Amorphous Silicon Photovoltaic Manufacturing Technology – Phase 2A

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SUMMARY

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

The APS Trenton Eureka module manufacturing line is mostly dedicated to development work under this subcontract. In the APS Trenton Eureka manufacturing facility, APS has been:

o   Developing high throughput lamination procedures;

o   Optimizing existing module designs;

o   Developing new module designs for architectural applications;

o   Developing enhanced deposition parameter control;

o   Designing equipment required to manufacture new Eureka modules developed during Phase I;

o   Improving uniformity of thin-film materials deposition; and

o   Improving the stabilized power output of the APS EP50 Eureka module to achieve the 55 Watt goal.

In the APS Fairfield Eureka manufacturing facility, APS has been:

o   Introducing the new products developed under Phase I into the APS Fairfield Eureka module production line;

o   Increasing the extent of automation in the APS Fairfield Eureka module production line;

o   Introducing Statistical Process Control to the APS Fairfield line; and

o   Transferring progress made in the APS Trenton Eureka module manufacturing facility into the APS Fairfield Eureka module production line.

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1.0 TASK 7 POWERGLASS MODULE ENCAPSULATION

Objectives

The objectives for this task are to evaluate the thin-film PV module encapsulation advanced substitute material and process identified in Task 1 of Phase I and then design and debug an automated encapsulation station utilizing the advanced processing method and material identified in Task 1. This evaluation will include the application of the encapsulation material to proto-type modules utilizing tempered substrate glass for qualification testing.

Encapsulation Material

In this task, UPG is continuing to investigate the advanced substitute materials and processes for thin-film module encapsulation identified in Task 1 of Phase I. These new materials will replace the glass/EVA/glass structure utilized in previous generation thin-film modules. The new structure will eliminate the back glass while a substitute material will encapsulate and protect the thin and thick films which are deposited on the glass superstrate. At the conclusion of Phase I of this project, it was determined that the materials judged to be the most attractive as the substitute encapsulation material are the silicone products from DOW CORNING CORP. These structural adhesive materials have been evaluated in terms of their substrate adhesion, scratch resistance, chemical resistance, water penetration resistance, compatibility with module fabrication techniques, air quality environmental concerns, cost, safe application, and application speed.

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

Scratch Resistance:
The candidates for advanced substitute materials all showed a weakness in the scratch resistance test as outlined in the SERI/TR-213-3624 qualification test procedure when compared to the glass/EVA/glass package. The 1/8" tempered or raw glass used

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as the back sheet in the glass/EVA/glass package holds up quite well to the scratch resistance test because the glass is thick and hard. None of the thin (less than 0.025") coatings used as candidate encapsulation materials (polyurethanes, epoxies, silicones, or plastic copolymers) can hold up to the same level of abuse as the back glass in the glass/EVA/glass package. Moreover, the silicone adhesive materials displayed particularly poor performance in that regard. UPG was able to modify the silicone to decrease its susceptibility to being cut. The modification of the encapsulation material consisted of adding a component to the silicone after the application of the encapsulation material to the module was performed. Various materials were tested as this additive to determine whether the product could pass the Surface-Cut Susceptibility Test and also not interfere with the electrical output of the PV module. The material found to be the best additive are glass beads in a size range of 0.0059" - 0.0035". Glass beads are chemically stable and mechanically robust. They have the hardness of glass which allows the encapsulation material to pass the Surface-Cut Susceptibility Test but have smooth surfaces which will not scratch the thin-films under the encapsulation material. This modification was made without significantly increasing the cost of the material.

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

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

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

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

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

Safe Application:
Toxicity studies of primerless silicone adhesive formulations have shown minimal industrial handling problems. This material

does contain an epoxy-functional group. As with all epoxy materials, precautions should be taken to avoid exposure to eyes or skin and inhalation of vapors. Spills of the uncured silicone can become extremely slippery. Sawdust or absorbent should be immediately applied to any liquid spill for temporary relief and the spill removed with high-flash mineral spirits or other suitable solvent.

Application Speed:
The silicone adhesive can be applied with a roller coater at a speed that easily surpasses the rest of the manufacturing line. The roller coater is designed to operate at a speed of 10 feet per minute while the overall throughput of the manufacturing line is one module (14.5" x 13") every five minutes.

Qualification Tests and Procedures

The silicone adhesive material has also been evaluated utilizing the Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules as described in the NREL document SERI/TR-213-3624. The Test and Inspection Procedures pertinent to the encapsulation material are:

    (1)   Electrical-Isolation Test (Dry Hi-pot)
    (2)   Wet Insulation-Resistance Test
    (3)   Thermal-Cycle Test
    (4)   Humidity-Freeze Cycle Test
    (5)   Surface-Cut Susceptibility Test
    (6)   Electrical-Isolation Test (Wet Hi-pot)

The basic silicone adhesive was able to pass all of the above tests with the exception of the Surface-Cut Susceptibility Test. As discussed previously, UPG was able to modify the basic silicone material to produce a new material which could pass the Surface-Cut Susceptibility Test without compromising the ability of the modified silicone to pass the other evaluation tests.

Encapsulation Station Design

UPG has chosen roller coating as the application technique to be utilized in the Automated POWERGLASS Encapsulation Station. 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 ensure a smooth coating, reverse coating is used. In standard roller coating, the coating roll and doctor roll (the two rolls on top) both rotate but in opposite directions. The backup roll (the roll on the bottom) rotates in the opposite direction of the coating roll. In reverse coating, the doctor roll is stationary and the coating roll and backup roll rotate in the same direction causing a shearing effect on the coating material. 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 will include powered conveyors, which transport the glass superstrate to and away from the coating assembly; explosion-proof motors and electrical connections; variable speed drive and precision control of all roll adjustments.

Some of the advantages of glass roller coaters are:

(1) Small amount of encapsulant 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 than spraying or curtain coating with less striations;

(4) A maximum of 15 minutes clean up time;

(5) Less waste of encapsulant during operation and at clean up time; and

(6) The speed of the coater may be synchronized with corresponding curing oven.

- Roller Coater Specifications -

Coating Roll: One (1) 4" diameter x 26" long, smooth ground nytril-covered coating roll.

Doctor Roll: One (1) 2-3/4" diameter x 26" long, smooth ground chrome-plated steel doctor roll.

Backup Roll: One (1) 4" diameter x 25" long, smooth ground neoprene-covered backup roll. This roll will be adjustable to allow for front edge.

The supply of coating material will be held in the trough formed by the doctor roll and coating roll with babbitt-faced seal plates sealing the ends of the rolls.

Controls: Two hand knobs will be incorporated into the doctor roll bearing assembly to move them in and out in relationship to the coating roll, providing a positive and accurate adjustment which is quickly and easily regulated. The upper coating assembly is adjustable in a vertical plane through two hand cranks located on each end of the coater which adjusts the roll assembly with a 0 to 4" range. Mission indicators will give a visual readout of the unifeed adjustment.

Construction: Welded tubular steel.

Bearings: All roll bearings will be antifriction, self-aligning.

Through Conveyor: A belt type conveyor will be incorporated to transport the glass through the roller coater. This powered conveyor will be 30" on the infeed side and 30" on the offbearing side of the coater. This through conveyor will be driven by the same motor that drives the roller coater.

Tempered Glass Superstrates

In Phase I of this project, UPG concluded that as long as the glass superstrate is tempered, no additional back glass sheet is required to pass the Hail-Impact Evaluation Test. These glass superstrates were thermally tempered early in the PV module fabrication process and UPG demonstrated that the remainder of the PV fabrication process did not affect the glass superstrates' ability to pass the Hail-Impact Evaluation Test. However, the thermal tempering process did add a processing complexity to the glass superstrates. None of the tempering vendors capable of tempering 1/8"-thick (3 mm) glass could perform the tempering process without altering the shape of the glass. The heating or

cooling process required for thermal tempering causes the glass to warp to a small degree. This glass warpage created difficulties in the subsequent processing of the glass plates into a PV module. The three processing areas that experienced the most difficulties were:

(1) Maskant Screen Printing
(2) Thin-Film Deposition
(3) Application of Encapsulant

Maskant Screen Printing -

The maskant screen printing step utilizes a screen printer with a vacuum hold-down table. The vacuum hold-down table requires a certain degree of flatness from the superstrates to perform properly. The thermal tempering process occasionally warped the glass superstrates enough to reduce the level of vacuum on the table. Without enough vacuum, the glass superstrate could shift its position on the table leading to a misplaced print.

Thin-Film Deposition -

The thin-film deposition system utilizes conveyors to transport the glass superstrates from one section to another. In addition, the glass superstrates need to be heated to achieve the optimum electrical characteristics as PV modules. Glass superstrates that are warped could present problems for both the conveyors and the heat transfer systems. If the glass is warped beyond a certain point, it becomes difficult to properly align to control direction and speed. Some excessively warped glass did become jammed in the transport system, although the yield at this point has been above 80%.

The effect of warped glass due to thermal tempering on the heat transfer of the superstrates has not been well defined. In the extreme cases of glass warping, the ability of the glass superstrate to be uniformly heated will be compromised. However, with the very slight degree of warping that has occurred with most of the glass superstrates, the loss of temperature uniformity may not be present. This area will require further investigation.

