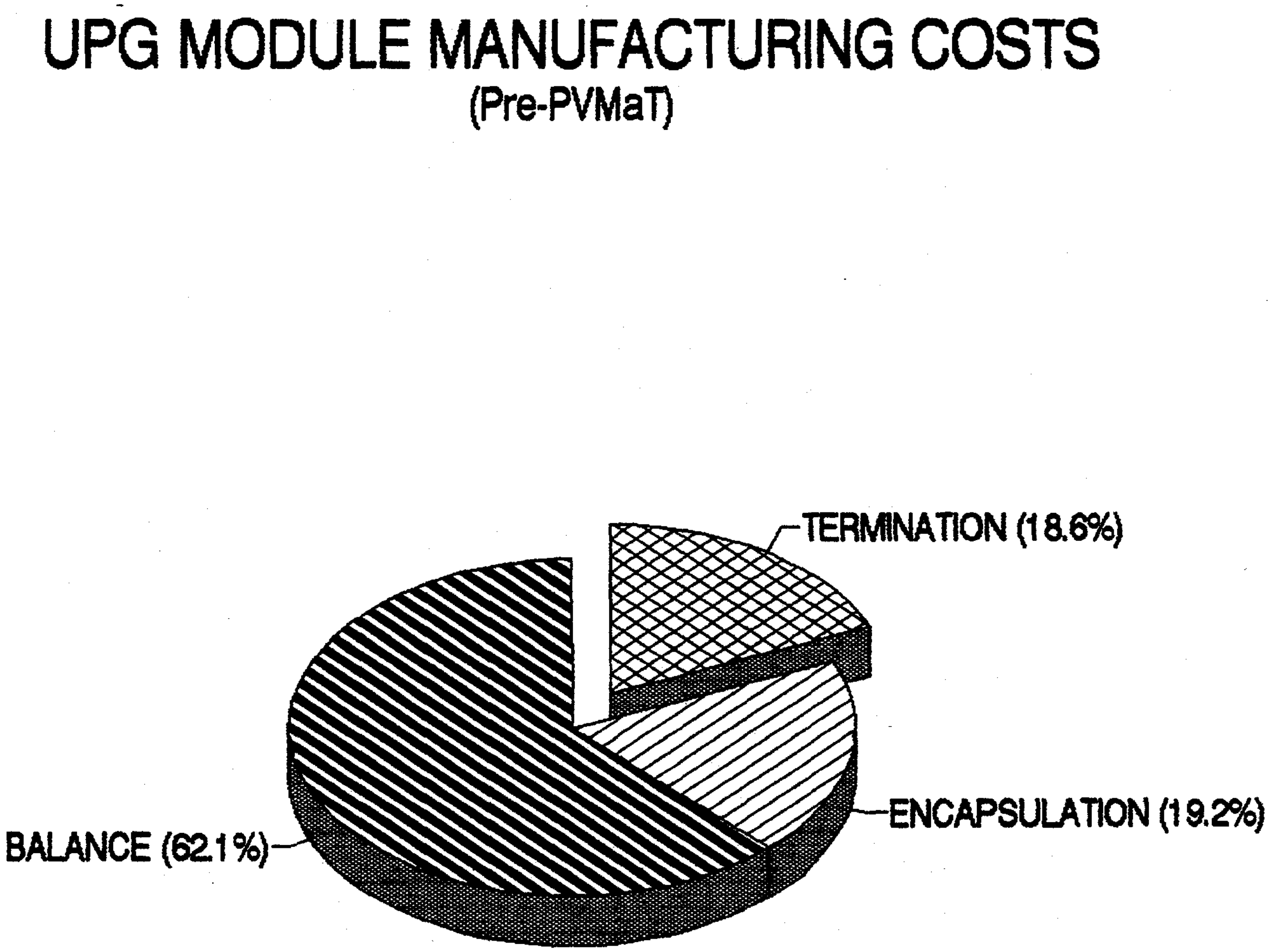


Figure 5. Manufacturing cost reduction of termination and encapsulation process steps as a result of the PVMaT Phase 1 effort.

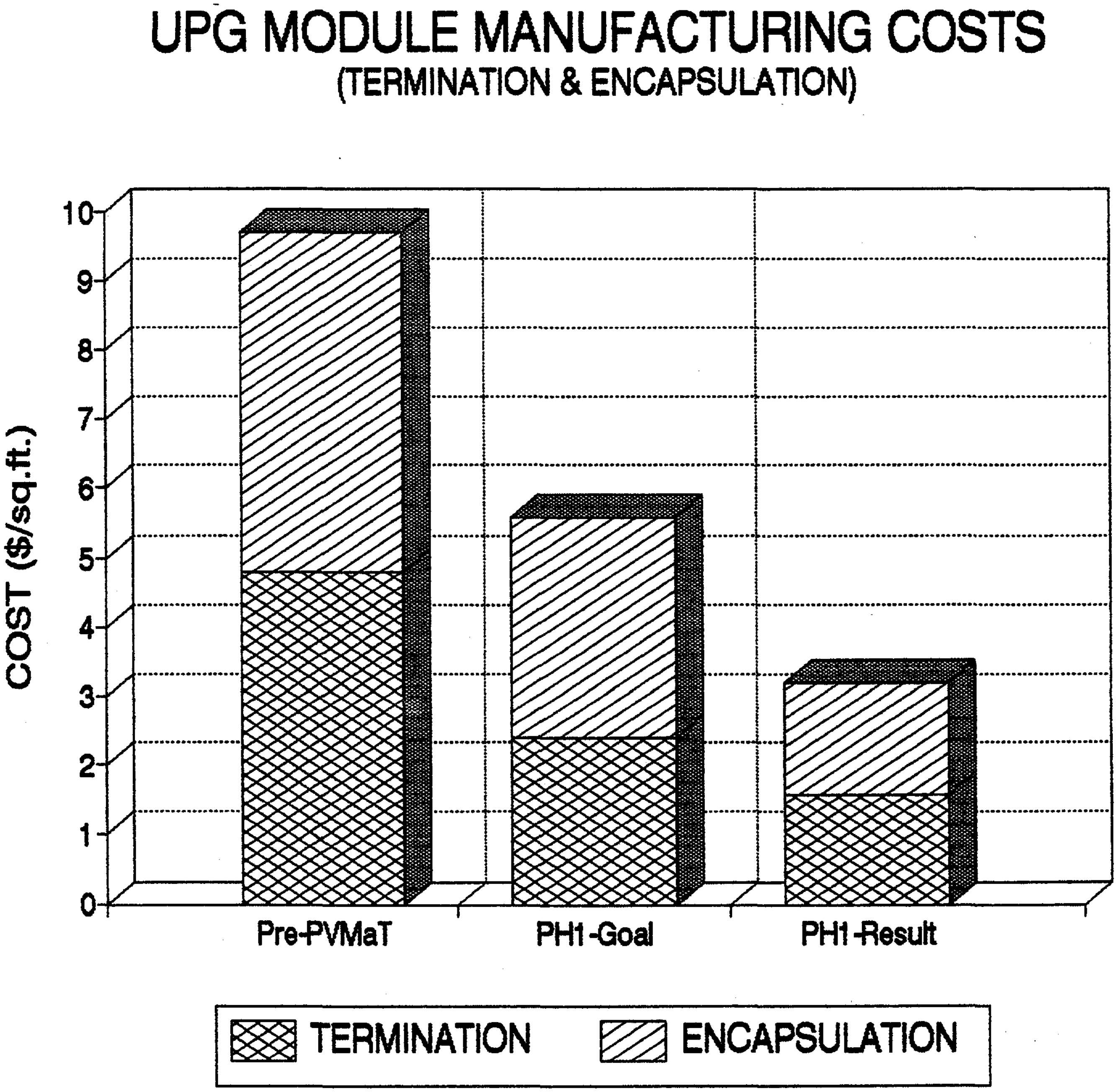


Figure 6. Cost reduction projections of the termination and encapsulation process steps as a result of the three-year effort under the PVMaT Project.

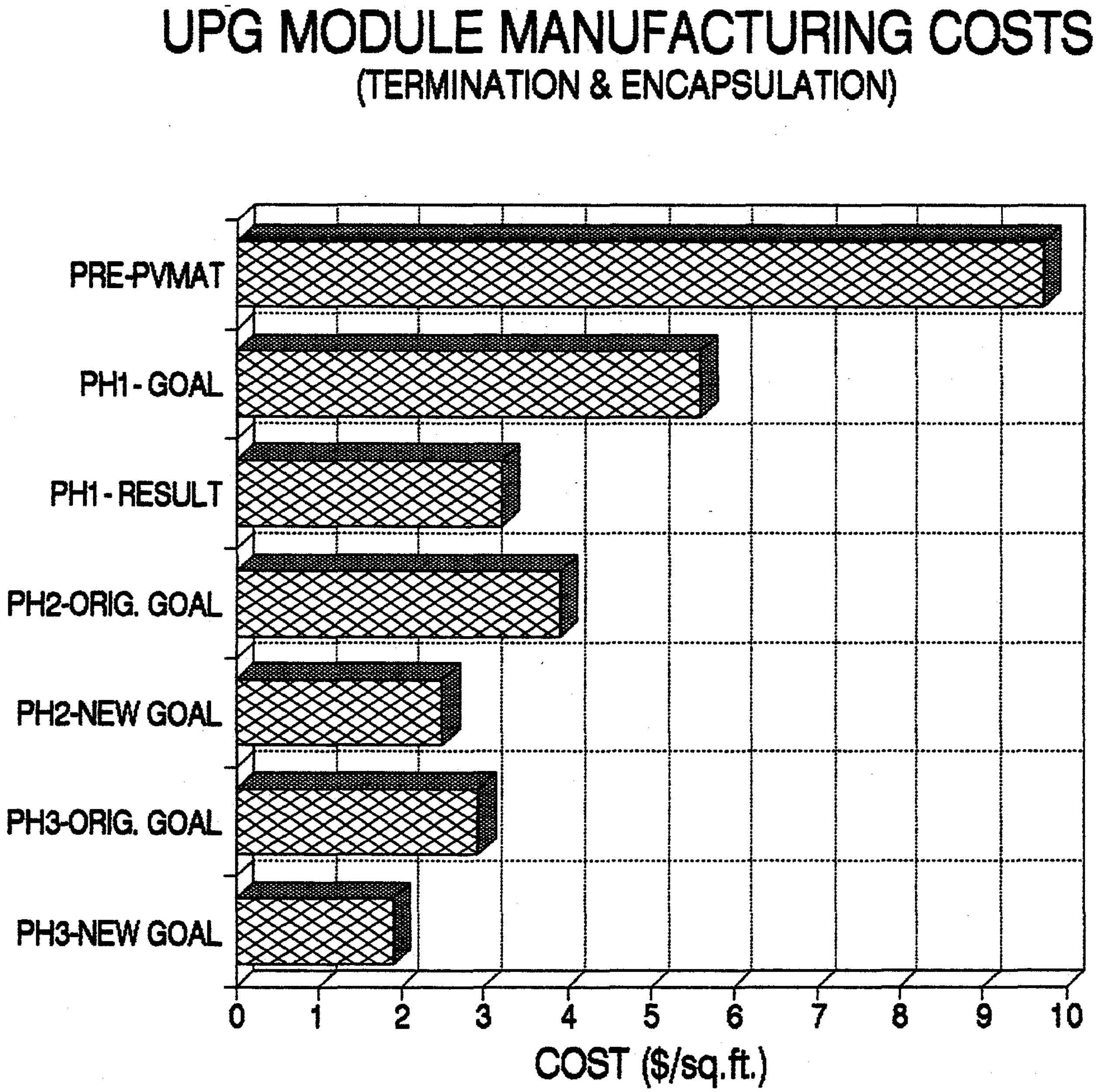


Figure 7. Costs of the process steps for the Post-PVMaT modules based on the list of steps in Table 1.

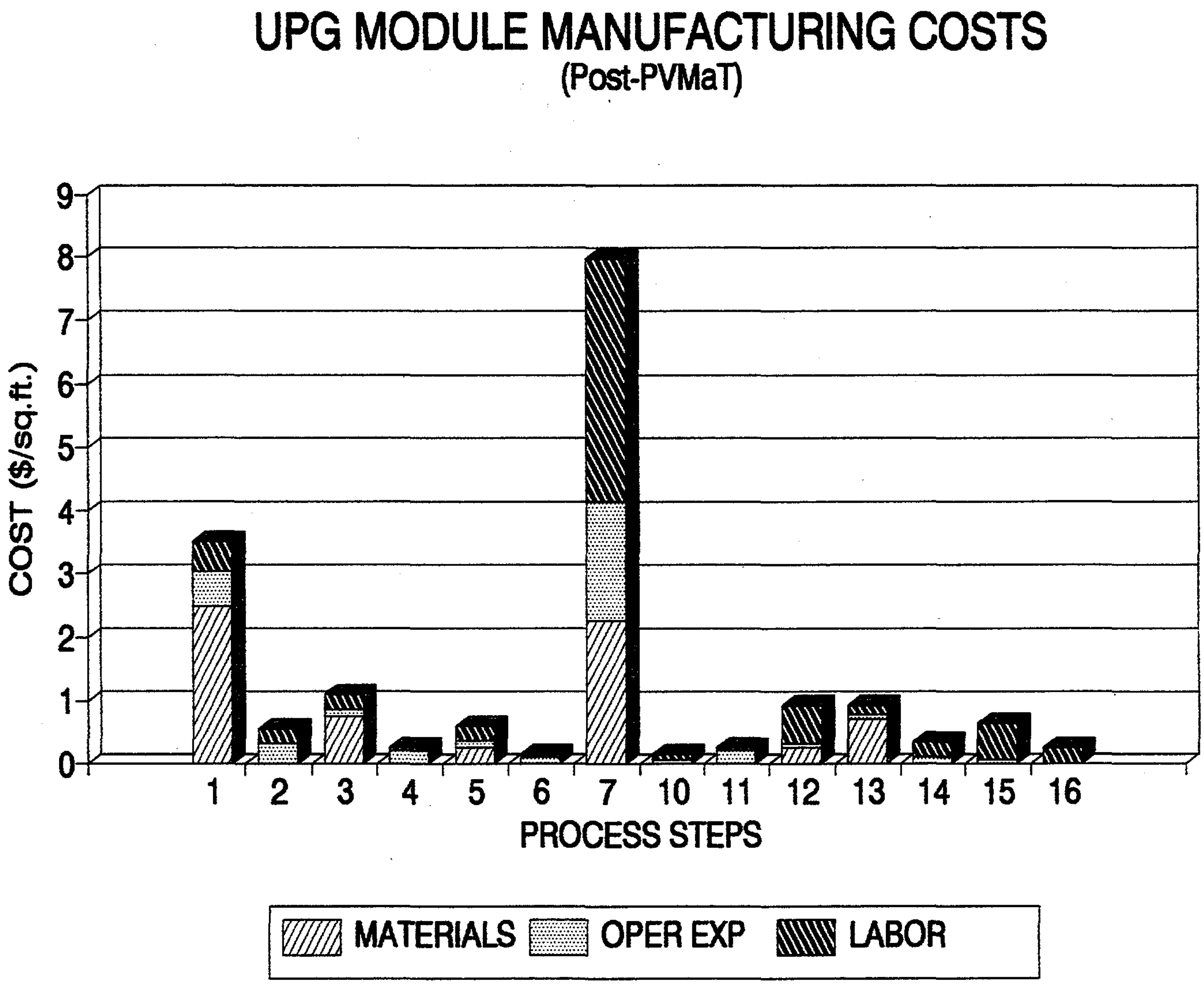


Figure 8. Total manufacturing cost reduction as a result of the three-year effort under the PVMaT Project.

