October 1992 • NREL/TP-411-5018

Photovoltaic Manufacturing Technology Phase 1

Final Technical Report
1 May 1991 – 10 May 1991

Chronar Corporation
Lawrenceville, New Jersey

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

NREL/TP-411-5018 • UC Category: 270 • DE93000026

Photovoltaic Manufacturing Technology Phase 1

Final Technical Report
1 May 1991 – 10 May 1991

Chronar Corporation
Lawrenceville, New Jersey

NREL technical monitor: R.L. Mitchell

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

Prepared under Subcontract No. XC-1-10057-16

October 1992

On September 16, 1991 the Solar Energy Institute was designated a national laboratory, and its name was changed to the National Renewable Energy Laboratory.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

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 A03

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.

1. Executive summary.

In response to Subcontract No. XC-1-10057-16, Chronar Corporation submits a proposal, prepared by Advanced Photovoltaic Systems Inc. (APS), for Phase 1 of the Photovoltaic Manufacturing Technology Development Program.

Amorphous silicon is chosen as the photovoltaic technology which Chronar Corporation and Advanced Photovoltaic Systems Inc. believes offers the greatest potential for manufacturing improvements which will in turn result in significant cost reductions and performance improvements in photovoltaic products.

We have chosen the "state of the art" APS Inc. "Eureka" facility as the manufacturing system which can offer the possibility of achieving these dramatic production enhancements. The "Eureka" system has the design capacity of 10MWp per year and following successful completion of process optimization was commissioned as a production facility in April 1991. This plant, which is situated in Trenton, N.J, utilizes 2.5'x 5' glass substrates as the starting material for the fabrication of 50 Wp (stabilized) amorphous silicon based glass/glass laminated power modules.

In response to Task 1 of the subcontract in section 2 we discuss the manufacturing capability of Chronar Corporations "batch" plants and APS Inc.'s "Eureka" facility and explain the relationship between the two companies.

In section 3 we identify five key areas which in the framework of the "Eureka" system could meet the objectives of Task 2 of this subcontract, that of manufacturing potentials that could lead to improved performance, reduced manufacturing costs, and significantly increase production. These are as follows:-

* Product design
* Automation
* Encapsulation
* Real time process and quality control
* Reduction in loss mechanisms.

The projected long term potential benefits of the improvements above are discussed in an absolute and comparative sense with the present capability of the "Eureka" manufacturing facility. We predict an average module wattage of greater than 85Wp with a direct cost contribution of less than 75c/Wp as a result of the above developments.

The problems that may impede the achievement of the developments described in section 3 are examined in section 4 with possible courses of action being described. It is worth noting that a significant number of the problems that we feel must be solved are of a generic nature and hence could be of general interest to the industry.

The final section of this document addresses the cost- and time-estimates for achieving the solutions to the problems which were described in an earlier section. Particular emphasis is placed on the number, type and cost of the human resources required for the project.

2. Task 1. Current capabilities in manufacturing and process development.

2.1 Chronar batch plant process. (and products)

Chronar Corporation has in excess of six years of experience in the design and installation of "turn key" manufacturing plants which can fabricate 1 MWp per annum of amorphous silicon based photovoltaic modules and panels.

The initial concept behind these installations was to provide a simple, relatively labor intensive, approach to the fabrication of single junction amorphous silicon based solar cells on a glass substrate. Substrates are batched, following each process, into cassettes containing 24 pieces and are manually transported and loaded into each processing step. By adopting such a "batch" process, equipment costs can be minimized and a great deal of flexibility can be incorporated into the manufacturing process.

The step by step module production process currently employed in the batch factories is as follows: - 2.5 mm thick float glass is either purchased precut to the 1 x 3 ft. substrate size or cut from a standard sheet at the plant.

The edges of the 3 x 1 ft. sheet are then swipped to facilitate handling at various stages in the process. The glass is then cleaned using standard equipment. The first layer of the photovoltaic cell is then deposited, namely the transparent, electrically conducting fluorine doped tin oxide layer, using an atmospheric chemical vapor deposition process. Throughput at this stage is approximately 12 inches per minute with the 1 ft. dimension of the substrate perpendicular to the direction of travel.

After process control has checked the electrical conductivity of the film and its visual quality the 3 x 1 ft. tin oxide layer is separated into 29 cells, some 0.4 inches x 3 ft. in dimension using laser scribing. The glass substrate, mounted on a microprocessor controlled XY table, is moved under a Nd YAG laser beam which is absorbed in the layer.

Following laser scribing the panels are checked, then they are mounted in a patented box carrier for the amorphous silicon deposition process steps. A standard batch plant uses 12 chambers connected in two sets of six (six packs) for gas supply and vacuum pumping purposes. Each of these individual chambers accepts 4, 3 x 1 ft. substrates held in the leaves of the stainless steel box carrier. The box carrier and substrate are firstly preheated to slightly above the optimum deposition temperature to reduce cycle time in the six packs. The a-Si:H P-I-N layers are deposited in a single chamber using the RF glow discharge technique. System parameters are controlled by a dedicated PC.

The total cycle time for this entire deposition stage is some 2 hours 30 minutes. A typical batch plant with 2 six packs (12 chambers) can achieve 100 runs per week of 72 sq. ft. on a 3 shift basis, giving a total throughput of 25KWp per week, with a stabilized average of 3.5 watts per square foot. The main advantage of deposition using the box carrier is the extent to which the majority of the surface area exposed to the gas flow and RF glow discharge is actually glass substrate and this is replaced as each new run is started, thus avoiding cross contamination between runs. This single chamber approach also significantly reduces processing complexity and cycle time.

After cooling, the amorphous silicon coated substrate is removed from the carrier and the layers are laser scribed in a similar fashion to the tin oxide scribing. In this case, the laser is a frequency doubled Nd YAG laser and the amorphous silicon scribe line allows the series interconnect, from metal to tin oxide, to take place.

Finally, the last layer of the PV cell is applied using thermal evaporation of aluminum. A contact mask is applied for isolating the metal layer. Again, the divide line or scribe line is slightly offset from the previous amorphous silicon line.

This final evaporation stage connects the tin oxide, amorphous silicon P-I-N structure and the aluminum into a series connected 29 cell format with a typical open circuit voltage of 22 volts and a short circuit current of, in excess of, 1 amp. This final metal layer dividing process can now be achieved with relatively standard laser scribing using a frequently doubled Nd YAG laser. This update to the process is currently being installed in several of the existing batch plants and is used as standard in the second generation Eureka process. The 3 x 1 ft. photovoltaic layer can now be tested using a Chronar built solar simulator. Electrical and solar characteristics of the panel are stored within the computer and can be subsequently displayed as a function of the precise position of the panel within the six pack yielding valuable process control information. Such information can be accessed at Chronar for all plates processes in all Chronar batch plants. It is, therefore, possible to draw on data from up to 16,000 3 x 1 processed plates per week. Every plate processed within the Chronar plant has a unique identification number applied to the panel as and when it is included within a process batch.