Application of Encapsulant -

The apparatus UPG currently utilizes for the application of the advanced encapsulation material is affected by warped glass. The roller coater which will be utilized in the Automated POWERGLASS Encapsulation Station is assumed to be affected by warped glass superstrates in a similar fashion. In order to deposit or apply a

uniform film of encapsulation material, the glass superstrate should be reasonably flat. The encapsulation application equipment and the encapsulation material will combine to form a film of material that is smooth and flat on the top surface. Although the silicone used as the encapsulation material is quite viscous, it will level out over the time required to cure. Because of this phenomenon, enough encapsulation material must be applied to fill in any low areas to ensure that all the high areas are sufficiently covered. This increases the amount of encapsulation material that is required to protect the entire PV module and therefore increases the cost of encapsulation.

Alternate Superstrates

An alternative to using tempered glass as the superstrate for PV modules is raw (untempered) glass which is thick enough to pass the Hail-Impact Test Evaluation without compromising the electrical power output of the PV devices due to optical absorption losses.

UPG first fabricated glass samples in various thicknesses and with the same areal dimensions as the POWERGLASS modules, mounted these samples on supporting structures similar to those utilized in the field, and sent these samples out for the Hail-Impact Evaluation Test. The following glass samples were sent:

Hail-Impact Evaluation Test

Sample No.	Nominal Thickness	Raw (R) or Tempered (T)	Pass (P) or Fail (F)
1	1/8"	T	P
2	1/8"	T	P
3	5/32"	R	F
4	5/32"	R	P
5	3/16"	R	P
6	3/16"	R	P
7	1/4"	R	P
8	1/4"	R	P

All samples passed the Hail-Impact Evaluation Test at 100% of the required kinetic energy (23.2 m/s) with the exception of Sample No. 3 (5/32" or 4 mm thick glass). Although this was a small sample size, it did appear that raw glass with a thickness of at least 3/16" (also known as 5 mm) is capable of passing the Hail-Impact Evaluation Test. As for the optical losses associated with this thickness of glass, data show that there will only be a 1% loss of light transmission in the region of the solar spectrum useful to amorphous silicon. Although 3/16" thick glass is 50% greater in weight that the 1/8" glass originally intended to be the POWERGLASS superstrate, it is still 25% less in weight that the glass/EVA/glass encapsulation system the new POWERGLASS module is designed to replace. The cost of tin oxide coated glass is dominated by the tin oxide coating itself and not the glass material. As an example, the cost of one square foot of tin oxide coated glass is approximately $2.50 while the cost of the glass alone is on the order of $0.20. Even if the cost of the glass alone were to double this cost increase would not affect the overall cost of the tin oxide coated glass appreciably.

In order to be certain that the results of the Hail-Impact Evaluation Test were valid, UPG submitted a larger sample size of 3/16" thick glass to undergo the evaluation. Although one sample of the 5/32" thick glass had passed the Hail-Impact Test, the other had failed, resulting in a 50% yield which is unsatisfactory for UPG. The 3/16" glass plates were mounted in the plastic frames designed and fabricated for the POWERGLASS modules to serve as both an edge protector for the glass PV module and as a means of mounting the modules with ease and security. These samples of 3/16" glass were sent to Sandia National Laboratories (SNL) for the Hail-Impact Evaluation Test. SNL has reported to UPG that all samples had been subjected to 400% of the baseline kinetic energy utilized in the Hail-Impact Evaluation Test without a single failure. UPG did not expect the alternative superstrates to be able to withstand such harsh treatment. This ability to stand up to such high kinetic energy may be due to the design of the plastic frame and its action as a shock absorber for the glass superstrate. UPG plans on continuing this evaluation with the thinner 5/32" thick glass mounted on the POWERGLASS plastic frames.

Libbey-Owens-Ford (LOF), a major glass manufacturing company, produces a glass product they call TEC, which stands for Transparent Electro Conductive. The product is soda lime glass with a coating of tin oxide doped with fluorine (SnO_2:F). The TEC 10 (10 ohms/square) and TEC 8 (8 ohms/square) can be utilized as superstrates for photovoltaic devices and modules. LOF manufactures this glass product in both 3 mm and 5 mm thicknesses. LOF has stated in a telephone conversation that they have the capability of depositing either TEC 10 or TEC 8 on 4 mm thick glass if the PV industry chooses 4 mm glass as a standard thickness.

Summary

The primerless silicone structural adhesive identified in Task 1 continues to prove successful in terms of the evaluation procedure outlined for thin-film PV module encapsulation. No failures have been identified due to the characteristics of the encapsulation material. The Automated POWERGLASS Encapsulation Station has been fully designed and specified. The installation and debugging of the station will begin during the next quarter.

Tempered glass has proven successful as superstrates for PV modules, however, manufacturing yield (less than 70%) utilizing these superstrates is not as high as expected. Alternate superstrates may provide an answer to the low manufacturing yields associated with tempered glass superstrates.

2.0   TASK 8   POWERGLASS MODULE TERMINATION

Objectives

The objectives for this task are to optimize the materials and processes utilized in the electrical termination of the POWER-GLASS modules identified in Task 2 of Phase I and then design and debug an automated termination station for the insertion and assembly of the advanced termination system. All future terminal components will be designed for use with automated insertion and assembly equipment/robotics. All designs will be analyzed in terms of manufacturing cost reductions.

Termination System

After analyzing various terminal designs in Task 2 of Phase I, UPG has identified a termination system which will surpass all the goals set forth at the beginning of this project. The early terminals were all designed to be soldered directly to the fired silver paste busbar on the glass superstrate surface. While this technique appeared to be inexpensive, both in material and in processing, the contact points proved to be inadequate when subjected to the Thermal Cycle and Humidity-Freeze Cycle Tests as specified in the NREL document SERI/TR-213-3624. This led to the development of a termination system that did not rely on solder-ing to form the bond between the terminal and the glass surface. This new termination system utilizes the excellent adhesive characteristics of the silicone structural adhesive used as the POWERGLASS module encapsulation material. This advanced terminal design does not utilize solder for mechanical or electrical connection and therefore avoids all the problems associated with the hazardous materials clean up and disposal of the solder, flux, and flux cleaners.

The advanced terminal consists of five basic components, all of which are readily available through commercial sources. The first component is a threaded hex standoff made of nickel plated brass. The standoff is press fitted into a stainless steel washer which serves as the surface that is attached to the glass superstrate with the silicone adhesive. The other three components consist of a stainless steel set screw, a nickel plated brass ball, and a silver plated copper spring. These last three components form the system that makes electrical contact to the silver thick-film busbar. The silver plated copper spring makes the contact to the silver busbar. The material and geometry of this spring are designed for high spring pressure with no deformation of the

spring, this is, the spring constant will not change over time due to compression. The nickel plated brass ball is designed to prevent the transfer of torque from the set screw to the spring. As the stainless steel set screw is tightened, the brass ball transfers only vertical force to the spring without the torsion produced by the set screw. The standoff is long enough to allow the three contact components to operate with enough room in the standoff for wire connecting hardware. The cost of this terminal easily meets the goal for the PVMaT project because of the availability of these standard components.

Evaluation Tests and Procedures

The advanced terminal design has been evaluated utilizing the tests and procedures outlined in the NREL document SERI/TR-213-3624. The tests and inspection procedures pertinent to the termination system are:

    (1) Electrical-Performance Test
    (2) Thermal Cycle Test
    (3) Humidity-Freeze Test

In addition, UPG wanted to ensure that the new terminal could pass the Terminal Torque Test as specified in the Underwriters Laboratories document UL 1703. This test requires a wire-binding screw or nut on a wiring terminal to be capable of withstanding 10 cycles of tightening and releasing from 12 pound-inches of torque for a No. 6 screw without (1) damage to the terminal supporting member, (2) loss of continuity, or (3) short circuiting of the electrical circuit to accessible metal.

The new terminal has demonstrated the ability to pass all the tests described in the NREL and UL documents.

Automated Termination Station

The advanced terminal utilizes the excellent adhesive characteristics of the silicone structural adhesive to be firmly attached to the glass superstrate surface. Instead of using solder, the advanced terminal utilizes mechanical pressure to form the electrical contact with the PV module busbar. This terminal design lends itself to the use of automated pick and place robotic systems for PV module application. Immediately after the silicone encapsulant has been applied and while the silicone is still in its quasi-liquid state, the terminal is placed on the printed silver busbar in a manner that displaces the silicone thereby creating a via in the silicone in order to gain access to the

printed silver busbar. Once the silicone is cured, the via is cleared and the terminal contact components are installed. This termination procedure has been developed with automation in mind. None of the individual operations are complex nor do they require a high degree of accuracy. The design of the Automated Termination Station is approximately 50% complete and the installation and debugging are expected to begin in the next quarter.

Summary

The advanced termination system developed in Task 2 continues to prove successful in terms of the evaluation procedure outlined for thin-film PV modules. The terminal components have been defined and several vendors have been identified to supply the components at prices capable of meeting the cost goals of this project. The materials cost goal for the termination system is between $0.25 and $0.35.