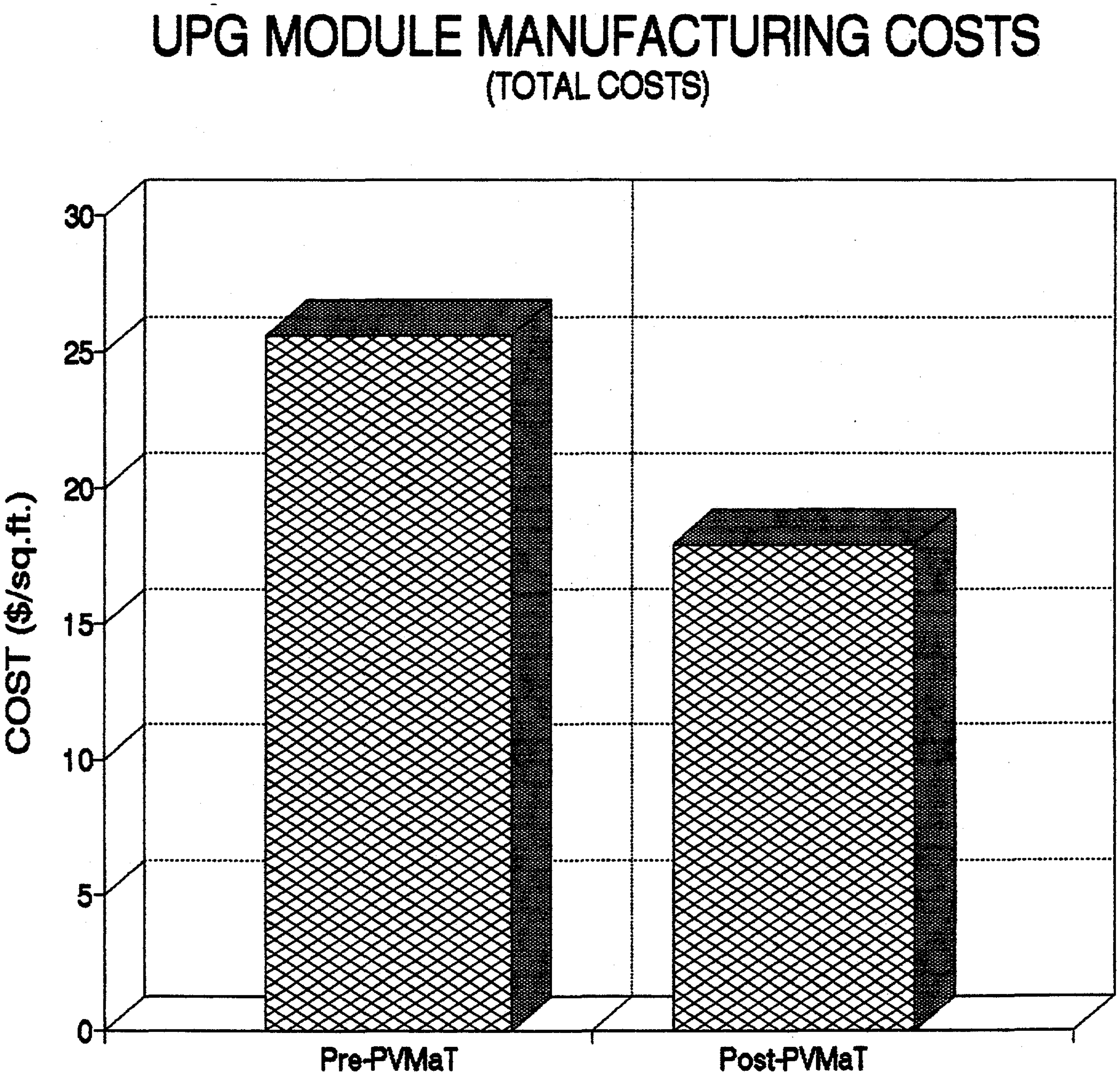
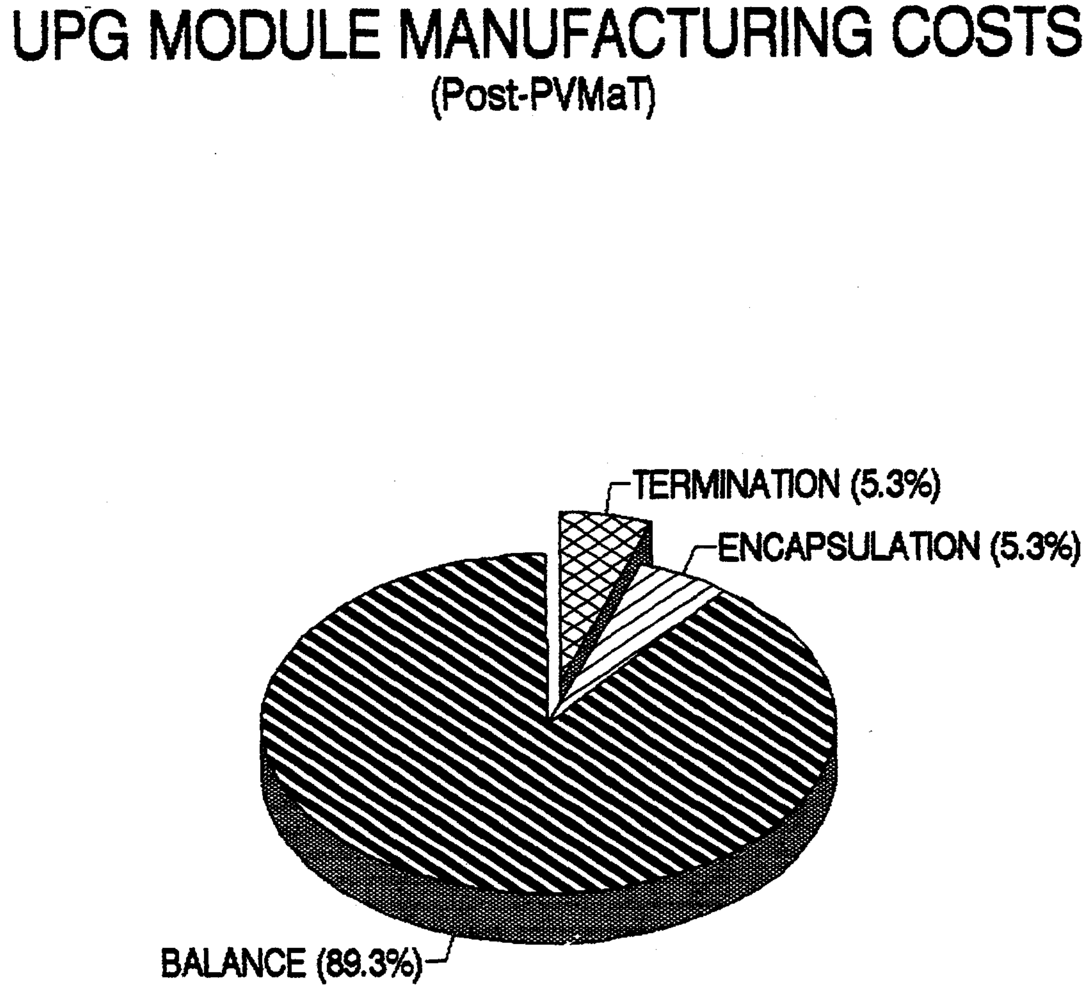


Figure 9. Ratio of the costs for the termination and encapsulation process steps to the balance of the process steps for the Post-PVMaT modules.



2.0 TASK 1: POWERGLASS Module Encapsulation

In this task UPG has investigated a wide variety of materials and processes for the encapsulation of amorphous silicon thin film PV circuits deposited on glass substrates. These materials were evaluated in terms of their substrate adhesion, scratch resistance, chemical resistance, water penetration resistance, compatibility with module fabrication techniques, and air quality environmental concerns. Methods and materials were sought which lend themselves to environmentally safe application, high volume throughput, low unit cost, and automated application techniques. Areas of focus included:

- o Materials
- o Application
- o Reliability
- o Cost

The materials considered fall into four main categories:

1. Polyurethanes
2. Epoxies
3. Silicones
4. Plastic Copolymers

The following is a list of the materials investigated:

Polyurethanes:

Hardman, Inc.	- Kalex 13361 A/B
Conap, Inc.	- Conathane CE-1163
	- Conathane CE-1175
Chase Humiseal Corp.	- Humiseal 1A27
	- Humiseal 1A33
	- Humiseal 1A20
Epmar Corp.	- EX165

Epoxy:

Ameron Corp.	- Amercoat 385P

Silicone:

Dow Corning Corp.	- Q3-6611
	- 577
Chase Humiseal Corp.	- Humiseal 1C49
General Electric	- RTV 630
	- RTV 128

Plastic Copolymer:

Plastic Flamecoat	- PF 110
	- PF 112
	- PF 160

Polyurethane

Hardman, Inc. - Kalex 13361 A/B
This material is a filled, nonabrasive, medium viscosity, two part, rigid urethane system, curable at room temperature, useful for low and medium voltage applications with superior thermal cycling performance. The viscosity of this material lends itself to screen printing. However, this material provided very poor protection against chemical attack to the encapsulated thin film. In addition, the adhesion of the polyurethane to the substrate was not adequate.

Conap, Inc. - Conathane CE-1163
This material is a single component polyurethane coating developed specifically for protecting printed circuit boards under adverse environmental conditions. It cures at room temperature in the presence of moisture to form a highly cross-linked film that appears glossy. Methods which may be used to apply CE-1163 include airless spray, pour curtain, dipping, and brushing. CE-1163 contains xylene, toluene diisocyanate, and propylene glycol methyl ether acetate. The organic solvent vapors which evolved from the material as it cured were strongly present. The cured coating was hard and adhesion to the substrate was excellent. The coating protected the thin aluminum film on the substrate from being attacked by a hot NaOH solution.

Conap, Inc. - Conathane CE-1175
This material is a single component polyurethane similar to CE-1163 except that it is water based. Since the CE-1175 is water based, clean up of application equipment is simpler, less time consuming, and less hazardous compared to the CE-1163 product. However, after application to test coupons and overnight cure, portions of the aluminum film appeared discolored. It is believed that the water contained in the product reacts with the thin film aluminum causing the discoloration.

Chase Humiseal Corp. - Humiseal 1A27
This material is an air drying single component polyurethane coating widely used for printed circuit board applications. The Humiseal 1A27 is low to medium viscosity allowing it to be poured onto the test coupons. The cured coating was hard and adhesion was excellent. After immersion in the hot NaOH for one hour, the underlying aluminum thin film being protected by the coating was etched by the NaOH, and the coating appeared damaged as evidenced by 1mm-2mm diameter holes in the coating itself. Adhesion remained unaffected.

Chase Humiseal Corp. - Humiseal 1A33
This material is a single component fast air drying polyurethane coating well suited for general printed circuit board applications. After application to test coupons and recommended cure, the test coupons were subjected to the hot NaOH immersion test for a period of one hour. The results of this test were identical to those found for the Humiseal 1A27.

Chase Humiseal Corp. - Humiseal 1A20
This material is a single component, durable and chemically resistant moisture curing coating for printed assemblies. After application to test coupons and recommended cure, the test coupons were subjected to the hot NaOH immersion test for a period of one hour. The results of this test were identical to those found for the Humiseal 1A27 and 1A33.

Epmar Corp. - EX 165
This material is a two component, unfilled, 100% solids polyurethane potting and casting compound for electronic circuitry. Upon mixing according to the manufacturer recommended ratios, the two component material was poured onto test coupons and cured at the recommended schedule. Tests could not be performed due to the poor cure which occurred. After removel from the cure oven, the material on the test sample was only slightly more viscous than before entering the cure oven.

Epoxy

Ameron Corp. - Amercoat 385P
This material is a two component, sprayable coating, highly stable in harsh, aggressive environments. It forms a tough, abrasion resistant, durable film suitable for immersion in fresh and salt water up to 140 F continuously and can be used as a tank lining for alkaline and salt solutions, petroleum fuels, sewage waste, and other chemicals. The material applied to test coupons proved to have excellent adhesion characteristics, resistance to chemical attack, and scratch resistance. A relatively mild amount of organic solvent (compared to the Conap polyurethanes) was detected by smell during application and ambient cure.

Silicone

Dow Corning Corp. - Q3-6611
This material is a one part, flowable, silicone elastomer that develops a strong, self priming adhesive bond to many substrates when cured at high temperatures (125 C). Application of the silicone adhesive to test coupons was performed by two methods; brushing and by screen printing. After curing, the silicone exhibited excellent adhesion to the substrates and excellent resistance to the hot NaOH bath.

Dow Corning Corp. - 577 Primerless
This material is a two part, flowable, silicone elastomer which develops a strong, self priming adhesive bond to many substrates when cured. Application of the silicone adhesive to coupons was performed by spatula. Parts were cured at 125 C for a period of one hour. After curing, the parts exhibited excellent adhesion to the substrates before and after hot NaOH immersion and excellent resistance to chemical attack. No etching of the underlying aluminum thin film was observed.

Chase Humiseal Corp. - Humiseal 1C49
This material is a fast curing, 100% solids single component silicone coating providing moisture protection for printed circuit assemblies. The Humiseal 1C49 was applied by directly pouring the material onto the test coupons. The material was then cured at 170 F for a period of 20 minutes per manufacturer's recommendation. After cure, the chemical resistance of the material was tested by immersing in hot NaOH solution for one hour. The 1C49 provided excellent protection to the underlying aluminum film from the NaOH. The adhesion remained excellent.

General Electric Corp. - RTV 630
This material is a liquid silicone rubber compound that cures at room temperature to a high strength silicone rubber with the addition of a curing agent. This two component product is "moderately pourable" according to the manufacturer. The two part product was mixed in the recommended 10:1 ratio of base to catalyst. The homogeneous mixture was then applied via spatula to a test coupon and cured per the manufacturer's recommended schedule. After the curing cycle, it was found that adhesion to the coupon was poor. It was subsequently determined that the manufacturer recommends a primer be applied to the surface of the substrate to be coated prior to application of the silicone elastomer. Never the less, the coupon was then subjected to the hot NaOH immersion test for one hour. The results of the immersion test found that the silicone did protect the underlying aluminum thin film from being etched although the adhesion was poor.

General Electric Corp. - RTV 128
This material is a single component adhesive sealant which cures at room temperature to a tough, silicone rubber. The immersion test results were identical to the GE RTV 630. The material provided excellent protection for the underlying aluminum thin film. The adhesion of the silicone to the substrate was excellent, however, the scratch resistance was poor. It was possible to scratch through a 0.075" thick film with a moderate pressure of a fingernail.

Plastic Copolymer

Plastic Flamecoat Systems, Inc. - PF 110
This product is a Dupont Surlyn based blend of materials which is UV stable, repairable, and environmentally safe. The softening temperature of the material is 176 F. Test coupons were coated and then subjected to the hot NaOH immersion test for the standard period. The results found that the adhesion and integrity of the coating were unaffected. The immersion test was performed at 77C. A subsequent test subjected another coated coupon to 30 minutes at 90 C in an oven. Upon removel, the thermoplastic was found to be soft and adhesion was poor, As the coupon cooled to ambient room temperature, the adhesion, toughness, and abrasion resistance returned to original values.