After testing, the complete 24 plate batch is subjected to heat treatment for 12 hours to stabilize the electrical contacts and to identify substandard panels. After heat treatment, the batch electrical and solar measurements are compared with the original test data. A change in key parameters of 10% or greater would cause the panel to be rejected.

The successful panels are then ready to pass to the encapsulation stage where it can be processed as a cut plate product or completed as a glass/glass sealed module. The cut plate product, once cut to the requisite size using relatively standard glass cutting equipment, can be encapsulated using proprietary acrylic resin applied to the thin film layers. While the cut plate encapsulation methods are selected to minimize the direct labor content associated with processing up to 50,000 units per month in a batch plant, the module encapsulation techniques are selected to achieve the desired product lifetime in operation in the field. These severe environmental requirements inevitably add significantly to both the direct labor and material cost of the finished product.

At the present time, in Chronar batch plants, the module encapsulation process, as can be seen in Figure 1, employs automatic processing equipment designed and built by Chronar. The tested panel is treated to remove any excess electrically conductive material from the edges and then 4mm wide aluminum foil bus bar contacts are applied to the two 3 ft. edges. Once the free ends of the two bus bars are configured to align with the purpose built connector the panel is covered with a thin layer of proprietary U.V. curing acrylic resin.

A second glass cover sheet 3 x 1 ft. is then laid on top of the resin coated PV panel and after passing through pinch rollers the glass/glass laminate is U.V. cured. Subsequently, once any excess resin is removed from the laminate, polycarbonate "U" cross section frame is applied to the edges. This frame contains two additional sealants; a PIB bead, to act as a water barrier at the edge of the laminate and a silicone layer to act as the frame bonding agent. Finally, the frame is completed with the electrical connection that received the free ends of the aluminum foil bus bars. The completed module is then ready for additional electrical testing including high potential insulation tests and sample environmental testing.

The encapsulation process flow for "cut-plate" products which are used in OEM applications and various consumer products such as the Sunergy[1] Walklite™ and the Solar Sentinel™ differs from the modules process for functional and cost reasons. As can be seen in Figure 1, the 1 x 3 ft. plate is first covered by a mask which covers the bond pad regions of the sections of the plate. A U.V. curing acrylic resin is applied to the panel and is subsequently cured. Following removal of the masking layer, the panel is cut to the required cut plate dimensions and the small plates are tested to electrical and mechanical specifications. Conforming product receives wire contacts and undergoes further electrical and mechanical tests prior to packaging and shipment to the customer.

---

[1] Chronar Trademark

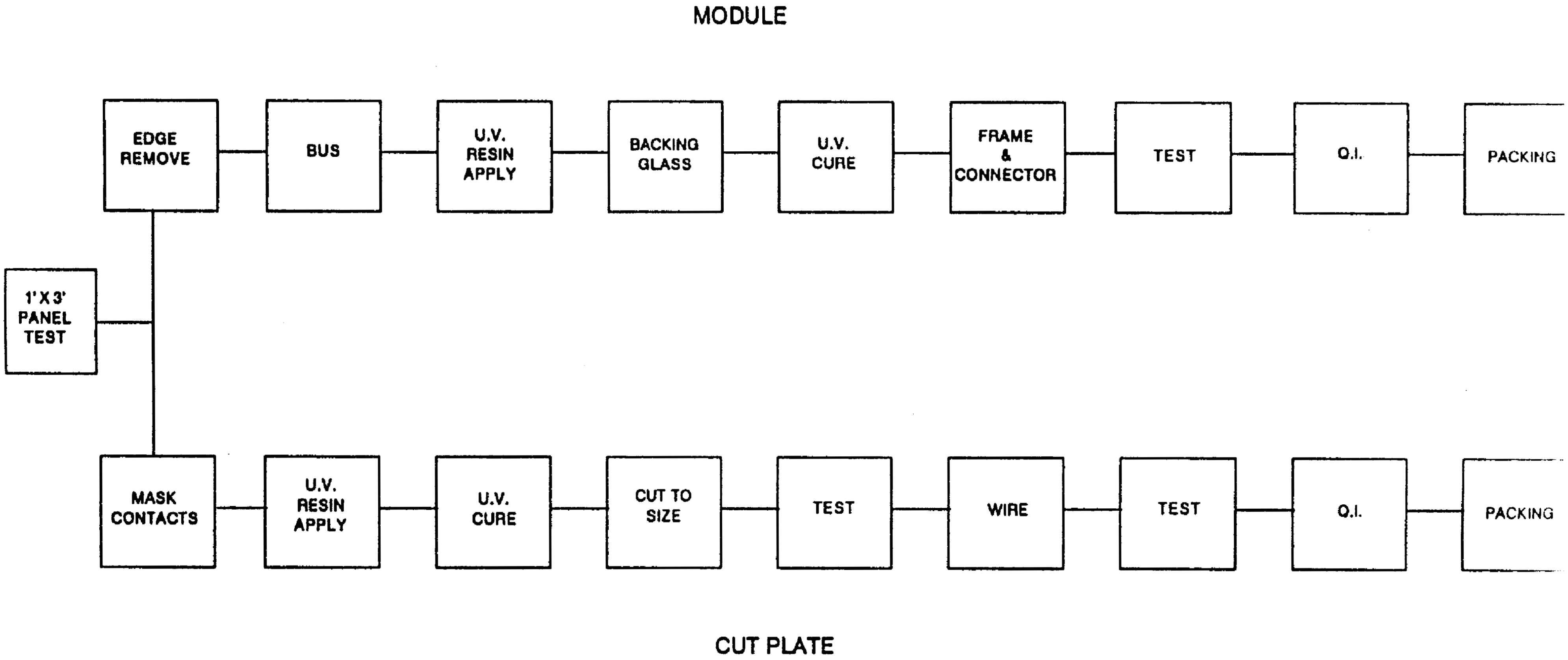


FIGURE 1. Batch Plant and "Cut-plate" Encapsulation Progress Flow.

2.2 Eureka process.

Building on the experience gained in the design and management of the Batch plants Chronar scientists and engineers developed a second generation manufacturing plant, code named "Eureka", which was aimed at meeting many of the deficiencies of the Batch plant product.