The termination process has been defined and determined to be compatible with automation techniques. The design of the termination automation is 50% completed. Installation and debugging will begin in the next quarter.

3.0 TASK 9 EUREKA MODULE DESIGN

Objectives

The second year objectives for this task are to optimize the new EUREKA power module designs and develop a new design for architectural applications. Design reports will be prepared which include market studies, customer feedback and technical aspects of designs.

New Products

Two new designs are being pursued. One is an improvement over the current EP50 that will be introduced when production commences in the new APS facility in Fairfield, California. The main feature of this new design will be its 60 watt stabilized output compared to the 50 watts of the EP50. Towards that end, a 55 watt module was developed in the APS Trenton development facility. The difference between this intermediate module and the 60 watt module will be the addition of ZnO, which the Fairfield facility will be capable of adding to the back contact prior to aluminum coating.

The other new design will be a semitransparent module for architectural applications. The goal is to achieve 20% transmittance with good visual uniformity. This is a longer term effort, with prototypes expected in 1994. Market information regarding this product is summarized here; a complete design report will be prepared when prototypes are built.

55 Watt EUREKA Module

The initial design of this module consists of process changes needed to achieve a stabilized 55 watts, as well as some encapsulation enhancements.

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

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

Of these changes, the thinner i-layer is the most critical, as it will add in excess of 5% to the stabilized output of the modules. The other changes will add about 2% each. The power outputs measured immediately after fabrication of plates made with these changes are consistent with these estimates, as are short-term

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laboratory light soaking studies. Long-term light soaking is underway.

In order to be able to add a cell, the edge bonded foil width was reduced from 0.375" to 0.30". This module also incorporates other encapsulation improvements that will be introduced when the Fairfield facility begins operation. These improvements deal with cost reductions and increase in throughput, and are discussed below under Task 11.

Prototypes of the 55 watt EUREKA module were fabricated in the Trenton Development Line and one was sent to NREL. The electrical parameters (unstabilized) for this 61" x 31" module are the following:

Run and Plate Number	V_{oc}	I_{sc}	FF	Power
PD103-12	56.4V	1.85A	67.9%	70.9W

Architectural Module

One new module design that will be introduced during this phase of the contract is an architectural module. Market information regarding this product is summarized here.

Methodology - Following an initial survey of architect, engineering, and builder respondents done to identify particular applications within the building sector, a survey of the construction products manufacturers was conducted to quantify the market barriers associated with the applications. Manufacturers of Balance of System components for architectural assemblies, particularly skylight and atrium manufacturers, and architectural glass manufacturers were asked to review the technical and market issues associated with the identified niche market sectors. Specifically, meetings were held with Super Sky Products, Regal Manufacturing, and the new products division of Libby Owens Ford.

Market Overview

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

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

Product Review

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

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

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

Light transmittance is an inherent part of the definition of fenestration products. Products which have no light transmission are defined as cladding panels, which comprise a significant portion of the building envelope. Cladding panes, specifically spandrel panels in curtain wall construction, had previously been identified as a suitable application by the architect and builder

respondents. However, for cladding material, it is required that the product has no visible light transmission. The low-level light transmission in existing APS product is easily remedied to produce a completely opaque panel for this application. However, because the vertical orientation of the module in a curtain wall application results in inefficient collection of solar energy, curtain wall applications do not represent the most viable market opportunity.

The highest value and most viable applications for the APS module has been determined to be in sloped glazing configurations such as atriums and skylights. These applications usually require white light transmission. Product suppliers have indicated application for modules with light transmission as low as 8%, which may be more accomplishable as a near term objective that the 20% target. However, the market for 8% transmission glass is limited and will not lead to broad product distribution. Thus, a 20% white light transmission has been confirmed as the objective for an architectural product. Most architects will also accept reasonable spectral nonuniformity in light coloration and pattern.

Various means of achieving the transparency have been reviewed and several methods have been tested. Those considered are:

Lasering - Multiple laser scribing was carried to the point of making a small (1'x1') sample. For this module, the aluminum scribe was repeated 28 times to achieve 10% open area. These scribes, together with a 1/4" clear border, resulted in approximately 18% open area; the relative contribution of the border area will be less for larger modules. One advantage of this approach is that the power lost is very close to the area lost, while with some of the other techniques being considered, more output has to be sacrificed. A more powerful laser than that used for aluminum scribing may make this approach less time consuming and is being considered.

Masking - Preliminary testing suggests that masking prior to either silicon or aluminum deposition is possible; both have been done for other purposes. A detailed analysis has to be carried out in order to determine the overlap needed and whether other losses might be suffered in addition to the area loss. Two disadvantages of masking are that alignment of the two masking steps to the required precision may be difficult, and the decision to manufacture semitransparent modules has to be made when processing is started.

Etching - Both aluminum and silicon can be chemically etched; this too has been done. Because of the need for toxic and hazardous chemicals, this technique is deemed less desirable than others, although it would offer the advantage that standard inventoried plates could be subjected to this type of processing.

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Sandblasting - This technique can also be made and is our fall-back position; it is currently used to clear the border area of modules. A shortcoming of the present sandblasting technique is the shorts are created in a small area surrounding the sandblasted region. Measurements indicate that shorting occurs up to about 1/8" from the edge of the sandblast area; these are isolated from the active area of the panel by a laser isolation scribe. Allowing an additional 1/16" for safety, would result in a nearly 40% larger power loss than the gain in transparent area for 1" wide cleared strips. If this approach were to be adopted, some effort would have to be made to localize the sandblasting damage to a smaller area. Masking the panel prior to sandblasting minimizes the amount of area lost, although isolation will probably still be required. In preliminary tests to determine the effectiveness of masking, we found that damage can be held to within 1/32" of the sandblast region.

Plasma Etching - This technique could also be carried out after the plate is finished, but would likely require the most sophisticated equipment.

Three of these techniques have been tried (it may ultimately be useful to combine several of these techniques).

Sandblasting is the fall-back position; small test samples have been made and full size EUREKA plates have been patterned to determine if the shorting that the larger sandblaster causes can be eliminated or reduced. This has thus far not been possible.

Lasering similar to that used for aluminum patterning has been applied to a small 1'x1' plate. Instead of one laser scribe, the cutting is repeated until the required area is cleared. The disadvantage of this approach is that the laser now used was designed for very narrow scribes to minimize the loss in active area. The amount of time that is required (or the number of lasers that would be required if no additional time could be used) eliminates current technology as a viable approach, except for much smaller degrees of transparency. The appearance of laser scribed transparent plates is more appealing than the sandblasted plates because the open areas are only about 1 cm apart compared to the 20 to 50 cm for the sandblasted plates.

It is possible to mask silicon deposition as well as aluminum sputtering. It is not clear how practical this might be. A test with silicon deposition has been carried out in which a small mask was introduced into the box carrier. This mask consists of 0.5" diameter cylinders of teflon, which are placed between two opposing plates. The gap between the glass and the teflon pieces was varied in order to determine the largest gap that will show a good demarcation line between deposit and no deposit. Results of

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the test will be available shortly.

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

4.0 TASK 10 EUREKA PROCESS AND QUALITY CONTROL

Objective

The objective of this task is to establish a high degree of process and quality control within the EUREKA manufacturing line in order to improve quality, yield and throughput of the line and to introduce Statistical Process Control (SPC) into the Fairfield facility.

Process and Quality Control

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

A complete review of the influence of the four selected critical control points on improvement of quality, yield, and throughput of the EUREKA manufacturing line was performed. The goal for this review was to determine the influence of control points, with actual control to be achieved later. Since APS is nearing operation of a new facility, tight controls of many of these critical areas have been put in place, although more stringent controls may be implemented at a later date.

Deposition Base Pressure – A graph was presented in the first Annual Report that showed the influence of base pressure on plate quality (FF); this graph is repeated as Figure 1. A conflict can exist between achieving a sufficiently low base pressure to produce a high quality product with a high yield and requiring a pumpdown time consistent with throughput requirements. Much effort has gone into reducing pumpdown requirements so that both high quality and high throughput can be achieved.

Two criteria have been established in order to control base pressure. The system must both be pumped on for a minimum time period, and also pumped down to less than some maximum pressure. If either does not occur, corrective action is taken. To increase the confidence in the pressure readings, two ionization gauges (as well as two gauges for monitoring the higher deposition pressures) are installed on the deposition systems. It is believed that these measures provide sufficient control of base pressure for silicon depositions. It is also planned to add the RGA measurements to the systems in Fairfield, but a procedure has yet to be developed for doing this.

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

In order to determine the importance of flow variations typically experienced in the system, the stability of flow controllers was determined. Thus several calibrations of all flow meters were carried out (this is more fully discussed below). From these measurements, a calibration schedule was derived for the controllers. All except one controller will be checked on a weekly basis, while one will be done twice a week. The addition of the flow calibration system to the deposition system is believed to provide sufficient control of flows during depositions. The frequency of calibrations may have to be adjusted and may well be done on a totally automated and daily basis in the Fairfield facility once it is in operation.