Plastic Flamecoat Systems, Inc. - PF 112
This material is a Dupont Surlyn based blend similar to PF 110 but with a softening temperature of 142F. After application, it was found that coating uniformity, scratch resistance, and adhesion were excellent. After hot NaOH immersion, the adhesion of the coating on parts which had cooled as well as parts that were still hot was tested. The coating on the parts which had after immersion exhibited the same excellent adhesion originally observed before immersion. The coating on the parts which had not completely cooled after immersion could be peeled away from the surface, Inspection of the aluminum film below the plastic which was peeled away revealed that no etching of the aluminum had occurred.

Plastic Flamecoat Systems, Inc. - PF 160
This material is based upon ethylene vinyl acetate copolymer (EVA). The melting point is the same as that of the PF 112 (149 F). Adhesion to the substrate was excellent. Softening occurred after NaOH immersion and adhesion reduced. However, while returning to room temperature, adhesion and toughness returned to original values. The aluminum below the EVA coating remained unaffected by the hot NaOH immersion.

Conclusions of the Candidate Encapsulation Materials Evaluation

These materials have been evaluated in terms of the following characteristics:

Table 2. Encapsulant Characteristics

1) Substrate Adhesion
2) Compatibility With Thin Films
3) Scratch Resistance
4) Chemical Resistance
5) Water Penetration Resistance
6) Compatibility With Module Fabrication Techniques
7) Air Quality Concerns
8) Safe Application
9) Cost
10) Application Speed

By assigning quantitative values to the ratings of the various encapsulants, UPG was able to compare the various encapsulants in a systematic manner to determine the most attractive encapsulant material.

Table 3. Encapsulant Evaluation

Encapsulant Characteristic	P	E	S	C
1. Substrate Adhesion	F	G	E	E
2. Compatibility With Thin Films	F	G	E	E
3. Scratch Resistance	G	F	P	F
4. Chemical Resistance	G	G	E	E
5. Water Penetration Resistance	F	F	E	G
6. Compatibility With PV Module Fabrication Techniques	G	G	G	G
7. Air Quality Concerns	P	F	E	G
8. Safe Application	F	F	E	G
9. Cost	E	E	G	G
10. Application Speed	E	E	E	G

Encapsulant	Value
P = Polyurethane	E = Excellent (4)
E = Epoxy	G = Good (3)
S = Silicone	F = Fair (2)
C = Copolymer	P = Poor (1)

After summing up the values of the various encapsulation materials, it was determined that the silicone based material was superior to all the others that went through the evaluation process.

Figure 10. Polyurethane encapsulation materials evaluation based on characteristics listed in Table 3.

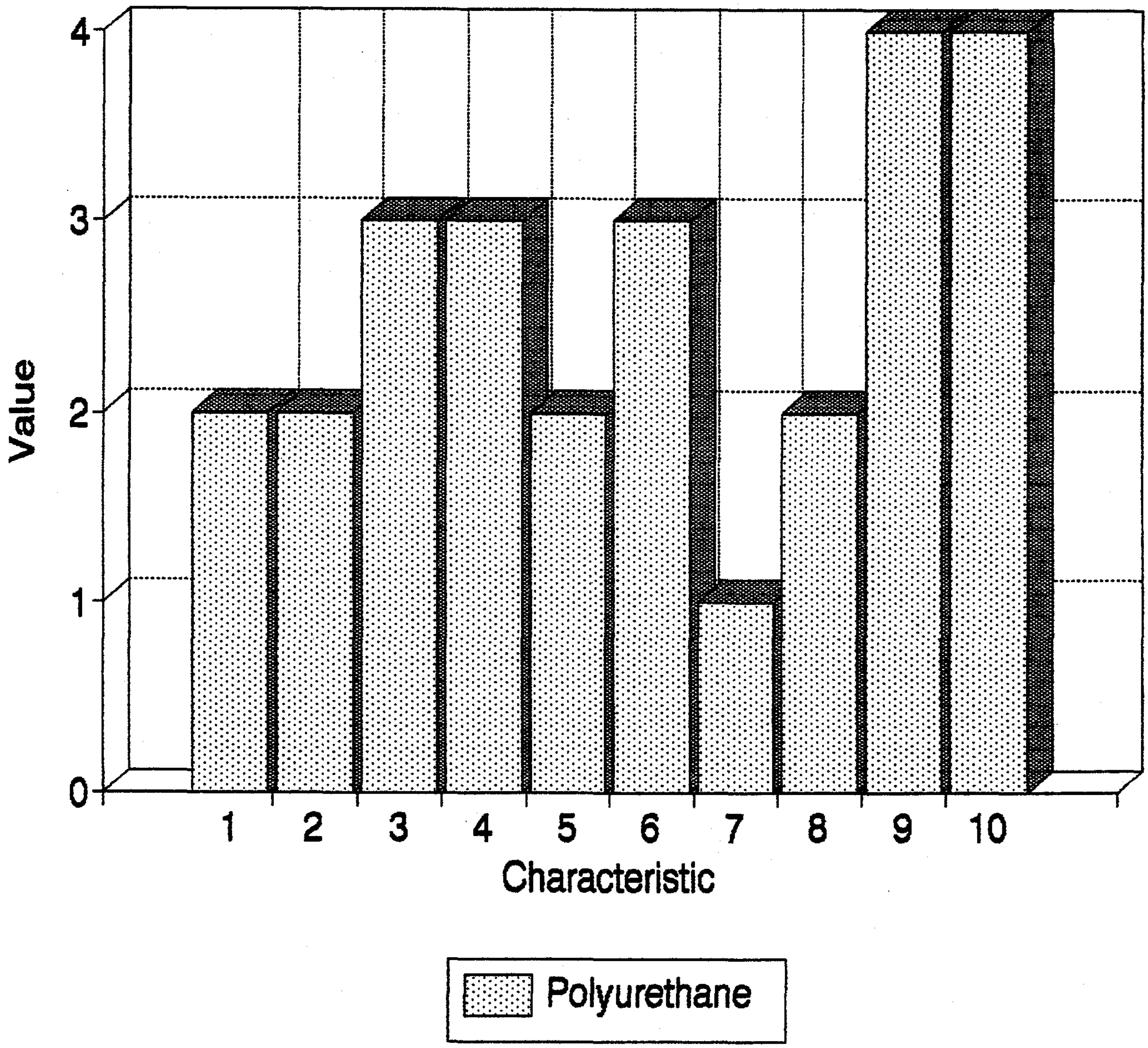


Figure 11. Epoxy encapsulation materials evaluation based on characteristics listed in Table 3.

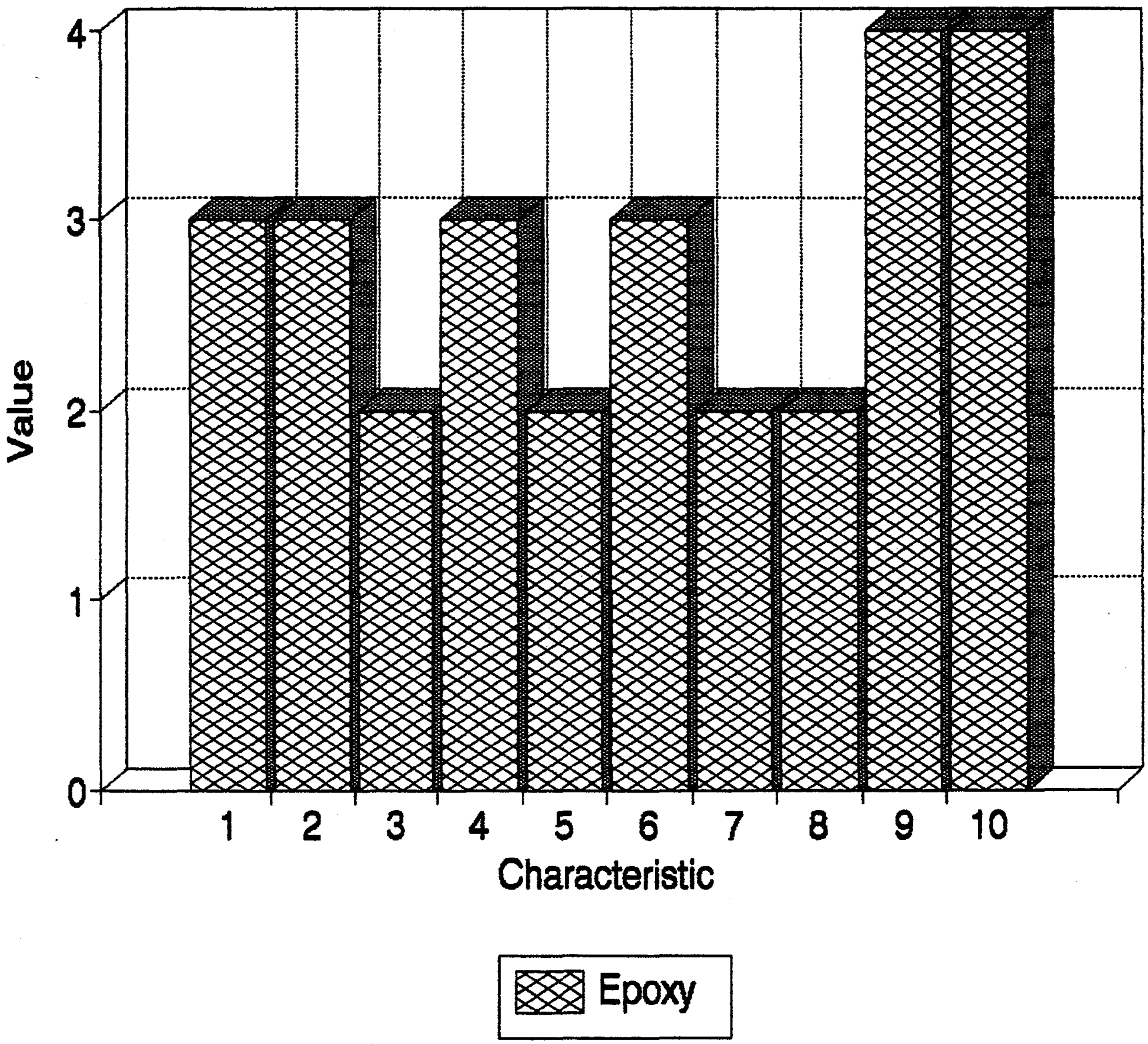


Figure 12. Silicone encapsulation materials evaluation based on characteristics listed in Table 3.

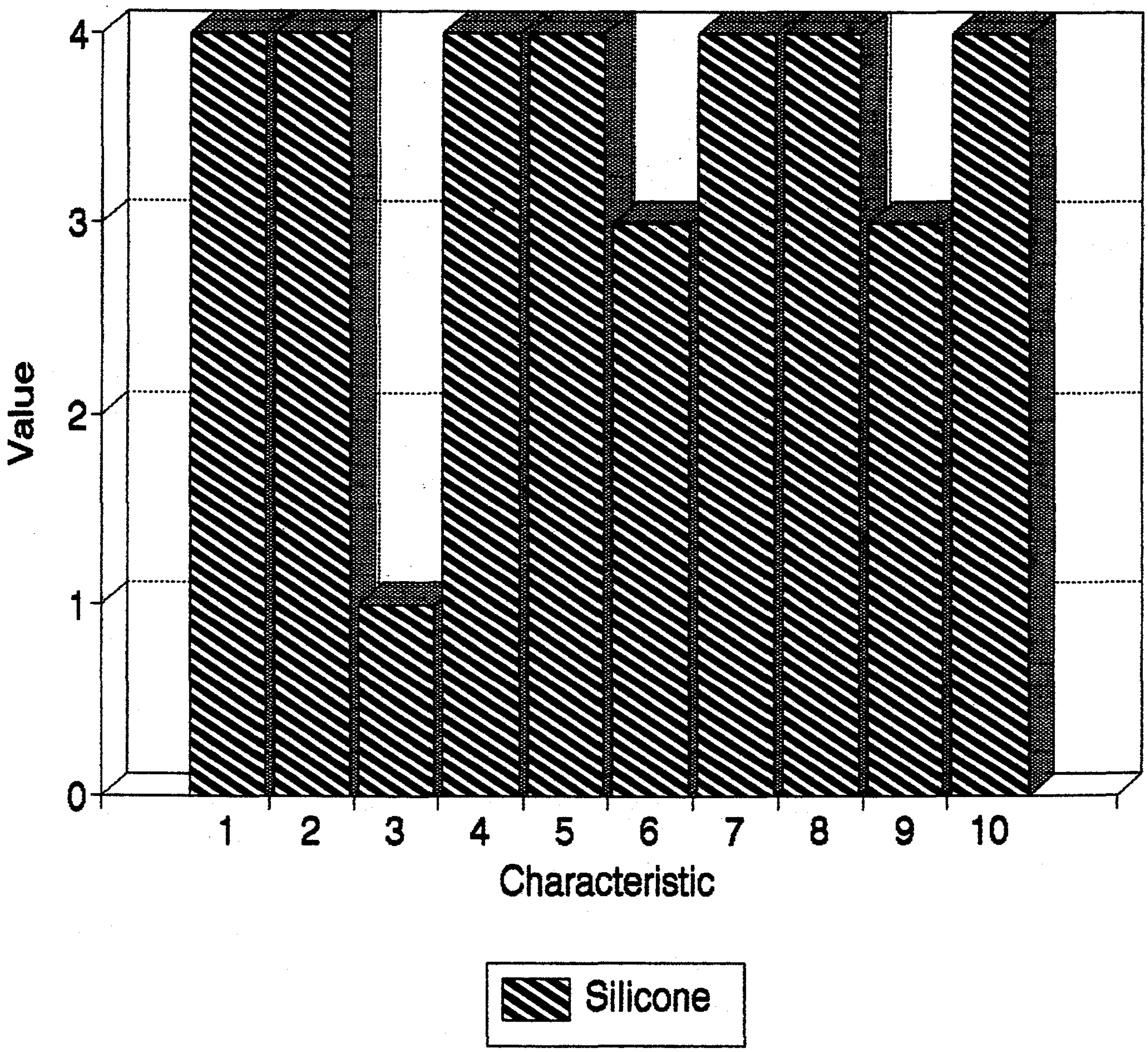


Figure 13. Copolymer plastic encapsulation materials evaluation based on the characteristics listed in Table 3.