Perhaps the two biggest criticisms of the Batch plant photovoltaic modules were the variability in product quality and the low power density. The Eureka manufacturing facility was designed to make high quality low cost 50 Wp (stabilized) power modules at an annualized rate of 10 MWp (stabilized) per year. This was to be achieved by using large area substrates, 61" x 31" x 1/8', and widespread automation. For comparative purposes the stabilized power output per square foot of Eureka is more than 15% greater than that currently achieved in the Batch plants where 3.5Wp/square foot (stabilized) is the norm, furthermore encapsulated Eureka modules can successfully pass all of the stringent environmental tests defined in the SERI document "Interim Qualifications Tests and Procedures for Terrestrial Photovoltaic Thin Film Flat Plate Modules"[2] something that Batch plant modules product was unable to do.

Figure 2. indicates the simplified process flow that occurs in the 10MWp Eureka production line. Standard soda lime float glass, following cleaning, is passed into an atmospheric chemical vapor deposition system (APCVD) where the TCO (tin oxide) is deposited. The appropriate scribe pattern in the TCO is achieved by means of Nd. YAG lasers (L1). The amorphous silicon (a-Si) semiconducting layers are then deposited simultaneously to 48 substrates in a single chamber plasma enhanced chemical vapor deposition system (PECVD). The a-Si is patterned by frequency doubled Nd. YAG lasers at L2. The back contact layer, typically aluminum, is then deposited by D.C magnetron sputtering in an in-line system. The back contact is patterned by lasers L3, similar to those used at L2, and the resulting functional panels are tested at I-V test station I-V1. Up to this stage the plant has been designed to operate in a fully automated fashion. The encapsulation process however is semi-automated here panels are laminated to another sheet of soda lime glass with EVA and are finally tested at I-V2.

At present the Eureka system, which is situated in Trenton, N.J, is in the process of manufacturing 50Wp power modules for the PVUSA project and is ramping up its production rate from one or two runs (48 - 96 panels) per day to four per day by August 1991. With the exception of several pieces of the automated glass transport system

---

[2] R. DeBlasio, L. Mrlg and D. Waddington. SERI/TR-213-3624:UC Category:270, DE90000321.

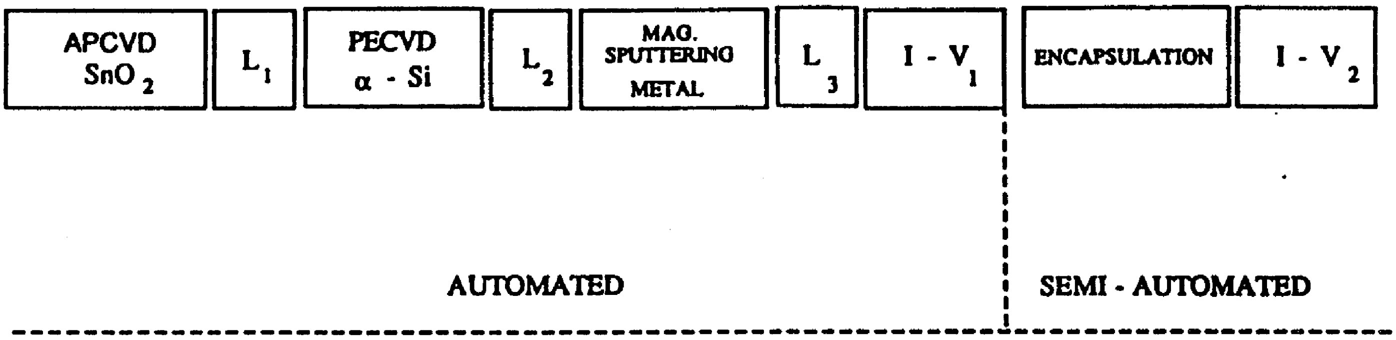


FIGURE 2. <u>SCHEMATIC "EUREKA" 10MW_p PRODUCTION LINE</u>

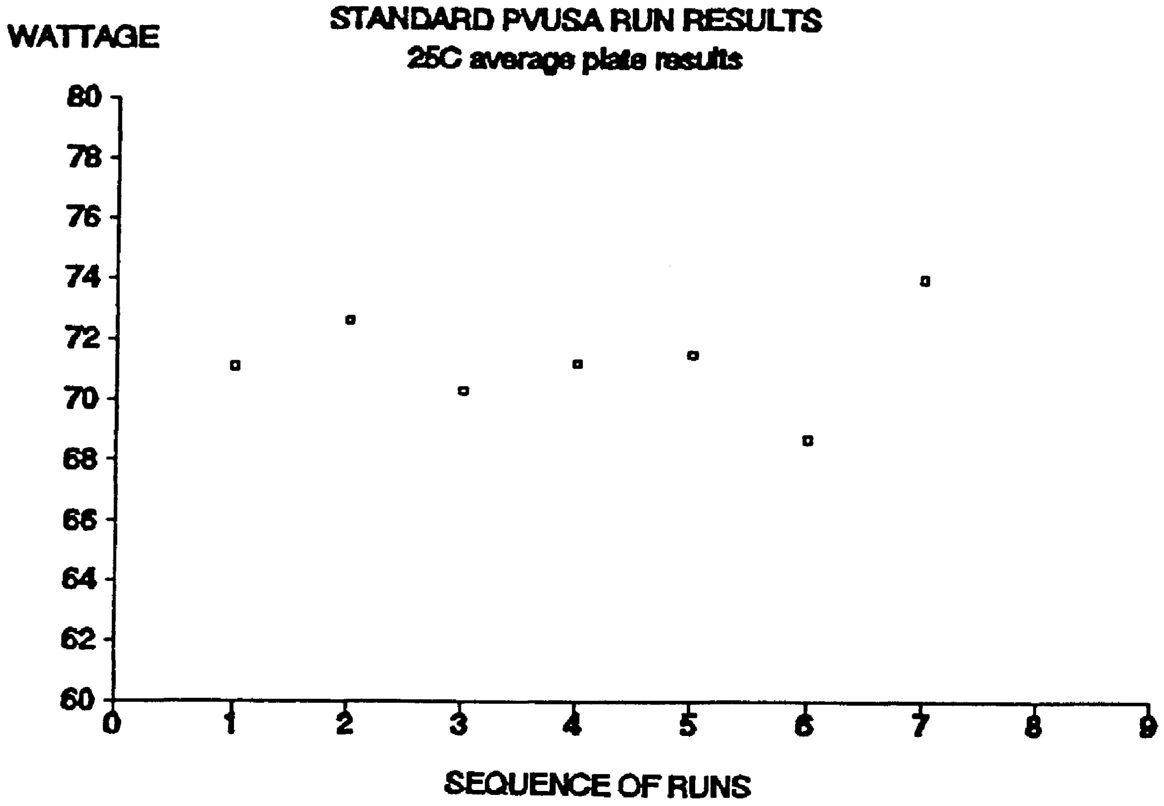
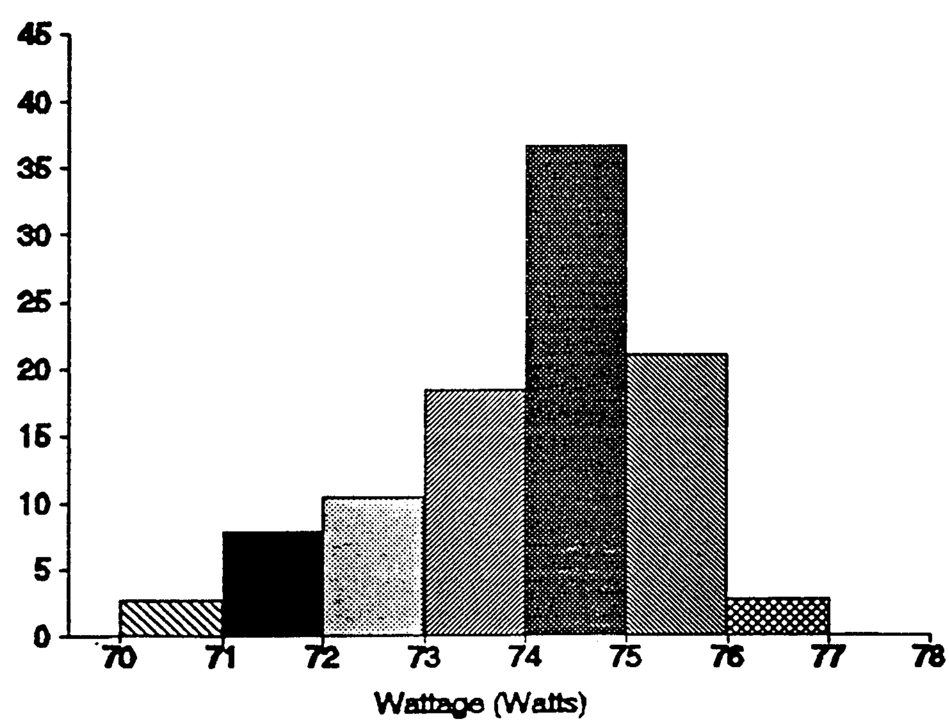