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

Figure 2 shows the influence of shorting on power output (the calculated curve is discussed below). Plates that have not been sandblasted lose on the order of one percent of power as a result of shorts (typically from aluminum scribing); sandblasting should add no measurable shorts, but has on occasion resulted in more than 10% higher loss and short-term yield losses near 50%. In order to control this step, a low light level open-circuit voltage measurement ($LLLV_{oc}$) is made after sandblasting (and just recently during the plate I-V measurement before sandblasting). The basic assumption made in using these measurements is that the light intensity is low enough so that the V_{oc} for each cell is equal to the product of cell shunt resistance and current. This will be the case if either cell resistance or light intensity are sufficiently low. If the light intensity is set to typically result in an I_{sc} of I, and the minimum $LLLV_{oc}$ allowed is V, then the power loss that this corresponds to can be calculated. Thus, V/I corresponds to an effective resistance, R, of the shunts, and at the maximum power point, a current, V_{mp}/R, will be lost to the shunts. Since the maximum power current is I_{mp}, the fraction $(V_{mp}/R)/I_{mp}$ (or $V_{mp}*I/I_{mp}*V$) is an estimate of the power lost.

For the EP 50, typical values are 38 V for V_{mp}, 1300 mA for I_{mp}. The light intensity is set to give an I of 0.5 mA and the cut-off V was chosen to be 4 V. Thus, the maximum power that is allowed to be lost in sandblasting is about 0.3%. This analysis is valid if the shunting is equally distributed over the plate. If the $LLLV_{OC}$ of a plate is less than 4 V after sandblasting, the plate is passed through the sandblaster a second time. If the voltage drops as a result of the second pass, then the sandblasting is halted and the problem corrected. These steps together with visual inspection for incomplete sandblasting are considered sufficient for monitoring and controlling the sandblasting procedure.

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

Laminator Temperature - With the introduction of the split cure and its short heating cycle in the laminator, control of the laminator temperature becomes more important. If the laminator platen temperature is too low, incomplete cure results, while too high a temperature causes bubbles to form. To control the platen temperature and its uniformity in the laminators installed in the Fairfield facility, the heating elements for the platen have been divided into four zones, each separately controlled. Four additional controls and monitoring steps are believed to provide the necessary temperature control of the lamination step.

Deposition Pressures - The influence of RF power on the deposition rate (thickness) is shown in Figure 3. It should also be noted that thickness measurements are more correct relative to each other than on an absolute basis. The relationship is very linear with an intercept near zero as well. Control of this variable is therefore important.

Uniformity

The main reasons for improving the uniformity of the silicon deposition are appearance and internal matching of I-V parameters. For architectural applications it is believed that the uniformity exhibited by the modules delivered to PVUSA needs improvement. For most of these modules, nonuniformity is confined

to a very thin deposit in one corner of the plate (Figure 4). While this corner comprises only a small area of the module, the nonuniformity can be very visible, more so for modules having thinner average silicon thicknesses. This thin spot may be 1/3 the thickness of the thickest region of the plate. Electrically, its influence is not very great, unless the silicon is thin enough to make laser scribing difficult. With the need to reduce i-layer thickness for improved stabilized output, the nonuniformity becomes an important issue. The two main causes of such nonuniformity are the RF connection to the powered electrode (which causes a decrease in thickness) and chemistry. Because silane is consumed during the deposition, the gas phase composition varies from top to bottom of the box carrier (the direction of gas flow) and this is reflected in a change in deposition rate, which is higher at the bottom than at the top.

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

Figure 4 shows an image of a plate made with the standard box carrier and under standard conditions. Such an image is representative of what is obtained under these conditions, although only slight plate-to-plate and run-to-run variations in thickness can alter details of the image.

The first approach at eliminating the gross variation seen in the lower left hand corner was to increase the size of the box carrier, thus allowing the glass plate to be removed from the region of thinnest deposit. The result of this change is shown in Figure 5, which is a plate made in a larger box carrier but with otherwise the same conditions as the plate in Figure 4. As can be seen, the closely spaced fringes of thin deposit have disappeared. An unexpected result of this box carrier was a much thicker deposit in an opposite corner on many plates. For some plates, this thickness would double over a very small region of the plate. Adjusting the flow rates of deposition gases to account for the fact that the volume of this box carrier is larger and hence the residence time lower, helped the situation, although the thickness is still somewhat greater in that corner than would be otherwise expected. Figure 6 shows an image of a plate made with 20% higher than normal flow rates in the box carrier.

Similar to adjusting the flow rates, reduced pressures also tend to improve the uniformity of deposit. Thus, the standard deviation of the 25 thickness measurements decreased from 16% to 12% (a 25% decrease) when the deposition pressure was decreased from 100% to 50% while maintaining the standard flow rates.

Another approach is to make the RF effect counter the chemistry effect. By making the RF feed point at the bottom of the box carrier rather than the front, the general increase in thickness from top to bottom resulting from chemistry should in part be offset by the decrease due to the RF effect. This has been tried in a small box carrier, with the results shown in Figure 7. Only a small region of thinner deposit is seen at the bottom of the plate.

It should be added that thinner deposits are much more noticeable to the naked eye than are thicker deposits, because as the deposit gets thicker, the appearance becomes darker and variations become less apparent. The images obtained with the digital camera are made under conditions that enhance uniformity variations; the visual appearance of the panels made with the larger box carrier are quite good. Attempts have been made to mathematically quantize the uniformity of plates. From both the thickness measurements and the photos, standard deviations can be calculated. For thickness measurements, the meaning is clear. This is not the case for the standard deviation of the more than 130,00 intensities of the photograph, although this latter number may be more meaningful for visual effect. In either case it appears that not enough weight is given to small areas of extreme variation that have a large impact on appearance. Other mathematical ways of describing the visual nonuniformity are being investigated.

Residual Gas Analysis (RGA) Measurements

An RGA (Transpector from Leybold Inficon, Syracuse, NY) has been in use for several months at the APS Trenton Facility. Two applications have been identified and tried for this instrument (and are foreseen in the APS Fairfield Facility). One is the standard application of a residual gas analyzer, which is to determine the quality of vacuum prevailing in a pumped down deposition chamber. This usage will not only detect some leaks but will also identify any abnormal or unusual outgassing that may be occurring. The second use is to monitor the deposition process itself. In analyzing background gases, the species of greatest magnitude is, as expected, water. Low levels of other species are also present, but to very much smaller extents. Thus, signals at mass 28 and 44, which could be CO and CO_2, are detected, as are others. The RGA can track 12 species in the trend mode; this will likely be the preferred detection mode once the species to be tracked have been identified. Among the candidate species are water at 18, nitrogen at 28, silane at 30, disilane at 60, trisilane at 90, a silicon-carbon cross species at 45, and others.

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

Flow Calibration

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

From several volume determinations, it is believed that the volumes are known to within 0.2%. To calibrate a flow meter or controller, the chamber(s) is evacuated, the flow is set, and the pressure rise time is measured. A 1000 Torr pressure gauge is used to detect both starting and stopping pressures. The valving and pressure readout have been connected to the deposition system

computer for more precise control and measurement. To test the system, the lower pressure set point was varied from 100 to 500 mTorr while the upper pressure was always set to atmospheric. These changes of lower pressure had no systematic effect on flow determination for a given flow rate. The entire set of flow controllers was then checked. It was determined that two controllers (H_2 and CH_4) were off between 15 and 20%, two (Ar and PH_3 mixture) were off between 5 and 10%, and the others (P-mixture and silane) less than 2%. The rather large discrepancies are likely the result of erroneous internal adjustments of the flow meters rather than faulty flow meters.

Three more calibrations have been carried out on a roughly weekly basis in order to determine the stability of the flow meters. The scatter in deviation of measured flows compared to set-points was typically 2%, with the exception of the methane flow control, which exhibited variations of more than 10% in the group of four measurements. The discrepancy was traced to an unstable zero point in the controller, although the exact cause for this has yet to be determined.

Data Analysis

One of the reasons for variation of electrical parameters from plate to plate, is the varying degrees of shunting that exists. Some shunt removal occurs when cells are reverse biased (shunt-busted) after aluminum scribing. During the shuntbusting operation, the resistance of each cell is measured both before and after reverse biasing. From these resistances, a shunt-free quality factor (Q_{sf}) is calculated. This quality factor is intended to represent the amount of power lost due to the shunting as $1-Q_{sf}$. A correlation for this factor was determined by deliberately introducing shorts in cells and determining the output as a function of cell resistance. The calculated cure in Figure 2 shows the correlation obtained. Not only was a Q_{sf} determined for power but also for V_{oc} and FF. I_{sc} was found not to change with the extent of shunting normally observed. Typically the effect of shorts is approximately four times greater on FF than it is on V_{oc}. The reason for carrying out these correlations is to facilitate judgment of the deposition quality without complications brought about by shunting of cells. Thus with these correlations, the values of the electrical parameters that would exist without shorts can be approximated.

Product Tracking

A bar coding technique is being tested for plate and module tracking throughout the process. A material and adhesive have been identified that might be used on plates and applied after plates are unloaded from the box carrier. Pre-numbered tags will

be used for this application. In addition to tagging product, box carriers will also be tagged to allow automatic association of preheat and deposition data with a given run. A bar code reader has been acquired and is being evaluated. The test in progress is meant to determine if there are any detrimental effects from passing these small 1/4" by 2" tags through the sputtering system. Currently, all plates are identified by hand scribing a number near one edge of the plate.