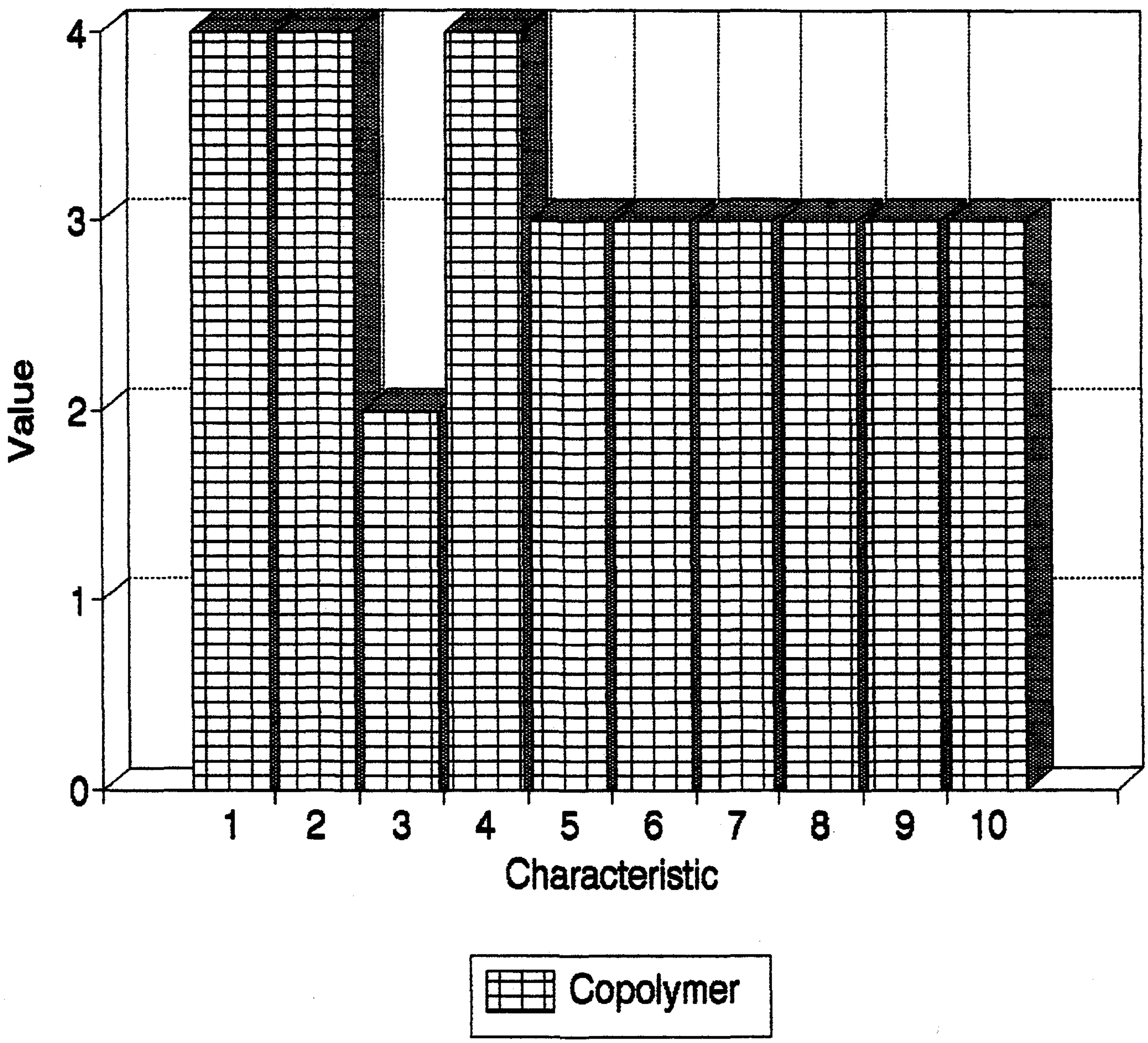
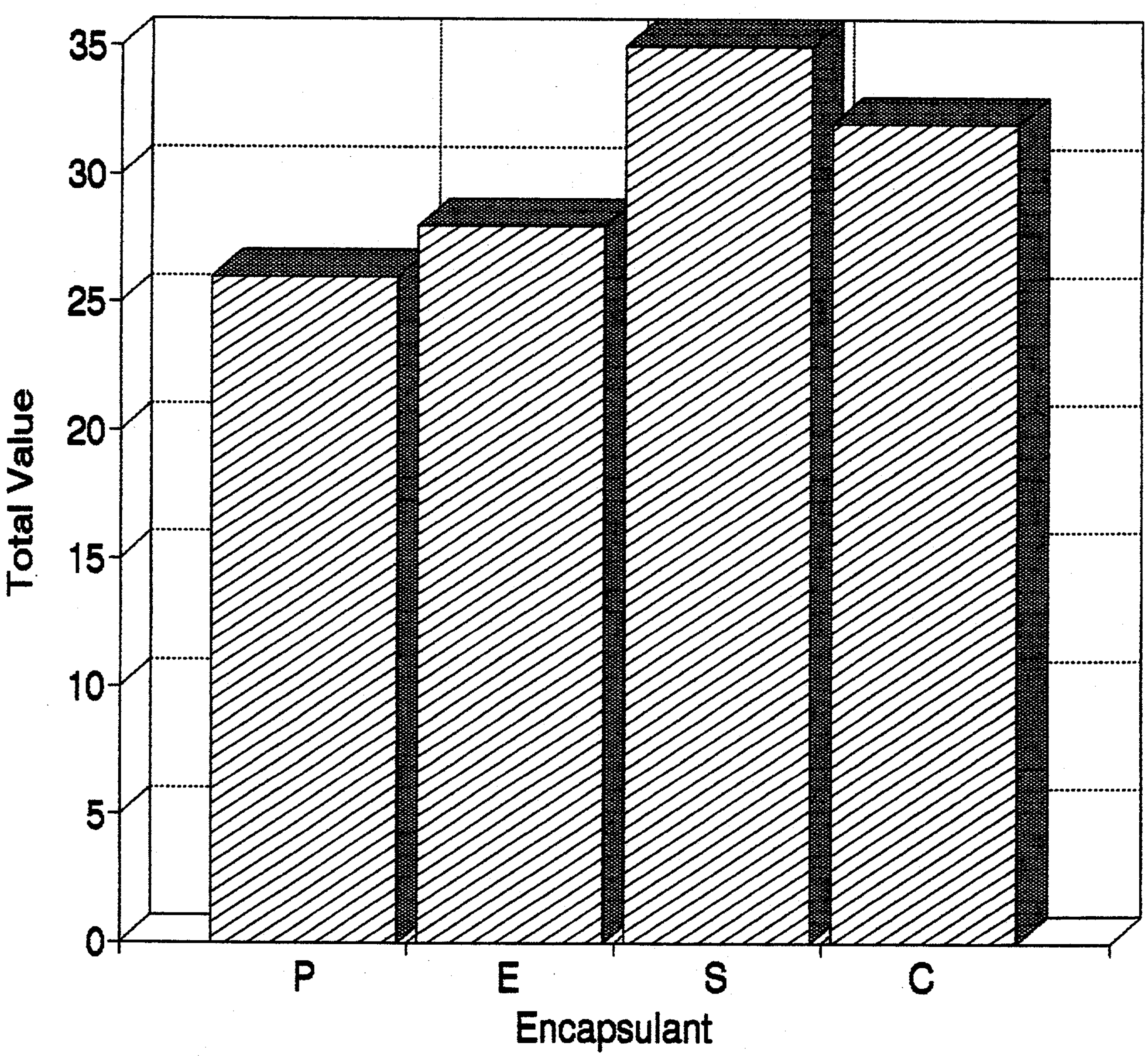


Figure 14. Encapsulation materials evaluation results where; P = polyurethanes, E = epoxies, S = silicones, and C = plastic copolymers.



Application Techniques

Spraying:

Application methods were sought which lend themselves to environmentally safe application, high volume throughput, and automation. One such application technique is spraying. During a demonstration at GRACO Inc. of Los Angeles, California, an attempt was made to spray the DOW 577 product, using air-assisted/airless spray technology, onto otherwise uncoated glass. The purpose of the test was to determine if the extremely high viscosity material could be sprayed to provide a uniform, thin (0.005" - 0.006"), coating over a one square foot area.

The experiments were conducted using only the base component of the two part DOW 577 product. Due to equipment limitations, the curing agent could not be included in the tests. This was due to the fact that the equipment which was available for use did not have mixing or metering capability. It was thought that if the method provided acceptable results using only the base material that the two part mixture would be relatively easy due to its lower mixed viscosity. The following data describes the viscosity of the DOW 577 product per Dow Corning's technical publication:

BASE
Viscosity @ 25C, centipoise 135,000

CURING AGENT
Viscosity @ 25C, centipoise 5,000

CATALYZED 10:1 ratio base to curing agent by weight
Viscosity @ 25C, centipoise 87,244

Spray parameters, such as, delivery pressure, air tip pressure, and air tip size, were varied to optimize the spraying process. Material was delivered from a five gallon pail to the spray gun by applying 3000 psi at a following plate. By the time the material had reached the spray gun, the pressure at the gun had dropped to 1000 psi. The base material left the spray gun in strings. The velocity of the strings was surprisingly low considering the pressure at the gun. Attempts were made to break up the strings into small droplets by atomization at the gun tip exit. The best results yielded strings that were approximately 0.50" in length and 0.001" - 0.002" thick.

A single pass of the gun at a distance of approximately on foot did not provide continuous coverage. Six to seven passes of the gun at the same distance provided close to continuous coverage. After 15 to 20 minutes standing, the voids began to fill as the material coalesced. Six to seven passes of the gun provided 0.012" wet film thickness.

DOW Corning Product Q3-6611 is a single component primerless silicone adhesive. Its viscosity is 95,000 centipoise @ 25C.

Since this material's viscosity closely matches the mixed two part product's viscosity, it was decided to try to spray the single component material to see if the lower viscosity material, compared to the base material used prior, would allow better spray performance. Glass was cleaned, coated with sputtered aluminum, and cut to 10 cm x 10 cm size. Approximately 30 of these samples were sprayed with silicone, varying the thickness of the coating.

The first result which was apparent was that the Q3-6611 material's lower viscosity provided a spray pattern which more closely resembled small droplets as opposed to the string pattern produced with the 577 base material. The thickness and uniformity of the coating was controlled by speed of application, distance between gun tip and sample, and the number of spray passes.

Wet film thickness of the samples ranged from 0.002" to 0.016". The parts were transported back to UPG and cured for one hour at 120C. Portions of the cured silicone coating were removed from each 10 cm x 10 cm sample for thickness measurements. The thickness of each coating sample was profiled in three locations along the length of the 10 cm strip removed for thickness measurements. For coating thicknesses in the range between 0.002" and 0.004", pinholes in the cured coating were apparent. Coating thicknesses from 0.005" to 0.006" had no apparent pinholes. Immersing samples into hot NaOH for a period of 30 minutes revealed that coating thicknesses of 0.005" or greater provided complete protection for the underlying aluminum from the hot NaOH etch.

The conclusion of these tests found that the single part DOW Q3-6611 material can be sprayed fairly uniformly with a continuous coating achieved with a minimum thickness of 0.005". The minimum thickness also provides protection to the thin film aluminum from the NaOH etch. From these results it may also be concluded that no fundamental problem exists which would prevent the spraying of the two part DOW 577 product since its viscosity is lower that the Q3-6611.

Roller Coating:

Another application technique which was investigated is roller coating. Roller coating glass is not new to the glass coating industry and the use of roller coaters to apply the paint for spandrel glass has been refined and is making an impact on the architectural glass industry. Roller coating equipment and methods have been designed that have many advantages over other methods of applying paint or other thick films to glass, such as spraying, curtain coating, and silk screen printing.

The roller coater incorporates a rubber covered coating roll, which works in conjunction with a chrome plated doctor roll and a rubber covered backup roll. The doctor roll is adjustable in relation to the backup roll, thus regulating the amount of encapsulant being applied to the top surface of the glass. To insure a smooth coating, reverse coating is used. Reverse roller coating as well as the durometer and grinding of the coating roll surface are critical to the application of uniform encapsulant material.

Other features of these machines may include powered conveyors, which transport the glass to and away from the coating assembly; explosion-proof motors and electricals; variable speed drive and precision control of all roll adjustments.

Some of the advantages of the reverse glass roller coater are:

1. Small amount of encapsulant material needed for start up of the roller coater.

2. Ability to leave the edges of the glass clean (both sides, leading and back edge).

3. Smoother coat with less striations.

4. A maximum of 15 minutes clean up time.

5. Less waste of encapsulant material during operation and at clean up time.

6. The speed of the coater may be synchronized with corresponding curing ovens.

A member of the UPG staff has visited two manufacturers of roller coating equipment and was able to have several modules coated with silicone encapsulation material. The equipment satisfactorily coated the modules in a thickness range of 6-12 mils. The application throughput of the equipment is suitable for production and only very small amounts of encapsulation material was wasted. At this point, because of the ease of set-up, application, and clean-up, roller coating appears to be the application technique which will be pursued to be incorporated into the UPG manufacturing line.

Glass Tempering

In addition to the identification and development of a high performance encapsulant, the availability of a tempered superstrate is required to eliminate the need for a back glass sheet. UPG has selected vendors capable of tempering superstrate glass with a TCO layer deposited on one side. These superstrates were processed resulting in samples from every major PV module processing step listed in Table 1. Annealed glass (untempered) was processed in a similar manner. All samples were sent to Sandia National Laboratories (SNL) for the Hail-Impact Evaluation Test. SNL reported that all the annealed glass failed the Hail-Impact Test while all the tempered glass (at all stages of PV module fabrication) passed. In fact, the tempered glass passed at 150% of the required kinetic energy.

UPG has concluded that as long as the superstrate is tempered, no additional back glass sheet is required to pass the Hail-Impact Evaluation Test.

Task 1 Summary

A wide variety of materials and processes for the encapsulation of amorphous silicon thin film PV modules deposited on glass substrates have been investigated. These materials have been evaluated in terms of their substrate adhesion, compatibility with thin-films, scratch resistance, chemical resistance, water penetration resistance, compatibility with module fabrication techniques, air quality environmental concerns, safe application, cost, and application speed.

At the conclusion of the first stage of materials investigation and selection, it was determined that the most promising encapsulation material was the DOW Corning 577 Primerless Silicone.

The DOW 577 Silicone can be applied in a variety of ways, however, because of the ease of set-up, application, and clean-up, roller coating appears to be the application technique which will be pursued to be incorporated into the UPG manufacturing line.

Plans For Phase II

UPG will continue to evaluate the advanced substitute materials and processes for thin-film module encapsulation identified in Task 1. The materials will be 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 and wiring within a panel or sub-array. UPG will continue with the development of the prototype modules utilizing tempered substrate glass. UPG will design and debug an automated encapsulation station utilizing the advanced processing methods and materials identified in Task 1. The original cost reduction goal for encapsulation in Phase II was set at 50% (cumulative), however, UPG projects that a cost reduction of 70% can be achieved.

3.0 TASK 2 POWERGLASS Module Termination

In Section 1.0 Background, a description was outlined of the process utilized by UPG to attach terminals on the Pre-PVMaT or PVUSA modules. Tin plated copper ribbon was soldered to the screenprinted busbars, fed through the EVA and back tempered glass, and then soldered to a standard spade quick disconnect terminal. The terminal was then attached to the back glass to relieve any mechanical stress from the copper ribbon and solder joints.

Reports from PVUSA suggest that this terminal system has proven to be quite reliable, with only one module failure due to this very robust terminal system.

Although reliable, the direct manufacturing cost of this termination procedure represented almost 20% of the total module manufacturing cost.

Therefore, UPG proposed in Task 2 to develop manufacturing technology capable of decreasing the termination costs while maintaining the high level of reliability and robustness of the Pre-PVMaT termination system.

Terminal Designs

The technical approach has been to design and fabricate several candidate module termination configurations to be compatible with the encapsulation materials and processes developed in Task 1. All termination components were designed for use with automated insertion and assembly equipment, so called "pick and place" robotic systems. All designs were analyzed in terms of manufacturing cost reduction of the former process and ease of use from the customers' viewpoint.