Figure 3. Typical "Eureka" average batch wattage results.

Figure 4. A typical power distribution in a Eureka run



the plant is operational. Figure 3 shows the average panel wattage for 7 consecutive production runs, ie. a weeks production, and figure 4 shows a "typical" distribution of plates within a run. These figures show that the defined manufacturing process is very reproducible and the spread of panels within a run are very tight. These are important requirements for a manufacturing process which is to result in a low cost, reliable photovoltaic module.

Although the encapsulation process is only semi-automated the module design is such that the minimum of labor is required to operate this important step of the manufacturing process. This simplified power module, as compared to the Batch plant product, reduces the cost of the operation and results in a more reliable product. In figure 5 a process flow diagram indicates how a power module is manufactured to meet the stringent environmental requirements of the PVUSA US1 project.

A panel which meets the electrical and mechanical specifications first has the edge conductive layers removed and then receives an aluminum bus down each of the 61" edges. In a parallel operation a piece of backing glass receives a layer of ethylene vinyl acetate (EVA) and a sandwich is formed using the two sheets of glass with the EVA acting as the connecting layer. The EVA layer is subsequently cured at an elevated temperature and the glass laminate is formed. The module is finalized by attaching aluminum mounting brackets and wires and connectors. The finished module is then measured at the final test station I-V2, a comparison is made with the initial panel measurement, and if it conforms to the product specifications is forwarded to representatives of the Quality Department for final inspection.

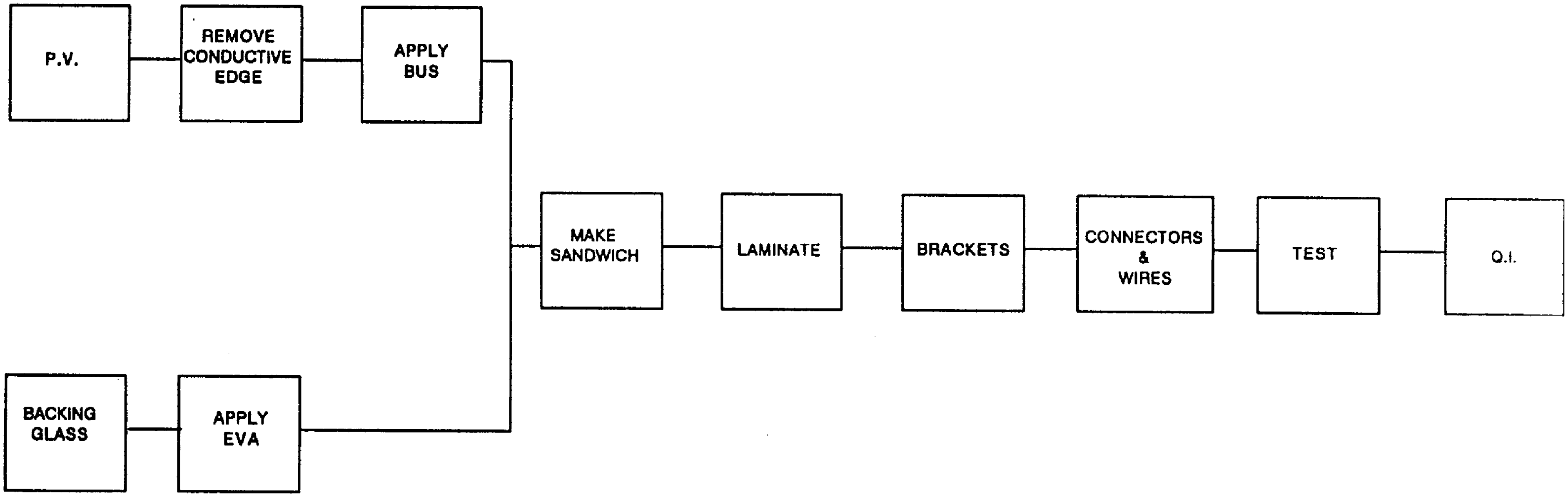


FIGURE 5. Process Flow for Encapsulation of Eureka Module.