Statistical Process Control (SPC) Course - Four APS employees participated in a three day course on SPC, including the QA managers at Headquarters and Fairfield offices.

5.0 TASK 11 EUREKA ENCAPSULATION AND TERMINATION

Objective

Two objectives of this task are to reduce encapsulation costs and increase module power through redesign of cell layout. Another objective is to work with UPG with laser processing plates for UPG POWERGLASS modules.

The major accomplishment in this task was the development of the split cure encapsulation process. Progress was also made with thinner ethylene vinyl acetate (EVA), foil bonding, welding through the hole in the cover glass, and testing of new shipping containers.

Split Cure Process

Laminating a module at the Trenton line required 10 minutes, which included one minute for loading and unloading of the laminator. To achieve the necessary throughput in the new Fairfield facility, it will be necessary to reduce this cycle time to six minutes. For the Trenton line, it was believed that an eight-minute cycle could be optimized to achieve the six minutes in Fairfield. From a series of tests to shave time off the ten-minute cycle, it did not appear that fine tuning would result in the required reduction in cycle time. The focus was therefore shifted to a split cure in which only part of the EVA cure would occur in the laminator and the rest in a separate oven.

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

1. Standard cure of a 9 minute cycle
2. 3.5-minute first stage split cure, followed by a 10 and 15 minute post-cure in laminator with no pressure applied
3. 3.5-minute first stage split cure followed by a one hour high temperature post-cure without letting the sample cool during transfer to the oven
4. 3.5-minute first stage split cure followed by a one hour high temperature post-cure letting the sample cool before transfer to the oven
5. 3.5-minute first stage split cure only

The first stage split cure is done at reduced laminator pressure but at the same temperature set point as before. In all but the last case, the gel contents averaged in the range 87 to 92%. With

only the first stage cure, gel content of about 90% was obtained in the center of the laminate and less than 30% at the edges.

An important part of the thin film processing sequence is heat aging, which is the final step before I-V measurement. Since the split cure includes an extended heating period, tests were carried out to determine whether the heating done for the EVA cure could also be sufficient for replacing the normal heat aging. Such testing indicated that samples subjected to the split cure gained about 1% less than did those that received the normal heat age treatment. It was then determined that testing of plates and modules gave slightly different results and accounting for these differences brought the split cure plates in line with those that were heat aged. Based on these results, it was decided to adopt the split cure process, provided that the resulting module passes environmental testing.

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

The split cure has several important advantages over the previously used process:
    a) The throughput of the lamination process is doubled.
    b) The lower laminator pressure during the split cure avoids
        EVA from being squeezed out between the two pieces of
        glass, and a much cleaner module results.
    c) The 12 mil EVA is less expensive, and more of it can be
        put on a roll, thus reducing down time when changing EVA.
    d) The cost of a heat age furnace is avoided.
    e) Operational costs of a heat age furnace is avoided.
    f) Factory floor space is freed up.
    g) The elimination of a step avoids the yield losses at that
        step.

Foil Bonding

In order to fully automate the encapsulation line, it would be advantageous to be able to bond directly through the hole in the cover glass, rather than bringing the foil out and bonding externally. Early efforts in that direction were promising, but never fully developed. The main difficulty is that in order to bond wire or a tab to the foil, the support for the foil must be very rigid, (e.g. as rigid as glass). Since the bonding is done over an active area of the panel, the foil must be insulated from the cell supporting it during bonding. Even a very thin film of adhesive material results in poor bonding. Two methods for dealing with this problem are being considered. One involves placing a hard material under the foil where bonding will take place either an insulator or a somewhat massive metal with an insulating backing. The second, less desirable approach involves laser isolating the part of the plate over which the bonding is done. There will be a small power loss associated with this approach, since a somewhat shorter cell will be in series with normal size cells. The net effect will be that one or two cells will operate at a slightly lower operating voltage since it will carry the same current as the others, yet be shorter. No detailed analysis of lasering time has been carried out, but since there is a laser station totally dedicated to laser isolating the edges of the plate, the extra time taken for this step should be tolerable.

Environmental Testing of Foil Bonds

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

Somewhat related to module testing is the testing of the shipping container. Three single-module shipping containers were subjected to drop tests (as per test procedures from the National Safe Transit Association; Project 1A). The containers were dropped from a height of 12 inches. Two of the containers were made of cardboard, and other than signs of minimal external damage in the corner, they passed the test; the module inside was not damaged. The third container was wooden, and it too protected the module with slight damage to the container.

6.0   TASK 12   AUTOMATION OF EUREKA MANUFACTURING LINE

Objective

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

The effort on this task has concentrated on the new APS Fairfield facility where equipment is being installed and tested.

Status of Fairfield Line

Lasers - All laser systems were tested in Trenton prior to shipment to Fairfield. All three systems, including the additional end isolation stage on the aluminum laser were then assembled and tested. The tin oxide and silicon lasers are fully operational, while the aluminum laser is being fine tuned. The aluminum lasers had to be returned to the manufacturer because of poor performance. They have since been re-installed, but may require additional service. The thinner i-layer and higher haze tin oxide makes back contact lasering more difficult than for plates with thicker silicon depositions. Several dozen plates with silicon deposition have been sent to Fairfield for testing of the lasers.

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

In order to accommodate this increase in throughput, a second mounting bracket/mold injection station was installed, debugged, and placed on-line.

In order to upgrade the line, several modifications had to be made. The laminator programmable logic controller (PLC) was reprogrammed to initiate the lamination cycle upon closure of the lid by the operator. Previously, the operator initiated the cycle by engaging the Start button, and thus, a possible source of operator error was eliminated by this change in programming.

Temperature time profiles were obtained for one of the boot and bracket cure ovens. Fifteen thermocouples were monitored; five

each (on the four corners and the middle of the module) on the first, middle, and top shelf of the fully loaded curing rack. After two hours from a cold start, temperatures ranged from 157 to 165°C set point. The temperatures in the center of the middle module and a corner of the top module were both 157°C. All other temperatures were in the range 162 to 168°C. During production, a cold rack will be introduced into a hot oven. Thus, these temperatures appear acceptable.

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

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

Manufacturing Process Procedures - Equipment Logs and SPC performance sheets were placed at all line operations of the encapsulation line. A daily report format was generated for line performance, which includes the use of a Pareto plot.

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

Previous to the time coverage of this report, the sputtering system passed both mechanical testing and process acceptance testing. The latter testing required lengthy evaluation of coated product, and hence, the results were not known until recently. Test measurements that were carried out include resistivity of both ZnO and aluminum, sheet resistance of both ZnO and aluminum, transmission of ZnO, and uniformity of these properties in both films. Tests for impurities were also carried out which were passed. The sputtering system is presently being optimized together with the aluminum laser station. In order to test the

sputtering and lasering systems at Fairfield, silicon deposited plates were sent there from the Trenton facility, since the deposition system is not yet operational. Results of these tests will be available in about two weeks. Some of the product will be aluminum scribed in Trenton for comparison with product totally processed at the Fairfield facility.

Deposition Systems - Both deposition systems and the two preheats are installed. Plumbing of the systems should be completed later in November, although the major components have been installed and some leak checking has taken place. Electrical hookups have yet to be made. RF generators are installed as is one set of matching networks (one of the RF systems was tested in the Trenton facility with actual depositions; it performed as expected).

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

Box Carriers - Two box carriers have been manufactured for the Fairfield line. These are the larger box carriers that have undergone testing in Trenton for improved uniformity (see Task 10 above). Some modification will likely be required in the future to improve on the pumpdown characteristics of these box carriers. Tests carried out in Trenton to determine pumpdown characteristics have shown that a small box carrier modified for improved pumpdown reached 30% lower pressure after one hour pumping than did the standard box carrier, while the larger box carrier achieved a 65% higher pressure than the standard carrier.

Both plate and module I-V testers are operational. Results indicate that excellent correlation exists between the testers, with the high-low range being between +0.3 and -0.5 watts.