The first terminal systems were designed to be soldered directly to the silver soldering pads on the glass surface. The four terminal designs were:

1) Spring Clip

2) Threaded Bolt and Nut

3) Wire Cage Clamp

4) Binding Post

The four candidate terminal designs were fabricated or procured and evaluated in terms of materials cost, ease of attachment and connection, and adaptability to multi-module systems.

The Threaded Bolt and Nut is the least expensive, followed by the Spring Clip, the Binding Post, and finally, the Wire Cage Clamp.

All four of the candidate terminals can be automatically soldered to the busbar pads with a robotic soldering station, however, only the Threaded Bolt and Nut would <u>not</u> require rigorous rotational orientation tolerance.

In terms of connection to a power cable or wire, the Binding Post would accept either a stripped wire end or a ring/spade lug, the Spring Clip and Wire Cage Clamp would accept only stripped wire ends, and the Threaded Bolt and Nut would accept only a ring/spade lug.

In multi-module systems, the Spring Clip and Wire Cage Clamp would require jumpers of wire since threading a wire through these terminals in a parallel configuration is not practical. The Binding Post and Threaded Bolt and Nut permit the use of flat rectangular copper busbar stock with center spaced holes for parallel and series strings. Based upon UPG's PVUSA system design, the use of the copper busbar stock would greatly reduce module to module interconnection costs.

The Threaded Bolt and Nut was determined to be superior to the other candidate terminal designs based upon materials cost, ease of attachment and connection, and adaptability to multi-module systems.

<u>Reliability of Soldering Directly to Silver Pad</u>

The first four terminal systems were all designed to be soldered directly to the silver busbar pad. A soldering method was developed to maximize the terminal torque strength.

Underwriters Laboratories document UL1703 entitled "Flat-Plate Photovoltaic Modules and Panels" describes terminal torque requirements in Section 27 - Terminal Torque Test. A wire-binding No. 6 screw or nut on a wiring terminal shall be capable of withstanding 10 cycles of tightening to and releasing from a torque value of 12 pound-inches without (1) damage to the terminal supporting member, (2) loss of continuity, or (3) short circuiting of the electrical circuit to accessible metal.

During the course of this effort, UPG developed terminal attachment procedures which resulted in terminal torque strengths well in excess of 35 pound-inches. This is almost three times the value specified by UL 1703 for a No. 6 machine screw (the Threaded Bolt and Nut Terminal). In most cases, it was the glass substrate that failed and not the solder to silver or silver to glass interface. However, after subjecting the terminated test coupons to the humidity/freeze cycle specified in the Interim Qualification Test Procedure (IQTP), the torque strengths of all the tested terminal attachment processes were reduced. In most cases, the torque strengths after the humidity/freeze test was still greater than the minimum level specified by UL 1703, but, UPG considers any reduction in the torque strength due to the humidity/freeze test to be a failure of the termination system to meet UPG's goals of module reliability.

Advanced Terminal System Design

UPG continued with the development of new terminal designs and attachment procedures until a new termination system capable of meeting the cost and reliability goals of the project was obtained. The new approach was to separate the mechanical and electrical functions of the termination system while the terminal remained an integral part of the module.

The new design utilizes the excellent mechanical and adhesive characteristics of the new silicone encapsulation material to provide the necessary structure to the terminal system. In addition, the advanced terminal was designed with all of the positive characteristics of the Threaded Bolt and Nut, that is, materials cost, ease of attachment and connection, and adaptability to multi-module systems.

One of the conventional techniques utilized by the electronics industry for attaching terminals is soldering. Although generally reliable and well established in the manufacturing environment, soldering requires the use of a flux during the solder flowing process to remove and/or prevent the formation of oxide layers on the termination surfaces. These fluxes are considered chemically active and should be removed after the soldering process is complete and before the termination joint is encapsulated or potted. If the flux is not removed it will eventually weaken the terminal joint to failure. The solutions required to clean this flux from the soldered surfaces of the terminal are either chloro-fluoro-carbons (CFC's) or other environmentally malign organic compounds. With this in mind, UPG developed a terminal attachment procedure that does not rely on the use of solder for making the electrical/mechanical connection. By eliminating the soldering process, the step of flux cleaning and the associated by-products of the cleaning step have been eliminated. Solder flux and the solutions to remove it are considered hazardous materials and must be handled accordingly.

After the new terminal design was fabricated and utilized in the assembly of POWERGLASS modules in both the glass/EVA/glass structure and the encapsulated glass structure, these modules were subjected to the Thermal Cycle Test. The thermal expansion and contraction induced by this test led to a failure of the terminal system to make a good electrical contact to the PV module electrical power collection points. Although these failures were easily repairable, one of the goals of the PVMaT project is to maintain or enhance the reliability of the POWERGLASS module. Therefore, the problem of contact reliability after encountering temperature extremes was investigated further and a change in the design and material of one of the terminal components was made to eliminate the problem caused by the temperature cycling. This terminal has successfully passed the Thermal Cycle Test. The changes made will not increase the manufacturing cost.

Module Fabrication

After finalizing the development of the new encapsulation and termination systems, full size modules were fabricated to allow qualification testing. The new termination system is adaptable to either the conventional glass/EVA/glass structure or the new encapsulant coated glass structure, therefore, both types of module structures were fabricated.

The PV circuit has been designed to place the positive and negative terminals in close proximity. This will allow both terminals to be protected by the same junction box, thereby decreasing that cost element.

UPG has designed and fabricated a frame for the POWERGLASS module to protect the edges from impact, protect the terminals, provide a strain relieved power cord, and a means for easily mounting the module.

Task 2 Summary

Four initial candidate terminal designs were fabricated or procured and evaluated in terms of materials cost, ease of attachment and connection, and adaptability to multi-module systems. The four candidate designs were:

1. Binding Post
2. Spring Clip
3. Wire Cage Clamp
4. Threaded Bolt and Nut

The Threaded Bolt and Nut had the best overall characteristics and the evaluation of this design was continued. All of the initial terminal systems were designed to be soldered directly to the silver pad on the glass superstrate. However, this attachment procedure suffered from a decrease in adhesion (torque strength) after being subjected to the humidity/freeze cycle test.

Therefore, a new approach was developed for terminal attachment which did not rely on soldering. This advanced terminal system has been through the IQTP with positive results and the changes made will not increase the manufacturing cost of the termination step.

Plans For Phase II

UPG will optimize the materials and processes utilized in the Phase I electrical termination of the POWERGLASS modules. The terminal components have been designed for use with automated insertion and assembly equipment. The terminal system will be analyzed in terms of manufacturing cost reduction. UPG will design and debug an automated termination station for the insertion and assembly of the advanced termination materials and processes identified in Task 2. The original cost reduction goal for Phase II was set at 70% (cumulative), however, UPG projects that a cost reduction of 80% can be achieved during that Phase.

Task 3 - Eureka Module Design

Objectives

The objectives of this task are to develop at least two new module designs based on PV plates generated by the Eureka manufacturing line. The designs are to maintain the Eureka modules' level of quality and reliability and direct costs associated with these products should be capable of demonstrating a 25% cost reduction over existing technology.

Milestones

M-1.7 Complete CAD iteration of prototypes of Eureka module designs (Q2) - Completed.

M-1.11 Complete design of full-scale enhanced Eureka modules and experimental fabrication (Q3) - Completed.

M-1.18 Complete fabrication of full-scale enhanced Eureka module (Q4) - Completed.

M-1.19 Gather and evaluate market, distributor and customer information regarding the new Eureka module designs (Q4) - Ongoing.

M-1.20 Complete the Phase I portion of the effort under Task 3 (Q4) - Completed.

New Products

Marketing input came from distributors and customers. Photocomm, of Scottsdale, Arizona, in particular, was influential in the early decisions. Since then, more formal marketing studies have been undertaken which will provide input for module development for the second phase.

Input from Marketing suggested three directions to pursue for new products. The most definitive input provided by market studies regarding module design, was to change the electrical connection point from the edge of the module as in the Eureka module made for PVUSA, towards the interior and thereby provide an unobstructed border. Thus, APS design and test efforts were directed towards a connection scheme in which the edges of the modules are left bare. Secondly, a smaller module was needed; one-half the size of the PVUSA module was thought suitable. Thirdly, a module voltage appropriate for 12-volt battery charging was deemed necessary.

The requirements outlined above resulted in the redesign of the EP 2, the original 38-volt power module used for PVUSA, into the EP 50, as well as two new modules for 12-volt applications.

The new modules are the EN 50, a full-size 50 watt module with a nominal 17-volt operating voltage, and the EN 25, a half-size power module with 25 watt output also nominally at 17-volts. The two new module designs share three main features that differ from the EP 2. The first deals with the lowered voltage of the modules. The voltage reduction is obtained by first increasing the cell width from 1.11 cm to 1.25 cm, thus reducing the number of cells. This results in a roughly 10% reduction in maximum power voltage to about 34-volts. To reduce this to 17-volts, the plate layout uses a mirror image cell design whereby cell patterning extends symmetrically outward from the center positive cell and effectively connects the two halves in parallel. This approach requires the two end cells to be connected and the common connection point to be brought out. To carry out this procedure, several new steps in the encapsulation process had to be added, as well as some additional equipment. The design required the junction covers to be at the center of one end of the module rather than at the corners as with the EP 2.

The second change is common to all three new designs. In order to have an unobstructed border in these products, access to the PV cells is gained through holes in the cover glass, rather than through the edge of the glass laminate. Two in-line holes in the center of one end of the module are used for the 17-volt modules and holes near two corners are used for the EP 50. The standard connector used for the EP 2 module terminates both the positive and negative leads.

The third new feature that the three modules share is the means of protecting the connection to the bus bars. The "terminal cover" used to accomplish this differs from its predecessor, the silicone "boot", in that it is molded in place on the back of the module, rather than glued to the edge (see Task 6 below).

In addition to being undesirable because of their location, the silicone boots that were used for the EP 2 were both labor intensive in their application and prone to assembly error. APS believes that the molded terminal cover placed on the surface of the glass results in a higher quality product because sealing of the connector is done on a flat surface as opposed to having to seal around the edge of the laminate. To maintain the excellent insulation properties that the edges of the APS modules had, the roughly half-inch border isolation area around the perimeter of the modules have been retained.

Additional power modules have been considered, but none have advanced past defining preliminary specifications.

APS is using the PVUSA qualification test sequence as a starting point to judge the quality of these and any other new products that will be developed.

Status

EP 50 - Manufacturing product specifications (MPS) for this product have been completed and approved for all critical steps of the encapsulation process. A complete engineering drawing package has been generated and approved. Other than hail impact (which was not done) testing has been successfully carried out that specifically addresses the differences between this product and its predecessor, e.g. static load testing to verify that the holes in the cover glass do not significantly weaken the module, humidity freeze cycling and thermal cycling. Cost reductions resulting from this program are calculated based on this product (see Task 5 Section on Cost Reduction).

EN 25 - Prototypes of this design were made, followed by a first cut at equipment modifications to accommodate the smaller size and the additional foil placement that this product requires. Several dozen modules were then produced and preliminary testing carried out, again to test the differences between this and previous product. With the exception of hail impact, testing of this product was successfully carried out and a small production run made. Drawings for the EN 25 have been approved and other documentation is in preparation.

EN 50 - Some of the equipment modifications needed for the EN 25 apply to this product as well and it too progressed to a production run. A drawing package for the EN 50 manufacturing product specifications has been completed.

Outline drawings of the three new module designs are shown in Figures 15 through 17.

Task 4 - Eureka Process and Quality Control

Objectives

The goal of this task is to improve module quality and throughput and to reduce manufacturing costs by gaining a better understanding of the process. Implicitly, process reliability is expected to improve as well. The effort in this area can be divided into three separate but related activities: in-line process control and monitoring, in-line product monitoring and off-line measurements on selected Eureka PV plates. Additionally, specific projects have been defined and will be discussed.

Milestones

M-1.8 Complete yield analysis review of Eureka modules (Q2) - Completed.

M-1.12 Complete identification of at least eight critical points in the Eureka Line that will be investigated during Phases II and III (Q3) - Completed (see Page 44).

M-1.21 Demonstrate yields of at least 97% at the process steps associated with at least two of the selected critical control points on the Eureka Line (Q4) - Completed.

M-1.22 Complete the Phase I portion of the effort under Task 4 (Q4) - Completed.