2.3 Advanced Photovoltaic Systems, Inc.

The original Phase I PV Manufacturing Technology proposal concerning the Eureka large scale amorphous silicon production process was submitted by Chronar Corporation. At that time, all of the technology relating to the second generation production plant was owned by Chronar. This technology has been created in the course of building a $13 million Eureka production line for the Sheet Metal Workers' National Pension Fund (NPF) pursuant to a Sales Agreement dated December 30, 1987. At the time the Sales Agreement was established, NPF had retained Chronar to select a site for a permanent Eureka production facility and to manage the facility on start up. Subsequently, Energetics Jungere Corporation (EJC), which is the immediate parent of Advanced Photovoltaic Systems, Inc. (APS) assumed these rights. APS was founded in 1990 being 100% owned by EJC, who, in turn, is 94% owned by NPF.

In November of 1990, Chronar's rights to operate the Eureka equipment were terminated and APS took an assignment of the lease on the Trenton facility where the equipment is currently housed. Since that time, EJC and APS have taken control of all operations at the Trenton facility. Title to each item of the Eureka production equipment had passed to EJC at the time delivery was made by Chronar to the temporary facility at Trenton. In addition to owning the Eureka production equipment, EJC purchased the Eureka technology from Chronar in September, 1990.

After Chronar decided to file for protection of the creditors under Chapter 11 of the US Bankruptcy Code on December 12, 1990, APS hired substantially all of the scientific and technical personnel formerly employed by Chronar, including Dr. Christopher Sherring, who authored much of the original proposal and Dr. John Macneil, who is identified as the Principle Investigator under the SERI contract. In short, by the end of 1990, EJC and APS had acquired: (i) the Eureka equipment constituting the entire "hardware" of the Eureka production facility, (ii) the know-how, trade secrets, patents and other "software" constituting the Eureka technology, (iii) the leasehold interest in the Trenton facility where the production facility is housed and (iv) substantially all of the scientists and technicians who had conceived of and worked on the Eureka project and the Phase I contract bid.

Since December of 1990, APS has committed its research and development resources to the enhancement of the stabilized efficiency of the single junction amorphous silicon photovoltaic layers as currently used in the Eureka manufacturing plant and continued the development of a new form of module encapsulation capable of passing the new wet high pot tests with a 5 ft. x 2 1/2 ft. module. Engineering resources have been focused on optimizing the uniformity of the Eureka production to the point where the latest runs have achieved average initial efficiencies consistent with the production goal of 50 watts stabilized per module.

APS currently has approximately 100 employees, the majority of whom have specialist scientific and engineering training. In addition to the considerable Eureka plant, APS is presently seeking ownership of the substantial research and development plant that it presently uses under an agreement with Chronar.

Negotiations have recently been concluded with the Photovoltaics for Utility Scaleable Applications (PVUSA) project regarding the award of a contract to APS for the completion of Eureka module qualification testing and the installation of 480K watts of single junction large area modules at the Davis, California site. Signing of the contract will be awarded shortly. The current schedule for qualification testing and the production of the necessary 9,600 modules will enable the full system to be installed by the end of 1991.

The permanent site for this Eureka production plant has been identified as Fairfield, California and the groundbreaking will occur on June 7, 1991. The current plan will see the plant fully installed and operational in a 60,000 sq. ft. purpose built factory by the end of 1992.

Once the first Eureka plant is optimized and shipped to its permanent location in California in 1992, APS intends to commence work in New Jersey on the second Eureka equipment set. Besides this, the major US commitment to amorphous silicon photovoltaic production, APS is also committed to optimizing the stabilized efficiency of similar band gap amorphous silicon multijunction modules for ultimate use in the Eureka production process and eventually in PV systems. To this end, APS has recently submitted a multiyear proposal to SERI under RF-1-11091 on Tandem Amorphous Silicon Modules and is currently preparing a proposal in response to RF-1-11061 for Amorphous Silicon Utility/Industry Photovoltaic Power Project in conjunction with a major western private utility.

3. Task 2. Manufacturing potentials envisioned to lead to significantly increased production capabilities and reduced manufacturing costs.

As opposed to the approach adopted by the semiconductor industry in the manufacture of integrated circuits where low yielding, high volume processes are deemed to be acceptable, APS feels that the way forward for the manufacture of low cost, thin film amorphous silicon based solar products should parallel that of industries such as paper and glass manufacture where highly automated plants typically employ highly refined in-line process and quality control systems.

With this comparison in mind, the overall approach that we intend to follow to significantly increasing the production capability of the Eureka manufacturing system and, simultaneously, reducing costs of fabricating a photovoltaic panel will be governed by the following factors, namely:-

1. Product design.
2. Automation.
3. Encapsulation
4. Real time process and quality control.
5. Reduction of loss mechanisms.

Clearly each of these categories has a strong bearing on the others and as the final product will be influenced by all of the above compromises are often necessary to produce the "best" product.

3.1 Product design.

Product design has not received the attention that it should have received in the development process for thin film solar products. Historically, the majority of photovoltaic products have been rather poorly designed by scientists who design the type of product that they would like. This approach is inefficient as it rarely addresses the following key issues which are of vital importance to a volume manufacturing business, namely:-

* Market demand.

* Quality

* Cost of manufacture.

3.1.1 Market demand.

As a number of products are likely to be manufactured by APS Inc. from "Eureka" material it obviously makes sense to design cost effective, quality products that meet a market demand. For utility type applications where cost/Wp is the overriding criteria of choice for the customer, the product should clearly be developed with this in mind, hence, attention should be paid to cost and functionality and not to cosmetic appearance etc.

When products are destined for either specialist OEM or consumer type applications, where typically a higher $/Wp is available for the manufacturer, additional issues must be addressed such as cosmetic appearance, packaging, size, etc.

By dedicating relatively modest resources in this area, a manufacturing facility will be able to yield much utilization of the photovoltaic panels it makes and, in turn, reduce the cost of all the products.

3.1.2 Quality

Quality must be designed into a product on the CAD system, not inspected out at final outgoing inspectors. The success for the Japanese automotive industry is, to a large extent, based on designing quality into its products. Aside from the (obvious) serious cost penalties named by scraping a product, at the end of the line, an efficiently designed product tends to be cheaper to manufacture than a poorly designed product. Savings are thus two fold and the customer receives a better quality product then he might otherwise have received.