FIGURE 1. DEPOSITION SYSTEM BASE PRESSURE

FF vs. Base Pressure
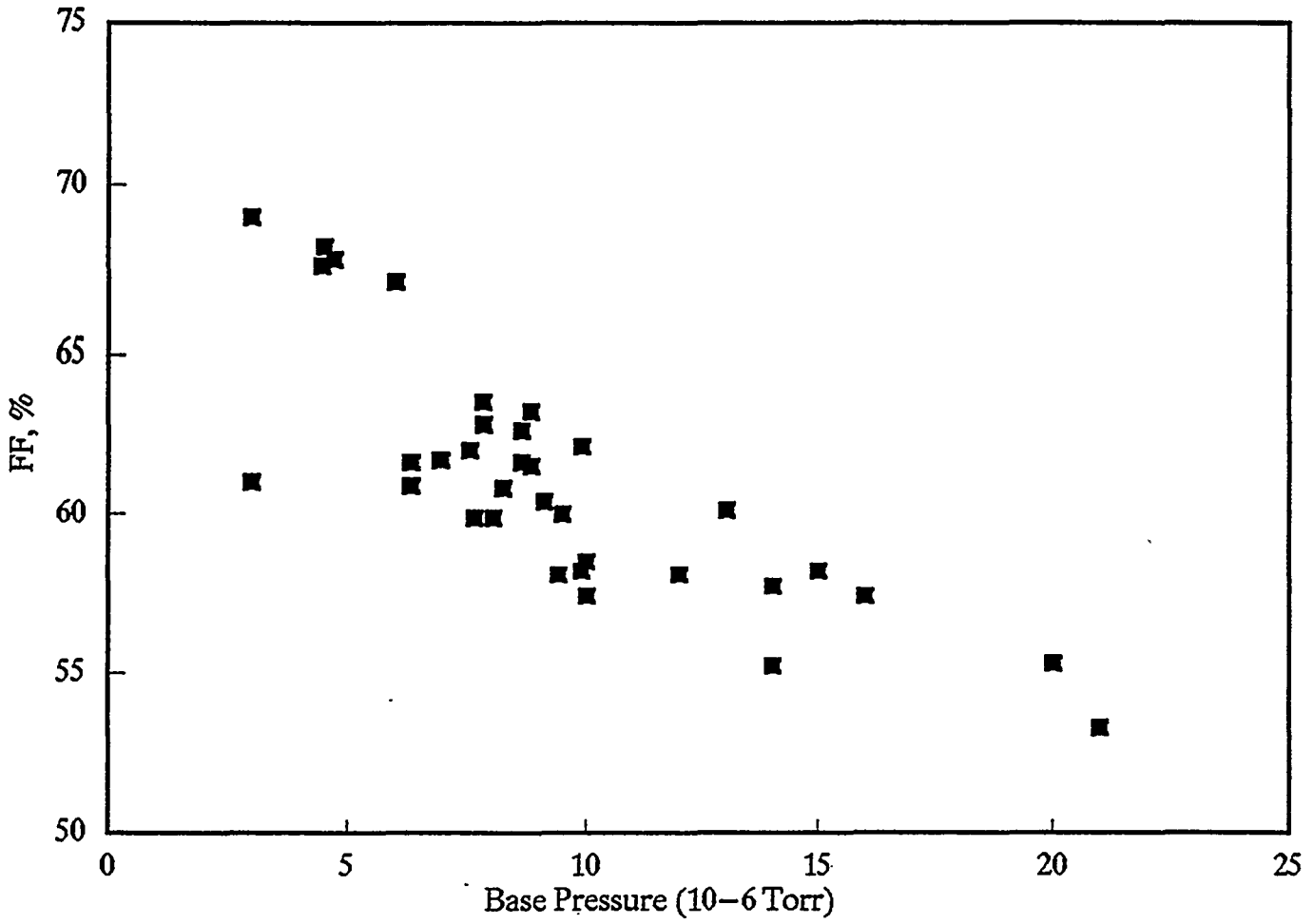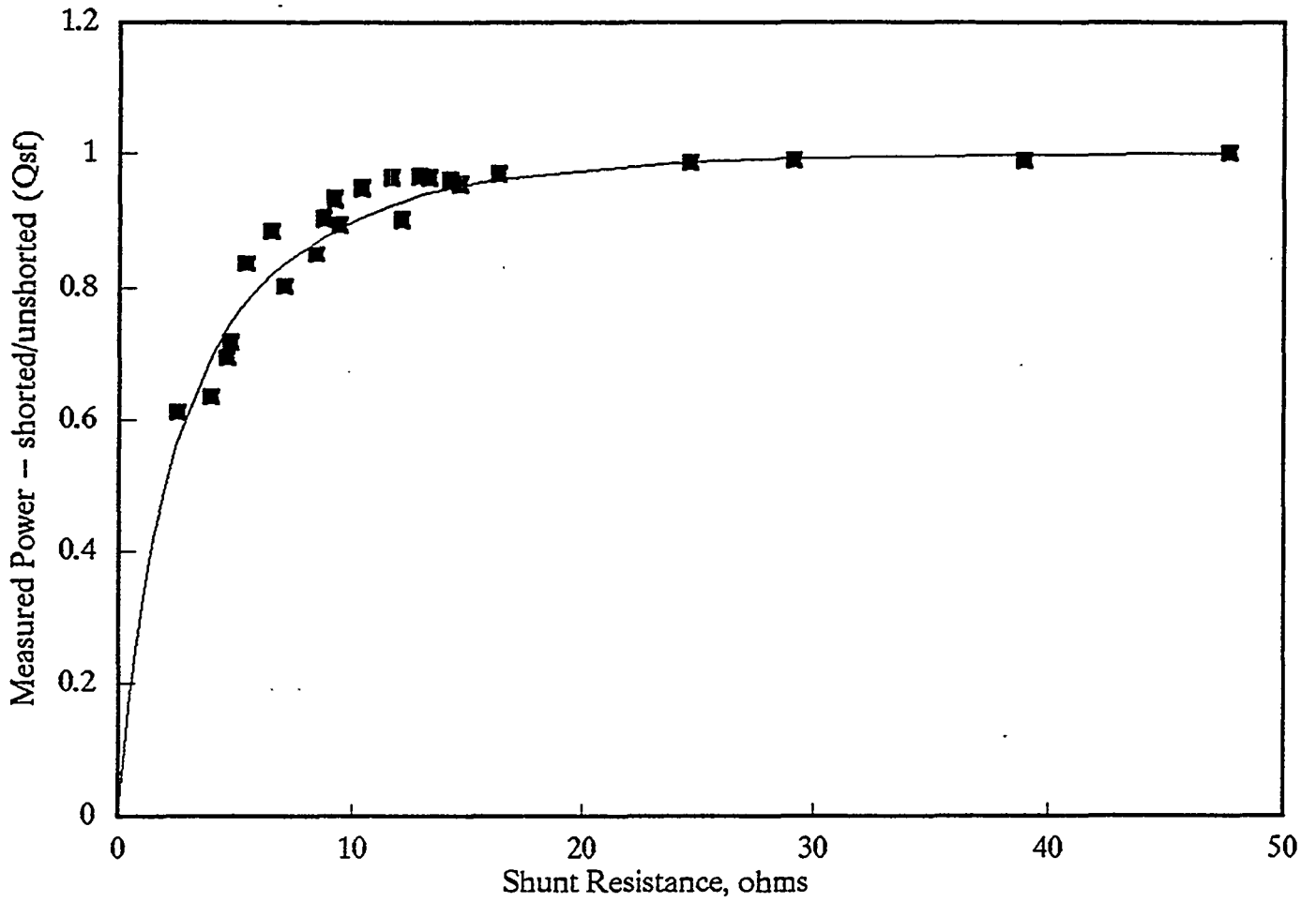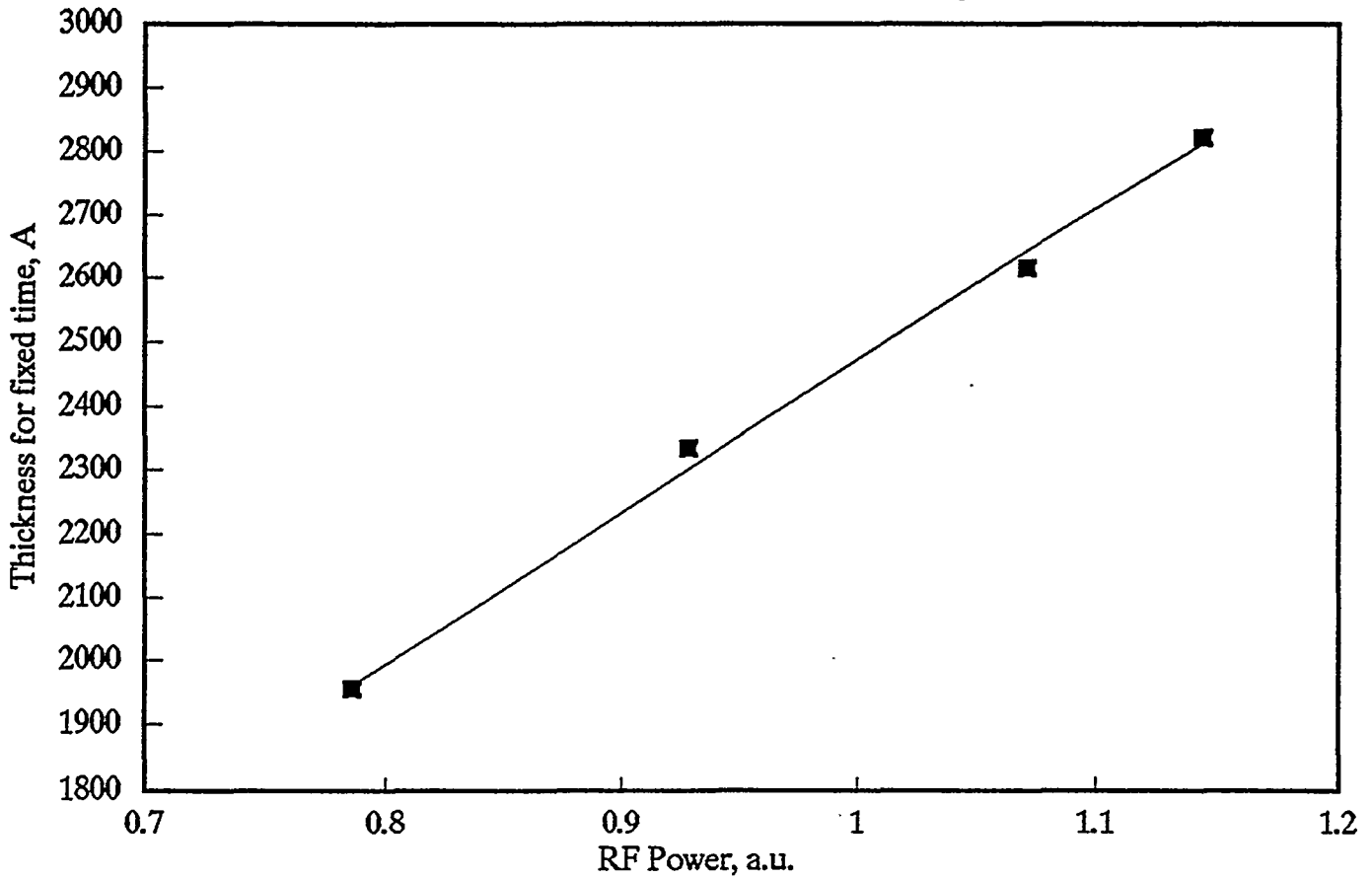
Power Loss through Shunts