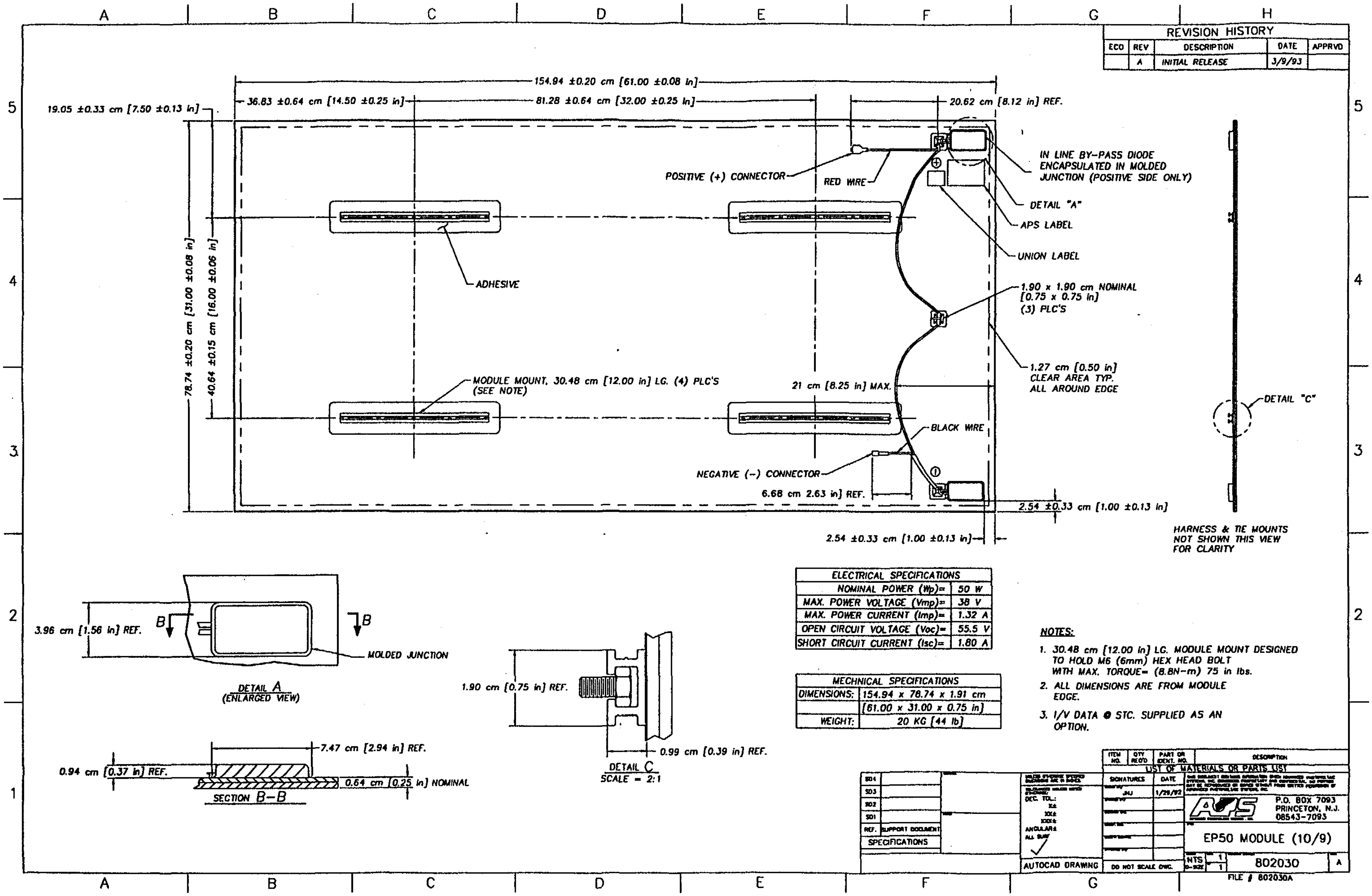


Figure 15 - Outline Drawing of EP 50

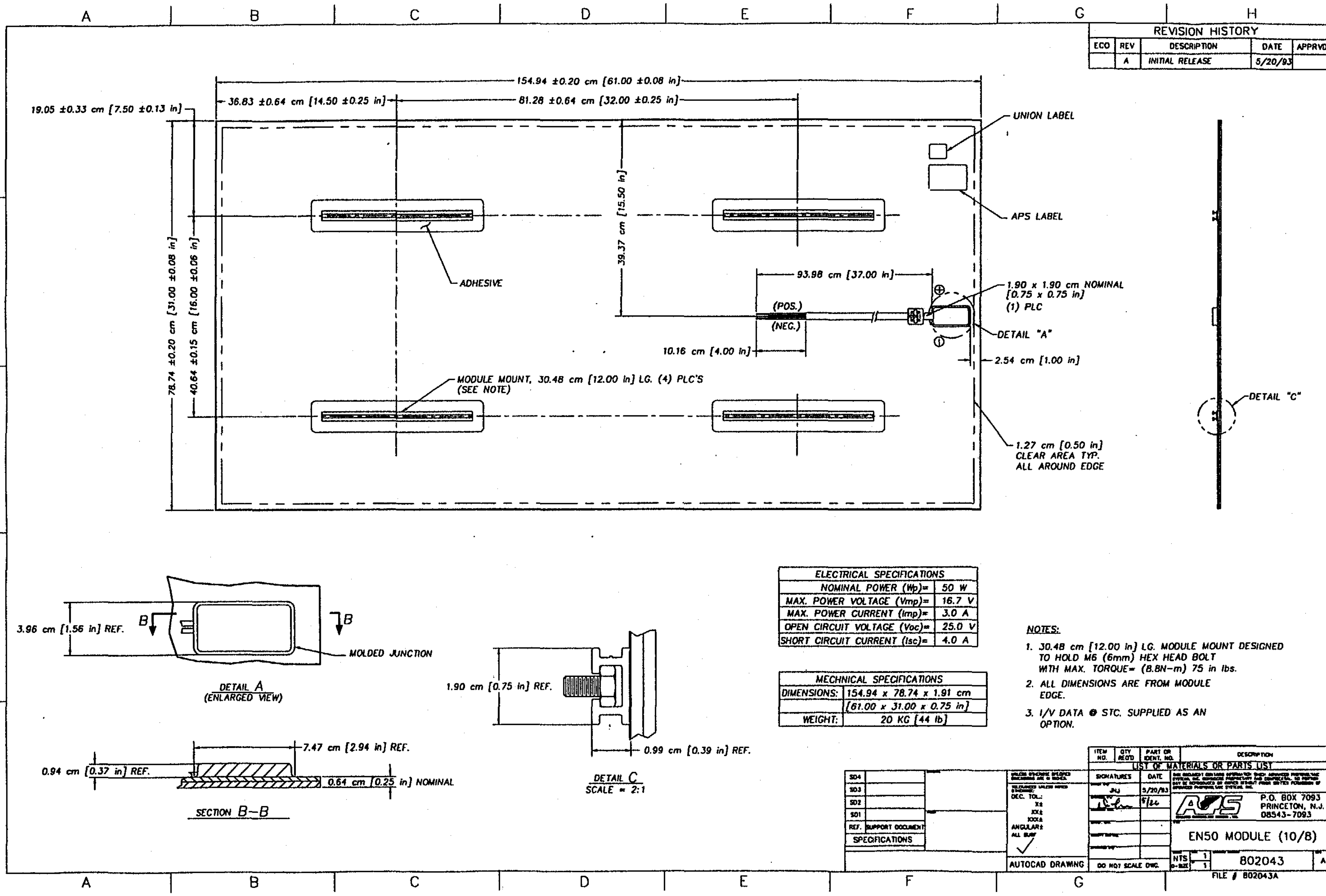
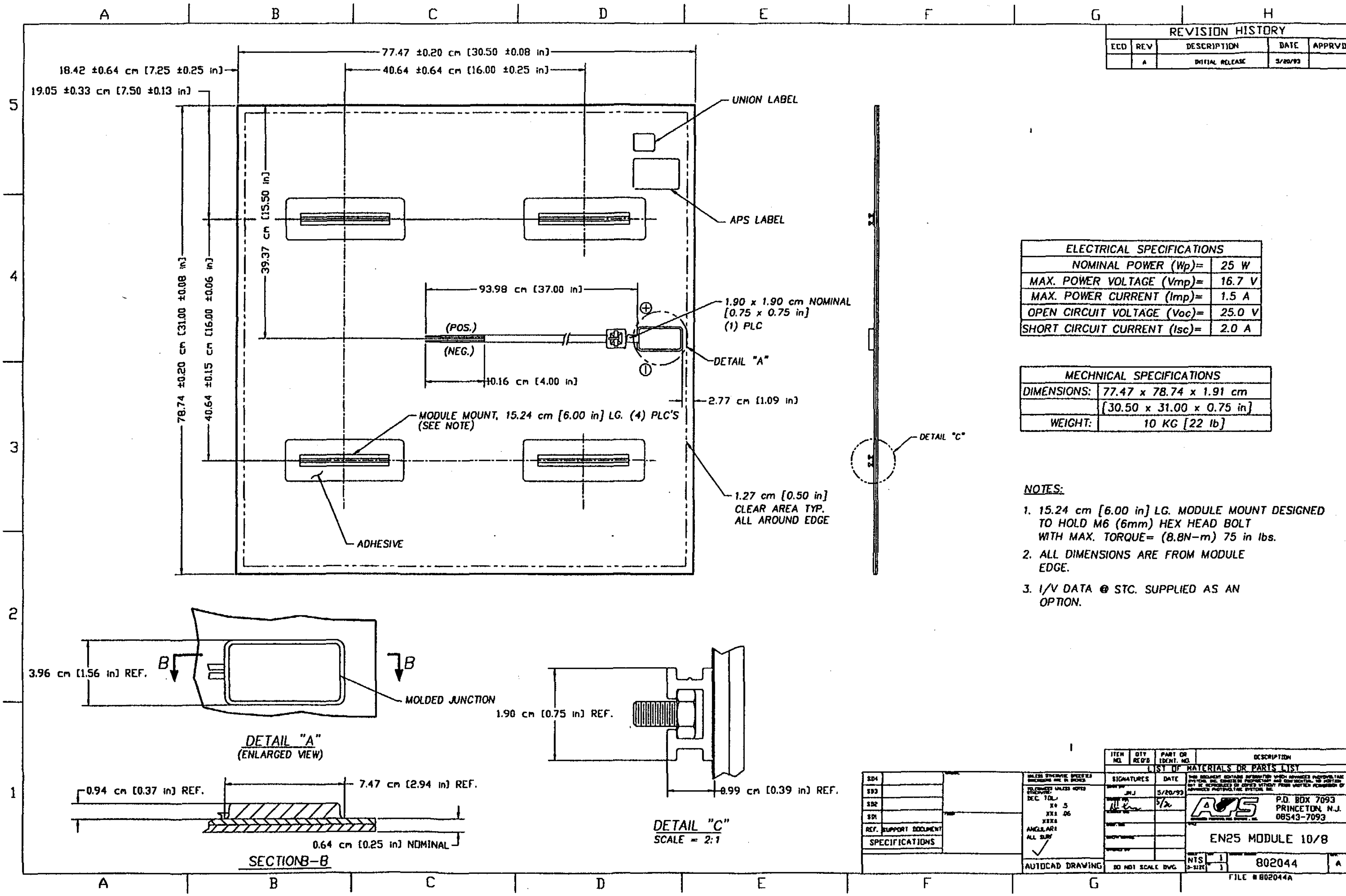


Figure 16 - Outline Drawing of EN 50



ELECTRICAL SPECIFICATIONS	
NOMINAL POWER (Wp)=	25 W
MAX. POWER VOLTAGE (Vmp)=	16.7 V
MAX. POWER CURRENT (Imp)=	1.5 A
OPEN CIRCUIT VOLTAGE (Voc)=	25.0 V
SHORT CIRCUIT CURRENT (Isc)=	2.0 A

MECHANICAL SPECIFICATIONS	
DIMENSIONS:	77.47 x 78.74 x 1.91 cm
	[30.50 x 31.00 x 0.75 in]
WEIGHT:	10 KG [22 lb]

NOTES:

1. 15.24 cm [6.00 in] LG. MODULE MOUNT DESIGNED TO HOLD M6 (6mm) HEX HEAD BOLT WITH MAX. TORQUE= (8.8N-m) 75 in lbs.
2. ALL DIMENSIONS ARE FROM MODULE EDGE.
3. I/V DATA @ STC. SUPPLIED AS AN OPTION.

Figure 17 - Outline Drawing of EN 25

APS Process

The current APS process is summarized in Table 4. Note that while the equipment for depositing tin oxide is in-house, APS currently purchases pre-coated glass from LOF. The cover glass used in the Trenton facility was obtained with holes pre-drilled.

TABLE 4. APS PROCESS

Thin-Film Process

- Deposit tin oxide coating with APCVD.
- Laser pattern the tin oxide coating.
- Load the plates into a box carrier and heat.
- Transfer heated plates in box carrier to deposition system.
- Deposit amorphous silicon coating.
- Unload box carrier and measure thickness.
- Laser pattern the a-silicon coating.
- Deposit back aluminum contact in sputtering system.
- Laser pattern the aluminum.
- Reverse bias each cell and measure shunt resistance.
- Heat treat plates.
- Measure IV parameters.

Encapsulation

- Sandblast a 0.5" clear border around the plate.
- Measure Voc of plate to verify that no damage was done.
- Ultrasonically bond aluminum bus bars to plate.
- Apply EVA to cover glass and join with PV plate.
- Cure EVA in laminator.
- Weld wire harness to foil.
- Apply brackets.
- Apply mold for terminal cover and fill mold.
- Place module in rack and put rack in oven for cure.
- Remove from oven and remove mold.
- Clean and inspect module.
- Perform leakage and bracket adhesion test.
- Measure IV parameters, apply labels and pack.

Changes from earlier processing are discussed in the text.

General Procedures

Process Control and Monitoring - Throughout the thin-film process, parameters are monitored to verify that the process is being carried out as defined in the MPS (Manufacturing Process Specification) sheets. Some of the important parameters now being monitored and controlled are the following (parameters specifically selected for study are discussed under separate headings). For tin oxide, measurements are made to verify that the coating meets APS' specification for optical transmission, haze, and sheet resistance. The a:Si deposition process is the most extensively instrumented. Here temperatures, pressures, flow rates, rf power levels and the timing of all steps are monitored and controlled. One of the deposition systems was automated for standard manufacturing runs, and for it, much of the deposition related information is acquired and stored by computer. This is the only system in use as of March, 1993 but is now mostly operated in the manual mode because non-standard runs are typically made. In the laser stations, beam power and quality, x-y table speed and position are monitored.

The encapsulation line is also instrumented, although not as extensively as the thin-film line. Air, water, and other process pressures and temperatures are monitored throughout the line.

In-line Product Monitoring - The product is checked, and measurements made at several stages of the process to detect line malfunctions or performance deviations. These measurements are used to keep track of the process itself in the instances where the process is not very well understood and hence, difficult to define precisely. The data collected in this area include alignment and laser scribe quality checks, cell isolation measurements, silicon thickness determinations and plate IV measurements.

QC checks in the encapsulation line include a test for bracket adhesion. In this test, the edge of the mounting bracket is pulled with force corresponding to more than 45 kg. in weight. After a sufficient number of samples were tested with no failures, the test was changed to a sampling procedure, with roughly 10% of product tested. A second QC check which is done on 100% of the modules is a leakage test of the terminal cover. In this test, the edge is immersed in a conductive surfactant solution which covers the terminal cover and leakage at 500 volts is measured. The final module check is again an I-V measurement, which provides the most useful and most used information on the process. Comparisons are routinely made between I-V measurements on thin-film processed plates and the modules resulting from them.

Off-Line Measurements - The off-line measurements consist of routine evaluations of one to four PV plates each day and of specialized analysis on an as needed basis, e.g. Auger analysis, and spectral response measurements. In the routine evaluations, a Eureka plate is cut into twelve 4" x 12" sections, each of which consists of a string of small interconnected cells, as well as nine isolated dots about 0.1" in diameter. On these plates, silicon film thickness is measured by capacitance; also measured are scribe widths, standard electrical parameters plus low light level measurements, series and shunt resistances and light degradation. Since all areas of the full plate are represented, these measurements provide information on the uniformity of the product (however on only a small sample of product made), both as-made and also after light soaking.

The electrical parameters obtained from plate I-V measurements are probably the most direct measure of control of the process. In the first monthly report, these were used as an overall evaluation of our progress and the spread (standard deviation as percent of average) in the electrical parameters for several months prior to the start of this Contract was presented (see Table 5; some experimental runs were excluded, e.g. tandem runs done for R&D).

Thus:

TABLE 5. PERCENT SPREAD IN ELECTRICAL PARAMETERS - 1992

(Power Spread Related To Electrical Yield Losses)

	Voc	Isc	FF	Power
January	6.5	4.0	9.0	15.0
February	3.6	3.8	6.8	8.8
March	2.3	2.3	2.5	4.9
April	2.3	2.4	2.9	4.4
May	2.7	3.2	3.4	5.5

A detailed analysis of available data through October, the last month of routine production, shows the yields for the encapsulation line (see Table 6). Note that from January to June, the yields apply to the original process of applying the silicon boot with adhesive to the EP 2 module. For September and October, the molded boot was used on all three new products.

TABLE 6. 1992 YIELDS FOR ENCAPSULATION PROCESS STEPS

Process Step	% Yield	
	January - June	September - October
Edge Isolation/Foil Placement	96	98
Lamination	95	97
Bracket Application	98	100
Boot Application	93	98
Cleaning/Inspection	93	88
Insulation Test	97	100
Final Inspection	98	96
Combined	73.3	78.7

The lower yields in September and October for the two inspection steps are mainly the result of more critical criteria on boot adhesion. A gentle inspection was replaced with a forceful adhesion test.