3.1.3 Cost for Manufacture

By addressing the customers needs and the relevant quality issues the most cost effective method to manufacture products can be established. Examples of some of the factors that should be considered at this design phase are:

- raw material cost reduction vs. increased labor content vs. reliability
- cost of product weight reduction vs. cost of delivering product to customer

3.2 Automation.

Only by extensive use of sophisticated automated equipment can one expect to make low cost, large area, reliable photovoltaic product in volume.

The Eureka facility was designed to be ultimately capable of making a 50Wp module every 90 - 100 seconds a task that could only be realistically achieved by extensive use of automatic glass handling equipment and computer controlled process systems.

In the Eureka manufacturing system, a similar rational could be applied for any similar manufacturing operation however, automation can bring the four following advantages which ultimately result in a more efficient, an hence more cost effective, manufacturing operation which will in turn result in lower cost photovoltaic products.

* Throughput.

* Reproducability.

* Control.

* Reduced labor requirement.

3.2.1 Throughput.

By increasing the throughput of panels and modules through the manufacturing line one can fully utilize the expensive thin film processing equipment to its maximum and reduce the depreciation contribution that the capital equipment has on the final cost on the photovoltaic products.

For a 10MWp plant which costs $20 million to make, with a 100% yield of 50Wp modules, which is to be depreciated over 5 years, disregarding additional costs associated with the initial financial commitment, a cost of 40c per Wp can be attributed to depreciation or $20 per module. As the relationship between the number of modules manufactured, presumably largely a function of demand, and the cost penalty per panel associated with depreciation of the plant is inversely proportional, it is desirable to maintain as high a volume of production as possible that can be sold.

It is worth noting that on occasions it is not merely the fact that employing sufficient personnel to meet the Eureka plants plate and module glass transport needs would be exceedingly expensive but also many tasks could not be safely carried out by humans at the rate that can be achieved by a machine .eg. moving substrates when they are hot or aligning 20 lb panels to a fraction of an inch.

Below in figure 6 are three scenarios for a $20M plant running at differing rates. If we assume a direct cost contribution of $1 per watt peak ie. $50 per module, we can examine the effect that increasing the useful throughput of the plant can make on the cost of the product. At 2.5MWp per year, the plant is running at a saleable 50Wp module every 400 seconds as the capacity of the plant is increased to 7.5MWp per year (133 sec per module) and ultimately to 15MWp per year (66.7 sec per plate), the total cost as depicted in Figure 6 falls from $2.6 to $1.26 per watt peak with no increase in the cost of the plant. Indeed the reality of the situation facing the owner of the manufacturing facility is that he will be able to reduce the direct cost of the product as the volume he makes increases due to economies of scale.

3.2.2 Reproducability.

As the task of moving the panels and modules through and between each processing step becomes more demanding, due to, for example, exacting mechanical tolerances or complexity of operation, it becomes increasingly undesirable to have humans involved as there skill in carrying out a function will effect the ultimate efficiency and reliability of the average module.

Several examples of the detrimental involvement of operators in the handling of Eureka panels and the setting up of the alignment of certain systems can be seen in table 1 below. The data was taken from a Q.A audit carried out before more advanced (automated) glass transport and control systems were introduced into the Eureka facility.

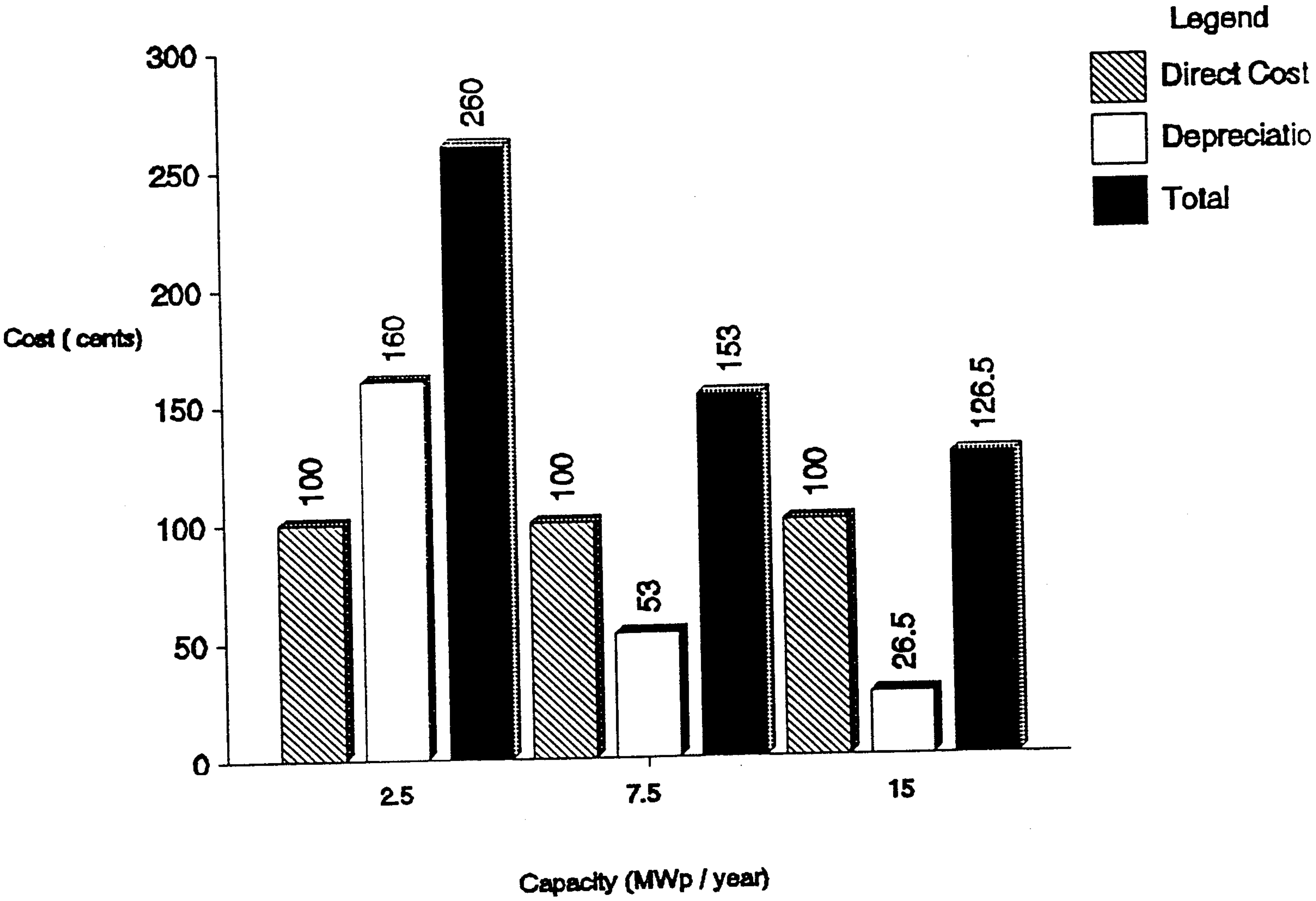
	Total processed		Rejects.		
		SnO2	Si	Al	Total
No Panels	336	16	19	9	44
Percent	100	4.7	5.7	2.7	13.1

Table 1. Rejected panels from 7 consecutive Eureka runs.