FIGURE 2   Influence of Shunts on Output Power

Influence of RF Power on Deposition Rate

measurements are averages for several plates each
thicknesses are normalized to a given deposition time
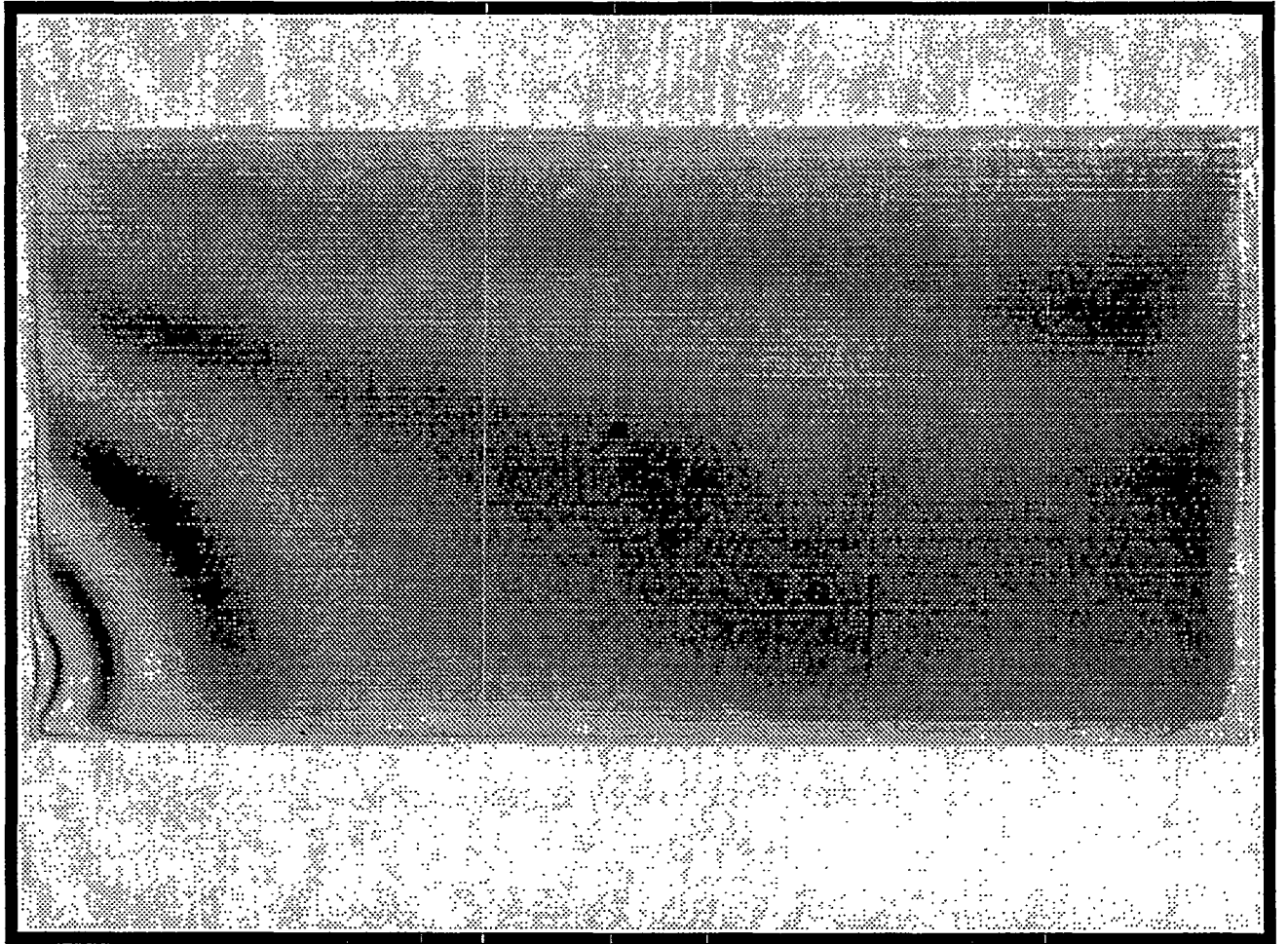
FIGURE 3   RF Power and Deposition Rate

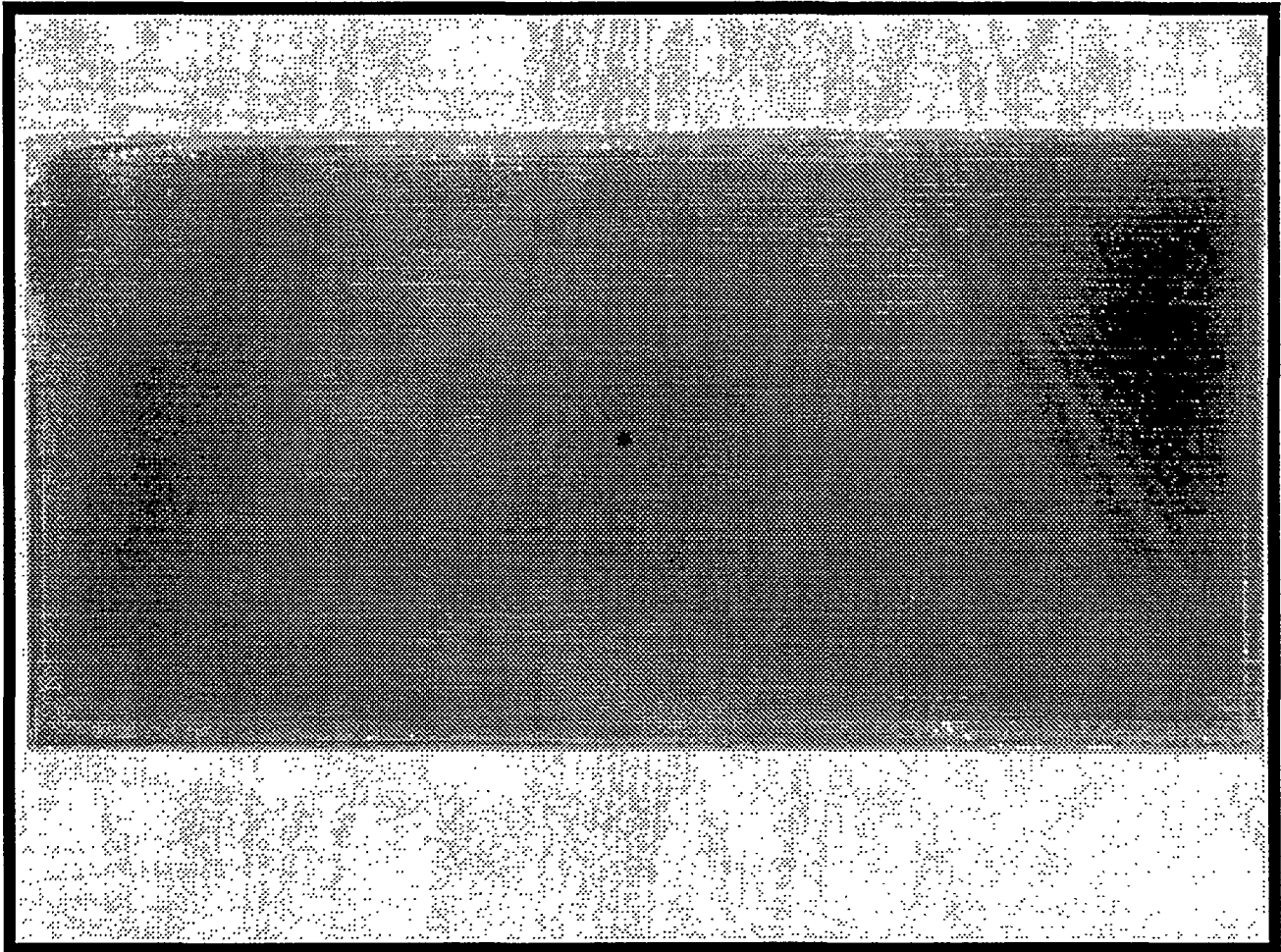FIGURE 4. Plate Made in Standard Box Carrier