Process Critical Control Points

Critical control points were chosen on the basis of experience and the likelihood that they were critical.

a. Thin-Film Line

- Base Pressure
- Flow Rates
- Deposition Pressure
- Deposition Temperature
- RF Power for Deposition
- Laser Power

b. Encapsulation

- Edge Isolation Quality
- Laminator Base Pressure
- Laminator Temperature
- Measurement Parameters

Since gases are mixed on-line, variations in flows change the gas composition and hence influence the material deposited. The choice of deposition pressure and temperature is based on tests in which these were varied and produced sizeable variation in results. The deposition system base pressure has been demonstrated to have a large influence on film quality. Figure 18 shows average run FF of plates as a function of base pressure. RF power is directly related to deposition rate. Laser power is critical in all three lasering steps, but is monitored most closely in the aluminum scribing station, less as an indicator of power as such, but rather to signal that something has changed.

In the encapsulation line, edge isolation was chosen because at one point (pre-PVMaT), poor edge isolation resulted in a 3 to 4 watt per plate average loss. Laminator base pressure has been correlated with bubbles in the laminate and temperature is related to the extent of EVA cure. The adhesive cure temperature is critical because precise control permits the minimum cure time to be achieved.

Special Projects

Specific efforts initiated in this program to improve the APS process are:

I-V Measurements - Short term repeatability of I-V measurements is excellent, with a standard deviation of less than 1% for multiple measurements. Longer term several percent drift and evidence of non-uniformities in light intensity are seen (in spite of careful calibration). Modifications to the light source placement and careful adjustment of intensities, together with continued monitoring of the measurements have reduced this problem, somewhat.

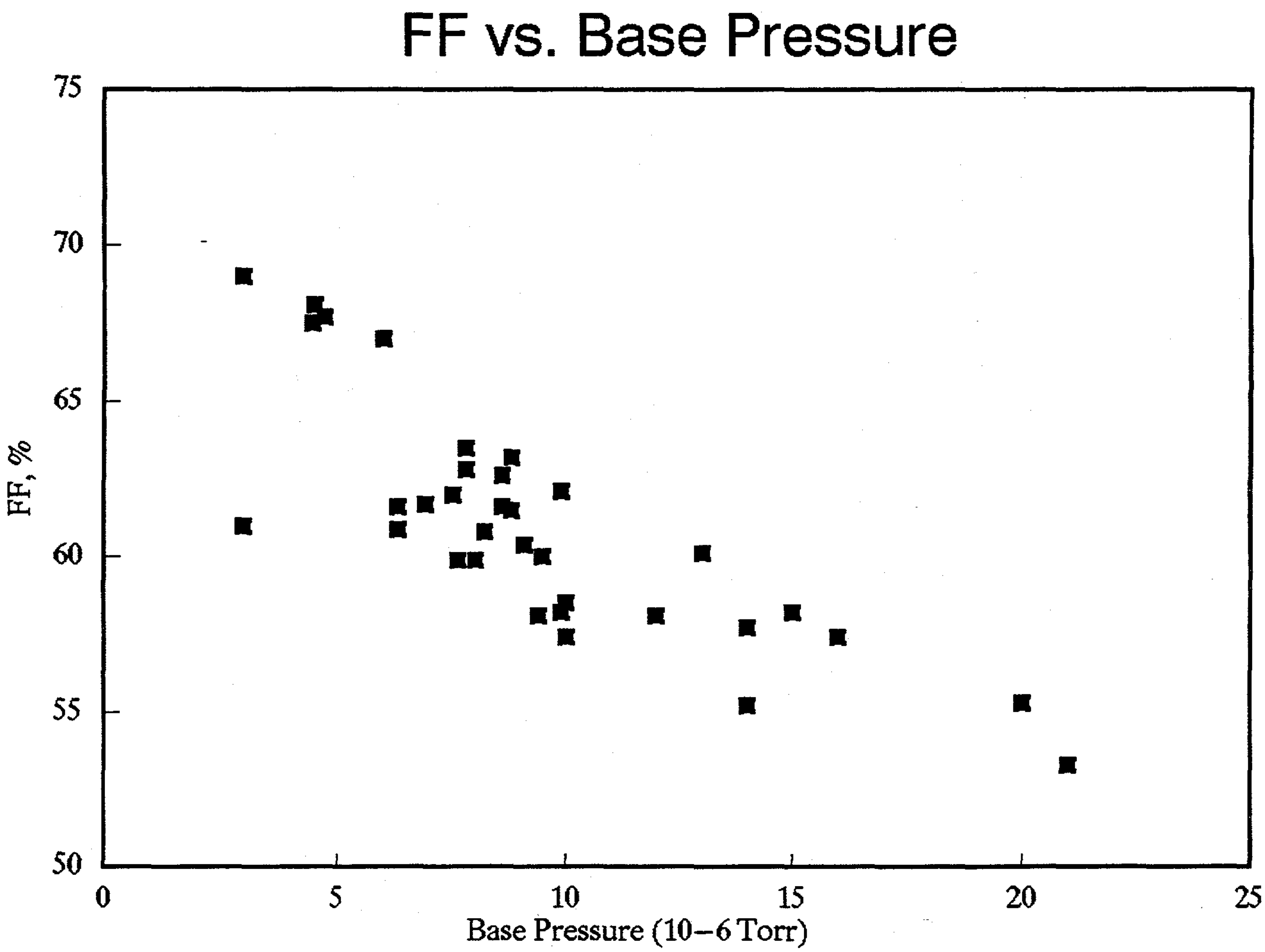


Figure 18 - Deposition System Base Pressure

Other steps have been taken to ultimately improve the precision of these measurements, but initially to provide tools to determine how well we are doing and what the limitations of the equipment are.

a. *Light Uniformity*

The differences in IV results obtained when panels are measured right side up and upside down is in large part due to the fact that the plates are thinner in different regions (see thickness measurements in this section below) and light intensity is also non-uniform. Thus, if higher intensity occurs where the silicon is thicker, a higher current will be obtained than in the opposite case. Since four flash lamps are used, the intensity of the four regions of these lamps can, in principle, be adjusted to result in the same intensity. To do this, special modules were made in which each of the four quadrants is separately accessible electrically. By measuring the output (as Isc normalized to the value obtained in the sun, a very uniform light intensity source) of each quadrant with different lamps on, the contribution of each lamp to each of the four quadrants can be mathematically determined. These numbers can be represented in matrix form.

By inverting the matrix, the intensities needed to obtain the correct current for each quadrant can be found. Unfortunately, the changes needed are outside the range of electronic adjustment ($\pm$ 5%), and some mechanical changes will have to be made; this has not yet been done.

b. *Tester Stability*

In addition to light intensity variations, the stability of the electronics needs to be determined and controlled. To determine the electronic stability, an "electronic standard" was made. This consists of a stiff regulated power supply (100V, 10 A) which is connected to the input of the IV Tester through a fixed power resistor in the 10 to 50 ohm range. A measurement of this combination should give the power supply voltage as "Voc",that voltage divided by the resistance of the resistor as "Isc" and a fill factor of 25%. Initial testing with this "standard" revealed several minor problems with the testers, which were corrected. A calibration with this device has been incorporated into our measurement procedure.

The result of these measurements has shown that the electronics contribute about half a watt to the uncertainty (based on standard deviation of repeated measurements over time) of the plate tester and less than 0.1 W on the module tester. In both cases, most of the observed scatter is due to the current measurements.

c. *Light Stability*

With the scatter in results being mainly due to light intensity variations from one measurement to another, attempts have been made to determine the cause of the variations. The flashlamps are powered by large high voltage capacitors which are discharged through a current limiting device. On the module tester, the capacitor voltages are monitored before and after the flash. The current through the flash lamp should be mainly determined by the initial capacitor voltage. An overall correlation between light intensity and capacitor voltage has been found, but it is not as direct as expected, and applies more to the larger variations seen from day to day than the variations seen from measurement to measurement. Since the ambient temperature near the testers is not controlled, it may play a large part in some of the variations seen and will be investigated.

Silicon Thickness Measurement - As stated above, typically one to four plates per day are evaluated in the laboratory, including thickness measurements of the a-silicon; roughly 100 separate determinations are made on each plate. There are several reasons why thickness uniformity is important. First, it is a measure of control of the process. If nothing is changed from run to run, then all the plates made should be identical. Second, it is likely that non-uniformities lead to some loss in power output, if for no other reason than that mismatches occur between different parts of a plate and lead to losses. A third reason comes into play when tandem devices are made; thickness has to be controlled much better and non-uniformities will have more serious effects. Finally, appearances count especially for the architectural market. To ultimately improve uniformity on a plate, more extensive measurements on thickness variations are needed than on 1 percent or so of the product made. Two approaches were taken:

a. ***Optical Thickness Monitor***

Preliminary testing suggested that light transmission measurements could provide reasonably accurate thickness estimates. From comparisons of optical transmission at several wavelengths with profilometer thickness determinations, it was concluded that 600 nm was the best region in which to make measurements.

A prototype in-situ thickness measuring device based on optical transmission measurements has been constructed and installed. Measurements are made at twenty-five points on each plate, with the data stored on disk for analysis. Since thickness variations are typically larger than IV parameter variations, these measurements provide a more sensitive measure of process conditions. Thus, some thickness variations seen from run to run have been attributed to variations in rf power applied to the discharge. Figure 19 shows the calibration of the apparatus, where "thicknesses" are obtained from profilometer measurements. Figure 20 shows typical thickness contours based on the 25 measurements.

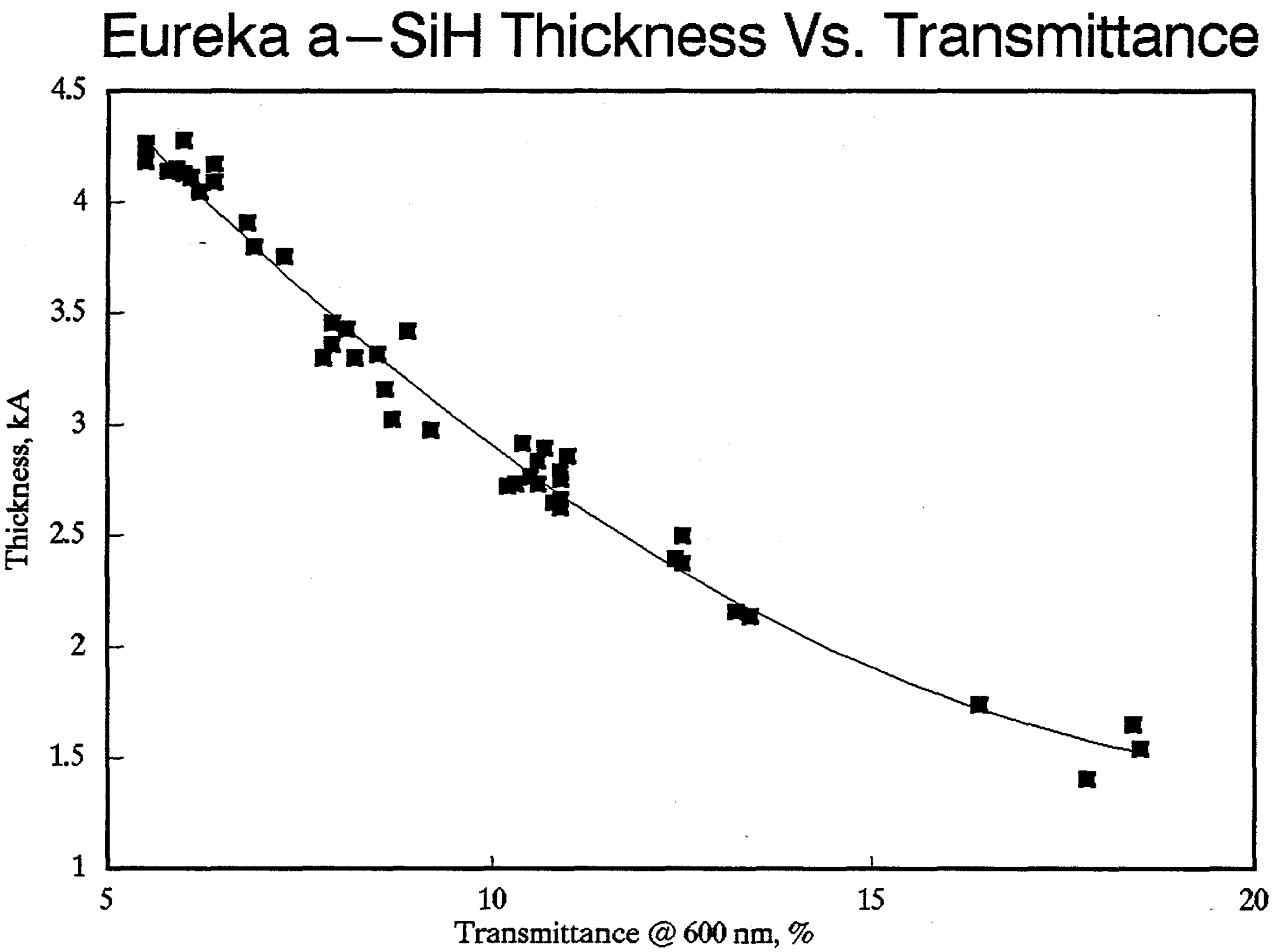


Figure 19 - Optical Thickness Monitor Calibration

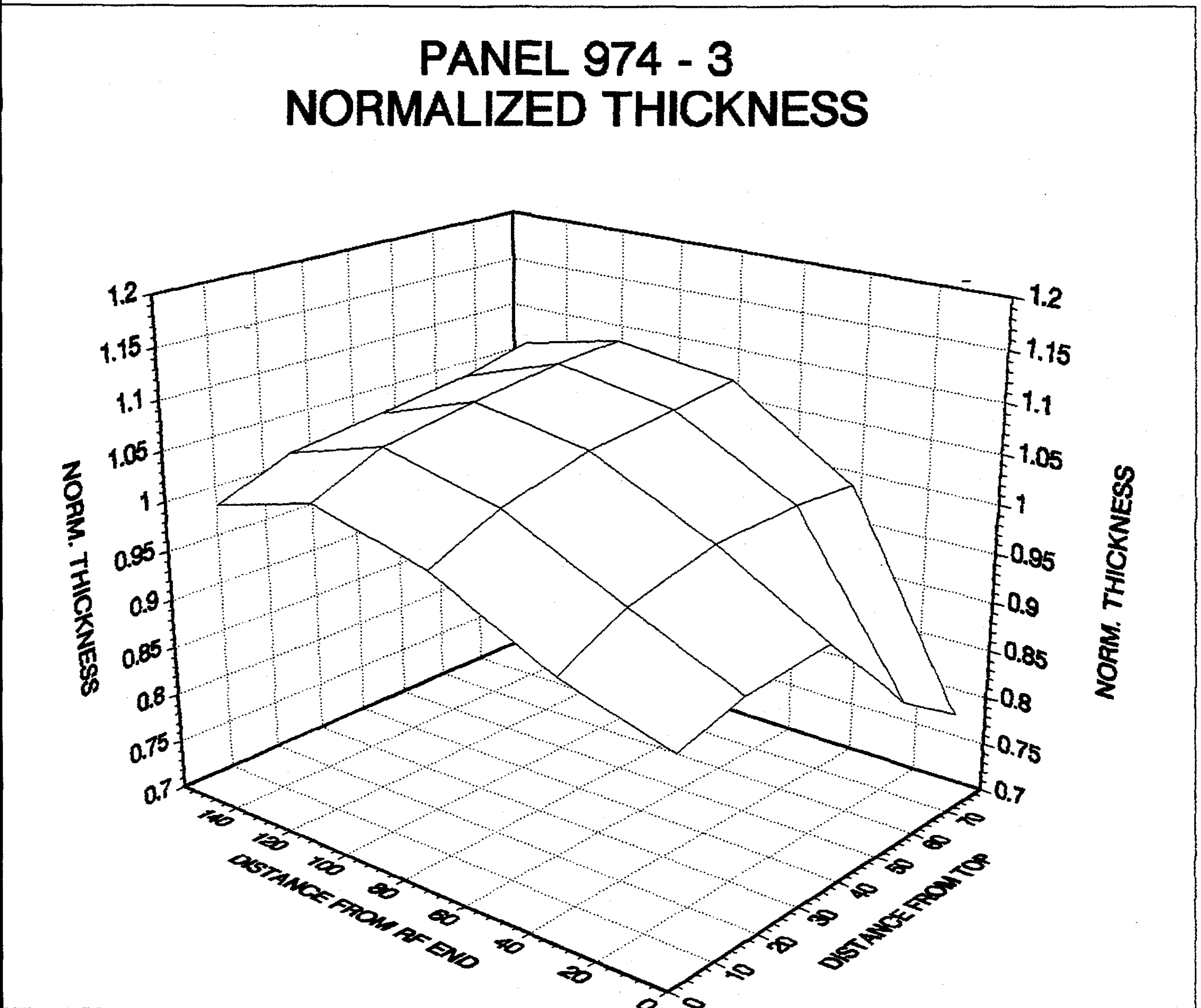


Figure 20 - Thickness Contour

b. *Photographical Thickness Measurement*

While the transmission measurements provide very useful quantitative information regarding plate to plate and run to run variations, they are not detailed enough for our purposes.