By careful equipment design and the appropriate glass transport system, 9 of the 44 were due to poor alignment of the systems the other 35 were due to mechanical damage to the superstrate, all of these defects could be avoided. As all of the defective parts were scraped, this is a very significant area for cost reduction.

As the method for fabricating the product becomes more sophisticated, it is anticipated that reproducability in the

Fig. 6 Breakdown of direct,depreciation and total costs for 3 production levels



manufacturing process will become increasingly important.

3.2.3 Control.

Through the extensive use of computer controlled equipment either for the active processing steps, such as tin oxide deposition or silicon deposition or the passive steps such as the movement of superstrates through the line, it is possible to ensure a degree of reproducability in the processing of the photovoltaic modules. Clearly the greater the control the machine has on the "critical parameters", those parameters which have a significant direct effect on the properties of the device or module, the tighter the distribution of parts processed and ultimately the higher efficiency, more reliable and cheaper the photovoltaic module will become.

There is a large number of parameters that could be monitored and controlled when manufacturing a complex product such as a solar cell, hence, the choice of critical parameters is vital for the maximum benefit to be achieved from the control system. The choice of these parameters is initially the result of laboratory Research and Development, typically, on small area devices, and the fundamental understanding that is the outcome of this type of study. Hence, a-Si PECVD deposition parameters such as pressure, flow rate, power, temperature etc. are all controlled in a similar fashion in the manufacturing environment as they were in R&D. Once the process is "scaled up" to a manufacturing level, however, disparities between the small and large reactor become apparent hence additional controls must be set in place. These addtional controls will result from R&D type studies on the manufacturing system or by the implementation of process control type systems such as Statistical Process Control (SPC).

Further benefits of the extensive use of PC controlled systems results when the individual systems are networked. This not only allows the individual system to operate at their optimum rate, for maximum throughput, but also enables the effective implementation of SPC, real time process control and quality system. As information from the beginning to the end of the line is available within the system, it will be of use for manufacturing planning, inventory, stock control and maintencance purposes.

3.2.4 Reduced labor requirements.

As the level of automation within the APS Eureka facility increases the requirement for direct labor in the manufacturing process will steadily fall. A considerable saving is expected to occur in direct cost of manufacturing a module as a result of automation.

3.3 Encapsulation.

One of the most common modes of failure for thin film module, in general a-Si based, in the field has been that of deterioration of the encapsulation of the product resulting in the corrosion of the thin film layers followed by rapid degradation of the module. As a result of these failures, a-Si modules have received a poor reputation and are rarely used in applications that require a reliable source of power generation. Hence, it is, therefore, essential that the a-Si based products encapsulation meets the expectations of the customer, this could vary from a 10 year warranty for the systems professional to a 5 year lifetime for the consumer product customer.

The main purpose of encapsulation is protection of the fragile thin films. Also the encapsulated product should be convenient to mount. These requirements translate into mechanical strength and electrical and electrochemical corrosion.

The requirements for mechanical strength is fairly obvious. The photovoltaic module is mounted outdoors where it is liable to wind loading and damage from hail. The need for stringent electrical and electrochemical isolation is less obvious. Small electrical currents flowing to and from the thin films can result in electrochemical corrosion if water is present in even minute quantities. Destruction of the thin films can rapidly result, due to the small mass of the films.

The structure of an APS "Eureka" module is glass/pv thin films/EVA laminate/glass. The Eureka modules are mounted by means of brackets and glued to the cover (backing) glass. Since glass is impermeable to water, the only leakage paths which could result in electrochemical corrosion are at the edges of the module. Removal of the thin films for a distance of 0.5" in from the edge gives the necessary isolation. There is no frame. The Eureka module is strong and well isolated.

The priorities for an encapsulation process which could be successfully applied to a thin film, in this instance a-Si based, device on a soda-lime glass superstrate can be summarized as follows:-

* Protection of thin film layers.

* Low cost.

* Low weight.

* Easy to mount in system.

* Minimize loss of panel output.

3.3.1 Protection of Thin Film Layers

By using the qualification tests described in the "Interim Qualification Test and Procedures for Terrestrial Photovoltaic Thin Film Flat Plate Modules" as a minimum requirement for the level of encapsulation for a power module product and accepting, a some what more relaxed specification for consumer products, sub 50 Volt applications, which do not need to pass the wet high pot or the wet insulation resistance tests the encapsulation problem is reduced to achieve the above requirements with the best compromise of the other factors.

3.3.2 Low Cost and Weight

The direct cost breakdown of the existing APS "Eureka" power module, excluding the cost of the superstrate or labor, is presented in figure 7. It can be seen that the sheet of EVA accounts for about 1/3 of the total cost and the backing glass and connectors attributing 1/4 or 1/5 of the total cost respectively. The direct cost of a Eureka power module is approximately $14 per plate as broken down in Figure 7. Cost reductions which do not significantly adversely effect the quality of encapsulation are to be found in all of the significant areas. It is anticipated that the direct cost could be reduced to $10 per panel during the course of this study for a similar power module by carefully refining each key cost area. It should be noted that as we intend to reduce the cost of encapsulating each panel that if the wattage of the module increases the cost of encapsulating each watt will be reduced in direct proportion to the rise in efficiency.

Labor, which at present runs at about $5 per panel will be addressed by improved product design and the greater use of automation. This figure could fall to $3 per panel with a simplified, more automated process.

As it is unlikely that only one product type will be manufactured by APS, Inc. "Eureka" facility the encapsulation aspects of "sub-modules" i.e. section of a 2 1/2' x 5' panel, which could be used in consumer types of applications,should also be addressed.

As most of the cost reductions are associated with using fewer materials it is hardly surprising that a by-product of the cost reduction exercise will be the reduction of the weight of the product. It is unlikely, based on APS "Eureka" manufacturing facilities panel configuration, ie. float glass/thin film layers, that any useful weight reduction could be achieved without directly reducing the product cost.