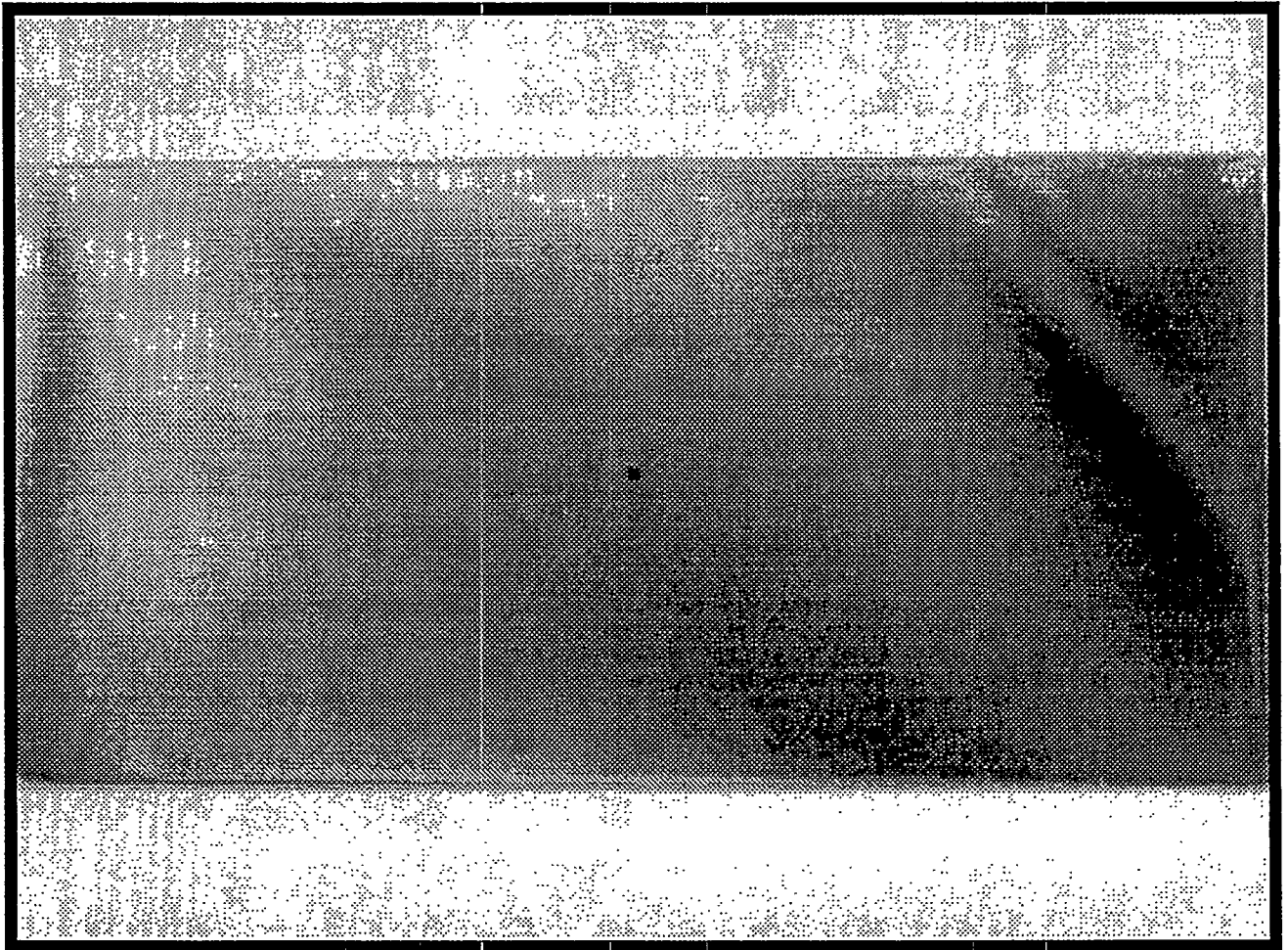FIGURE 5. Plate Made in Modified Box Carrier

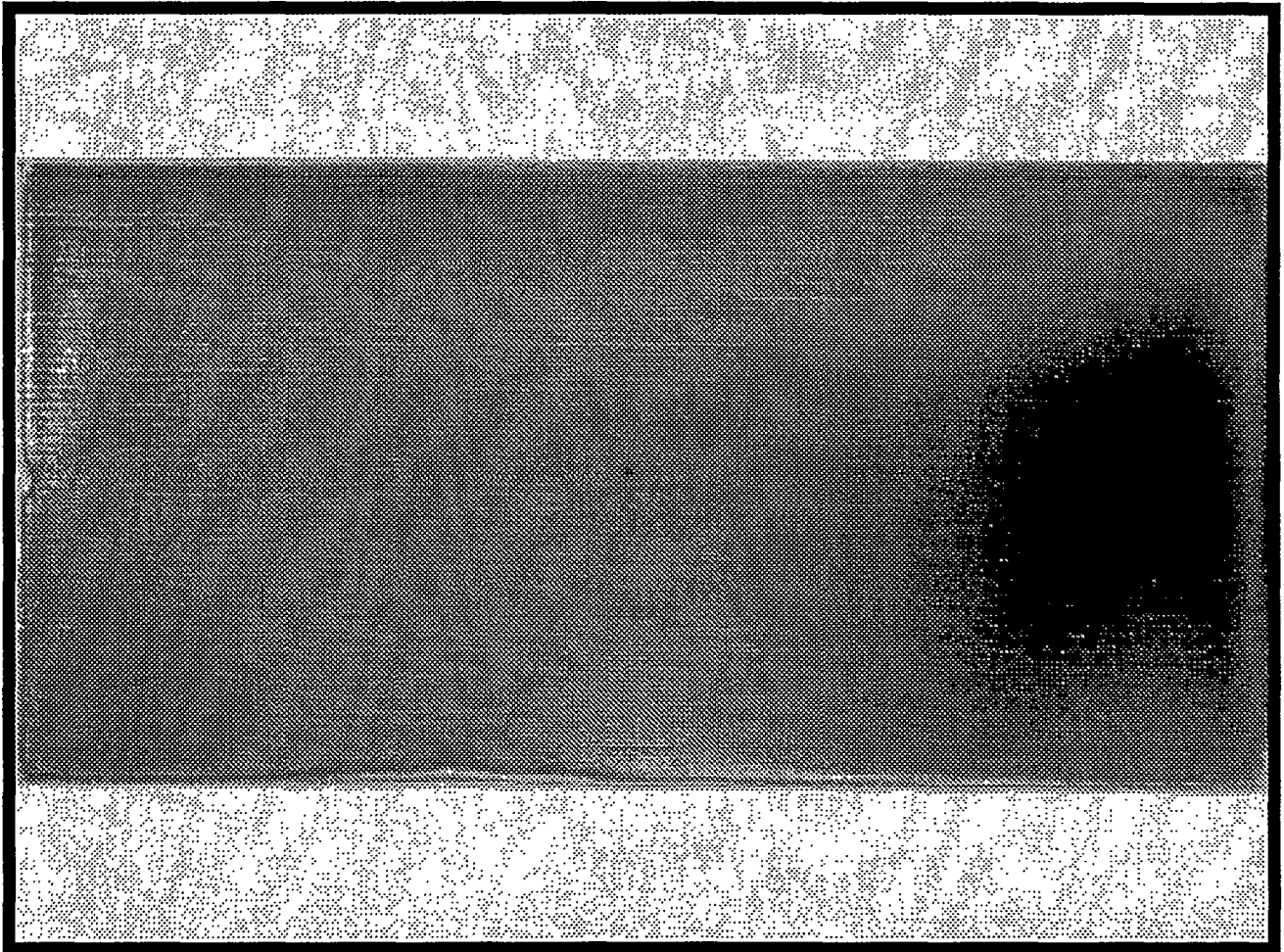FIGURE 6.   Plate Made in Modified Box Carrier with Higher Flow

FIGURE 7. Plate Made in Standard Box Carrier with Bottom RF Connection

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	14.

15. Supplementary Notes
NREL technical monitor: H. Thomas

16. Abstract (Limit: 200 words)

Utility Power Group (UPG) and its lower-tier subcontractor, Advanced Photovoltaic Systems, Inc. (APS), continued work to develop their manufacturing lines. UPG focused on the automation of encapsulation and termination processes developed in Phase 1. APS focused on completion of the encapsulation and module design tasks while continuing process, quality control, and automation projects. The goal is to produce 55-W (stabilized) EP50 modules in a new facility.

17. Document Analysis
a. Descriptors
   amorphous silicon ; manufacturing ; encapsulation ; modules ; 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 46
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