The appearance issue deals with extremes in thickness. Thus, over most of the area of the plates, the thickness varies by about 50%. However, over a small region, near one corner, the thickness is about one-third that of the average for the plate. While this is a small region and the effect on power output is very small, this region stands out when it comes to appearance.

To address this more localized non-uniformity and the appearance issue in general, APS has acquired a solid state still camera to photograph the plates. By taking photos through interference filters the thickness variations appear more pronounced in that fringes appear at intervals related to the center wavelength of the filter. By capturing these images on computer, they can be manipulated and compared, and in general, differences between plates quantified.

Uniform lighting is critical for meaningful images to be obtained; at this point an array of multi-vapor lamps is being set up and adjusted for this purpose.

Documentation - Manufacturing Process Specifications (MPS) have been generated for the module encapsulation workstations in order to define the process steps, to introduce additional process controls and to obtain essential parametric information. Statistical techniques are being applied to some of these data, both to obtain baseline information on the process and to evaluate and control the process.

Task 5 - Eureka Power Module Encapsulation And Termination

Objectives

The two specific goals of this task are to achieve cost reductions in the encapsulation process and to reduce power losses between module and plate.

Milestones

M-1.13 Complete investigation of materials cost reduction in Eureka module encapsulation (Q3) - Completed.

M-1.23 Complete investigation of plate-to-module output loss on the Eureka Line (Q4) -Completed.

M-1.24 Complete investigation of cost reduction in encapsulation on the Eureka Line (Q4) - Completed.

M-1.25 Complete the Phase I effort under Task 5 (Q4) - Completed.

Cost Reduction Effort - Cost reduction can be achieved in several ways; use of less expensive raw materials, design of the process to use less labor (including more automation) and increasing the power output of the module or its yield. Probably the most important result of the new module designs is the throughput that the new process makes possible. While this is not strictly a cost reduction, at least not for the Trenton Plant with its limited production capacity (more equipment and floor space is needed with the old module design than with the new one), it is extremely important for the 10 MW facility in California.

As discussed under Task 3, the means of accessing the bus bars has been totally redesigned. In order to seal the edge of the EP 2, where the foil was brought out, an expensive sealant was used, that in addition to high cost, required days to fully cure. The amount of work-in-progress necessitated by this long cure time presented a problem that would have been extremely serious in the larger operation that will exist in APS' new plant in Fairfield, California. The handling that the modules were subjected to in the three to five day cure resulted in significant glass damage and reduced yield as discussed earlier. The new in-line molded terminal cover requires only a few hours to fully cure and be ready for testing and packing. The terminal cover as now used has evolved in several stages from the first design. The initial design had erratic yield due to periodic appearance of excessive voids in the molded material. There were also signs of poor adhesion, although those may have been in part due to mechanical damage after the mold was removed. Both problems were greatly reduced with the redesigned mold. Studies of adhesion under a variety of conditions resulted in some modification of the cleaning and molding procedure which also improved adhesion.

Thus, cost reduction has focused on reducing labor costs through simplifying and automating the process. While the new molded terminal cover is still applied mostly manually, this step has the potential of being automated in the future. New dispensing equipment has been tested for applying the terminal cover; this equipment will be used in Fairfield. The equipment both mixes the components of the material in line as well as dispenses a predetermined amount. Currently, mixing is done as a batch process and dispensing is controlled by the operator.

As stated above, full automation will significantly reduce labor costs. Refinements to the new foil bonding process are being investigated to approach this goal. Since the new design has the foil accessible through holes in the cover glass, the possibility exists to bond directly to the foil through the hole, rather than bring the foil out and bond externally. Early tests suggested that this approach can work, but details have to be worked out.

An area that will have to be streamlined is the lamination itself, where cycle time has to be reduced by several minutes for the Fairfield operation. Some material cost reduction has been realized by the use of the less expensive raw materials that have replaced the combination of adhesive and silicone boot that was previously used. Other material cost savings such as thinner EVA (12 mil versus the 18 mil EVA now used) and possibly thinner glass will be evaluated at a later date; 12 mil EVA has been ordered.

Cost Reductions Achieved During Phase I

Both material and labor cost reductions were realized during this program in addition to improved yield.

In going from the pre-PVMaT EP 2 to the EP 50, developed under PVMaT, a reduction in yielded encapsulation material cost of 14% was obtained. This reduction is the result of replacing the silicone boots and adhesive with the new molding adhesive.

Direct labor cost reductions were also realized, but these have to be estimated from the labor content of individual steps because the EP 50 was not produced on a scale similar to that of the EP 2. Savings occurred in two areas; first the process using the molded terminal cover has a lower net labor content and second, an optimization of the line layout lowered labor costs an additional 20% for a 28% total reduction.

Labor costs are grouped by station into three categories. The first (lamination) includes sandblasting, foil bonding, EVA application and lamination. The second (booting) includes cleaning harness welding, bracket and boot application. The third (QC) consists of cleaning and QC checks of bracket and leakage test. These labor costs are tabulated in Table 7, together with a summary of the remaining direct costs. The same values are given for plate material and labor costs for pre-PVMaT and PVMaT costs since the benefits of the progress made in the plate line will only be realized in the new APS plant in Fairfield, California.

TABLE 7. MODULE DIRECT COSTS $ / SQ. FT.

<table>
<tr><th></th><th><u>Pre-PVMaT</u></th><th><u>PVMaT</u></th></tr>
<tr><td>Plate Line</td><td></td><td></td></tr>
<tr><td>Material</td><td colspan="2">2.01</td></tr>
<tr><td>Labor</td><td colspan="2">0.91</td></tr>
<tr><td><u>Total Plate</u> :</td><td colspan="2">2.92</td></tr>
<tr><td>Encapsulation</td><td></td><td></td></tr>
<tr><td>Material</td><td>2.86</td><td>2.46</td></tr>
<tr><td>Labor</td><td></td><td></td></tr>
<tr><td>Lamination</td><td>0.43</td><td>0.32</td></tr>
<tr><td>Booting</td><td>0.71</td><td>0.47</td></tr>
<tr><td>QC</td><td>1.16</td><td>0.86</td></tr>
<tr><td><u>Total Encapsulation</u> :</td><td>5.16</td><td>4.11</td></tr>
</table>

Costs are based on yields of Table 5 and includes IV yields (not given in Table 5). Wages are taken to be \$10.00/hour which includes fringe benefits.

It is expected that once the line is operating in the new facility near full capacity the labor cost will be cut by an additional factor of more than two.

Reducing Power Loss - The power loss between plate and module can readily be estimated; it originally amounted to the loss of one cell, or approximately 0.5V in operating voltage. Plates are now prepared for initial measurement in such a way as to make the measurement as similar to the module measurement as possible. Differences in output between modules and plates are typically between about 0 and 3 watts. Measurement precision contributes about 1 watt to this difference; larger differences are rare and when they do occur, they indicate a problem either with measurements or in the assembly of the module.

There is a power loss associated with the resistance of the aluminum bus bar, but it is small and can readily be calculated.

For the EP 50, the foil length on each edge is 150 cm. The foil is 0.95 cm wide and 0.0051 cm thick. At 25°C, the resistivity of aluminum is 2.71 microohms per cm, and the maximum power current of the EP 50 is 1.32 A (0.0088 A/cm).

Integrating the IR losses along one length of foil results in:

$$\int_0^{150} \frac{1.32^2}{150^2} \bullet \frac{2.71 \times 10^{-6}}{0.952 \times .0051} x^2 dx = 0.049\text{W}$$

or 0.098 W total for both bus bars. Similar calculations can be made at other temperatures and for the other modules. For the EN modules, the current at the edge connectors is the same as for the EP, but for the center connector is twice this value, resulting in four times the IR losses for that strip. The EN modules also have a contribution from the two cross strips connecting the two edge foils. These strips have a combined length of 74 cm and carry half the current of the module. A summary of these losses for the three modules at two temperatures is the following:

	25°C	50°
EP 50	0.10 W	0.11 W
EN 50	0.35 W	0.40 W
EN 25	0.09 W	0.10 W

Some gain in module output can be achieved by reducing the 31 square inch dead area at the two ends of the module. This is the area between a laser isolation line and the cleared border area. Samples have been made incorporating both changes. They are under evaluation.

Task 6 - Automation In Eureka Manufacturing Line

Objectives

The objectives of this task are to increase the automation of the line and achieve a 90 second/plate throughput.

Milestones

M-1.9 - Complete SnO_2 scribing investigation for 90 second/plate laser systems for Eureka modules (Q3) - Completed.

M-1.26 Complete silicon scribing investigation for reaching 90 second/plate throughput systems for Eureka modules (Q4) - Completed.

M-1.27 Automate thin-film deposition chamber loading for the Eureka Manufacturing Line (Q4) - See text.

M-1.28 Complete the transport system for the Eureka Encapsulation Line (Q4) - Not Completed; see text.

M-1.29 Automate the final quality control steps in the Eureka Encapsulation Line (Q4) - Not Completed; see text.

M-1.30 Complete the Phase I portion of the effort under Task 6 (Q4) - Not Completed; see text.

At the start of the Contract, much of the thin-film line was automated, although not necessarily optimally so. Some of this automation has been enhanced and missing links have been added. Four areas we are focusing on are:

Silicon Deposition - One of the two deposition systems has been automated. In addition to executing a standard deposition procedure, the software records some of the important process parameters during the deposition. Thus, pressures, flow rates and temperatures are recorded at time intervals of the order of seconds. Based on several months use, some changes and additional features are contemplated for an update. These deal with adding flexibility, safety, self-test features and increased data gathering ability; the latter may include parameters from related equipment.

Box Carrier Loading - The box carriers are the containers in which the tin-oxide coated plates are held in the silicon deposition chambers. Unloading after silicon deposition is already automated through the sputtering station. The equipment needed for loading has been assembled and tested. It will be installed in Fairfield.

Heat Age Station - Transportation of plates from the sputtering system to and through the heat aging station is done in a batch process in Trenton. This will be an automated in-line process in Fairfield.

Lasers - This critical equipment has been made more reliable and its throughput increased. To improve reliability, instrumentation has been added to monitor beam power and quality. Automated in-line power measuring equipment has been installed at one station; this measures and stores on disk for later analysis the laser power prior to lasering each plate. Secondary registration sensors have been added to prevent misalignment of scribes. Water flow and other critical parameters are monitored and cause system shutdown if warranted.

A detailed investigation was made to determine the requirements for achieving a 90 second cycle time for the laser stations. Of the two main components of the laser stations, the x-y tables can readily be made to operate at the required speed. Tests on the x-y tables for California confirm this. To achieve quality scribes, laser power, repetition rate and beam quality have to also be within specified limits. These limits have been identified and lasers and associated optics have been obtained for Fairfield. For scribing the back contact, it was determined that an additional laser station will be required to perform the end isolation scribes our modules incorporate. This station has been made and is being tested.

Encapsulation Line - Much less automation is introduced into the encapsulation line. Individual pieces do, however, automatically handle the plates. Much of what has to be added is transportation equipment to move the plates from station to station; this has been acquired for the California plant.

Some of the initially constructed equipment was designed to handle only one size plate. With the need to develop the half-module and the lower voltage products, some redesign has taken place so that the equipment has sufficient flexibility to handle these variations without lengthy adjustment and delay.

Fairfield Plant

The encapsulation line has been installed in the new facility in Fairfield, California. Except for the final QC area, plate/laminate transport is automated. Plans to automate lamination loading and unloading are under study.

Equipment for the thin-film line has mostly been delivered to Fairfield. The entire line will be automated (with the exception of opening and closing doors on the deposition chamber and box carrier) from glass unloading from crates to transfer of plates to the encapsulation line after IV measurement.

Document Control Page	1. NREL Report No.	2. NTIS Accession No.	3. Recipient's Accession No.
	NREL/TP-411-6263	DE94000294	

4. Title and Subtitle

Amorphous Silicon Photovoltaic Manufacturing Technology - Phase 2A

5. Publication Date

February 1994

6.

7. Author(s)

G. Duran, K. Mackamul, D. Metcalf - UPG
A. Koniares, D. Skinner, H. Volltrauer - APS

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Utility Power Group
Chatsworth, California

Advanced Photovoltaic Systems, Inc.
Princeton, New Jersey

10. Project/Task/Work Unit No.

PV450101

11. Contract (C) or Grant (G) No.

(C) ZM-2-11040-06

(G)

12. Sponsoring Organization Name and Address

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

13. Type of Report & Period Covered

Technical Report
1 May 1992 - 30 April 1993

14.

15. Supplementary Notes

NREL technical monitor: H. Thomas

16. Abstract (Limit: 200 words)

This report describes teamed research by Utility Power Group (UPG) and Advanced Photovoltaic Systems, Inc., (APS) to advance photovoltaic (PV) manufacturing technologies, reduce module production costs, increase average module performance, and increase the existing production capacity. UPG and APS conducted parallel efforts to develop their manufacturing lines. Areas of focus included encapsulation and termination, product design, process and quality control, and automation. UPG improved the existing encapsulation system by developing advanced encapsulation materials and processes, resulting in a module that does not require backing glass. UPG also developed advanced termination materials and processes. APS performed development activities centered on the EUREKA manufacturing line. Developments in the APS EUREKA encapsulation system were in addition to the UPG activity on encapsulation, and they offer an alternative approach to the problems of encapsulating large-area, thin-film modules.

17. Document Analysis

a. Descriptors

amorphous silicon ; manufacturing ; modules ; encapsulation ; photovoltaics ; solar cells

b. Identifiers/Open-Ended Terms

c. UC Categories

270

18. Availability Statement

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

19. No. of Pages

66

20. Price

A04

Form No. 0069E (6-30-87)