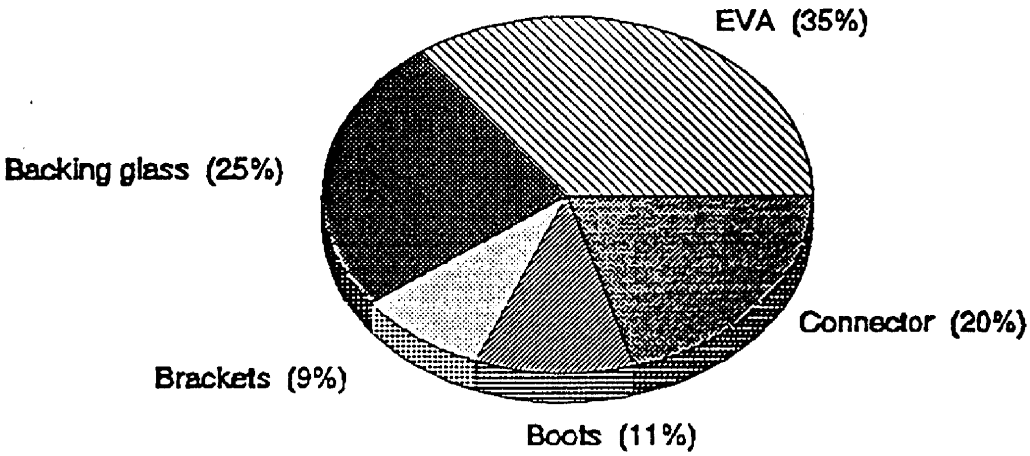


Figure 7. Direct cost breakdown for encapsulation.

3.3.3 Ease of Mounting

The method of mounting a module or "sub-module" is strongly dependent of the mounting structure that is available for the customer. This could vary from a professionally designed support structure which could accommodate thousands of modules for a small power station to a tree for a single sub-module in the field. With the above examples as the extremes it is clear that a variety of differing methods of supporting or mounting modules are required. The ideal situation would be for one universal mounting method to avoid the additional cost associated with a diversity of products.

3.3.4 Minimize Loss of Panel Output

The border isolation around the edge of the module and the attachment of the busbar result in over a 5% loss in active area for the present APS "Eureka" power module. The width of the isolated area could be decreased if the surface conductivity of the glass in that region could be decreased. We have observed that the method used to remove the thin films at the border damages the glass, increasing its conductivity. A more benign method of removing or masking of the appropriate deposition processes would eliminate this problem. Therefore the width of the isolated border could be decreased, increasing the active area of the module.

An alternative method of busbar attachment which does not decrease the module active area, the loss at present is about 1.5%, has been found and if it proves to be successful the total loss of active area in the module could drop to 2% of the total area.

3.4 Real Time Process and Quality Control

In an attempt to reduce module production costs, increase module performance and throughput, the Eureka photovoltaic manufacturing facility must fully automate production and quality control. In order to perform the above tasks, we must be able to:

A. Increase the predictability of the process.
B. Identify the cause of extraneous variables.
C. Evaluate the process without interrupting it.

With the use of distributed data acquisition and control systems, statistical process control (SPC) can be incorporated into the process(es) which can be a very useful tool. By using SPC in the manufacturing environment, we can define the relationship between process parameters and resulting product attributes (eg. film thickness, uniformity, and conductivity), we are able to detect and correct causes of variation, and quantitatively measure the process capability. By interpreting data consisting of numerical values from gauges and the status of alarms and switches, the probable cause of process disturbance can be determined. Some of the SPC displays that could be incorporated into the Eureka process without interrupting it are: Xbar and Range Display, Histogram Display, Median and Range Display, and a x-y plot Scatter Diagram.

Quality control plays a big part in the overall theme of real time process control. The data from automated processes is the result of sophisticated inspection, testing, and in-process measurement devices. Quality Control measurement on the photovoltaic device during its fabrication can be used in making a quality product and to determine whether or not a need exists to recalibrate, adjust or repair equipment. Some of the quality control measurements that are performed but could be automated are: glass washer water, SnO_2 uniformity and sheet resistance, cell isolation, film thickness, Al sheet resistance and cell isolation.

Timely information is the key element to improving productivity and quality and reducing costs. If process variations are determined to be present, efforts can be focus on eliminating them, minimizing their effect, and compensating for them. The main goal therefore in a real time supervisory control system, is to keep the process at its operating capability and bring it back from process variations.

3.5 Reduction on Loss Mechanisms

The light conversion efficiency loss mechanisms that exist in the APS "Eureka" manufacturing line can be, broadly speaking, sub divided into three categories:

* Non-uniformity of layers.

* Active area utilization

* Defects.

In an ideal world one would like have perfectly uniform layers with no defects but however, in a manufacturing environment this is not possible and the effort applied to reducing these loss mechanisms must be studied in the context of a cost vs. benefit basis.

3.5.1 Non-Uniformity in Layers

Before attempting to analyze various loss mechanism, it is best to show where our manufacturing output stands at present. Table 2 provides this information.

Table 2. Manufacturing results based on the six Eureka runs.

Run #	# of plates	$\langle V_{oc}$ (V)$\rangle$	$\langle I_{sc}$ (mA)$\rangle$	<FF (%)>	$\langle P_m$ (W)$\rangle$
220	40	54.5 ± 0.3	1950 ± 35	68.3 ± 1.3	72.6 ± 1.6
221	38	56.5 ± 0.6	1866 ± 37	67.6 ± 1.9	71.1 ± 2.4
222	36	56.4 ± 0.6	1812 ± 33	69.8 ± 1.5	71.2 ± 1.7
223	37	57.2 ± 1.8	1841 ± 31	68.2 ± 1.7	71.5 ± 1.9
224	37	57.5 ± 0.4	1780 ± 45	68.2 ± 2.5	69.8 ± 2.2
225	38	57.2 ± 0.3	1888 ± 29	68.6 ±1.3	74.0 ± 1.3
Average	6 runs	56.6 ± 1.1	1856 ± 60	68.5 ± 0.7	71.7 ± 1.4

In analyzing the above results one should consider the fact that our panels have 69 cells in series with a total area of 157.53cm^2. This gives an average V_{oc} of 0.820V and J_{sc} of 11.8A/cm^2.

We have identified two primary loss mechanisms which limit the power output of our existing module. These are in order of importance:

- a-Si thickness and compositional variations across each panel
- a-Si thickness and compositional variations between chambers of plasma box.

Studies at APS have shown that the thickness across a module is relatively uniform but variations do occur and are greatest in the region of the panel as shown in Figure 8. The effect of the thickness non-uniformity on photovoltaics parameters can best be seen in Figure 9 where these parameters and thickness are plotted along the top-bottom section of a typical panel.

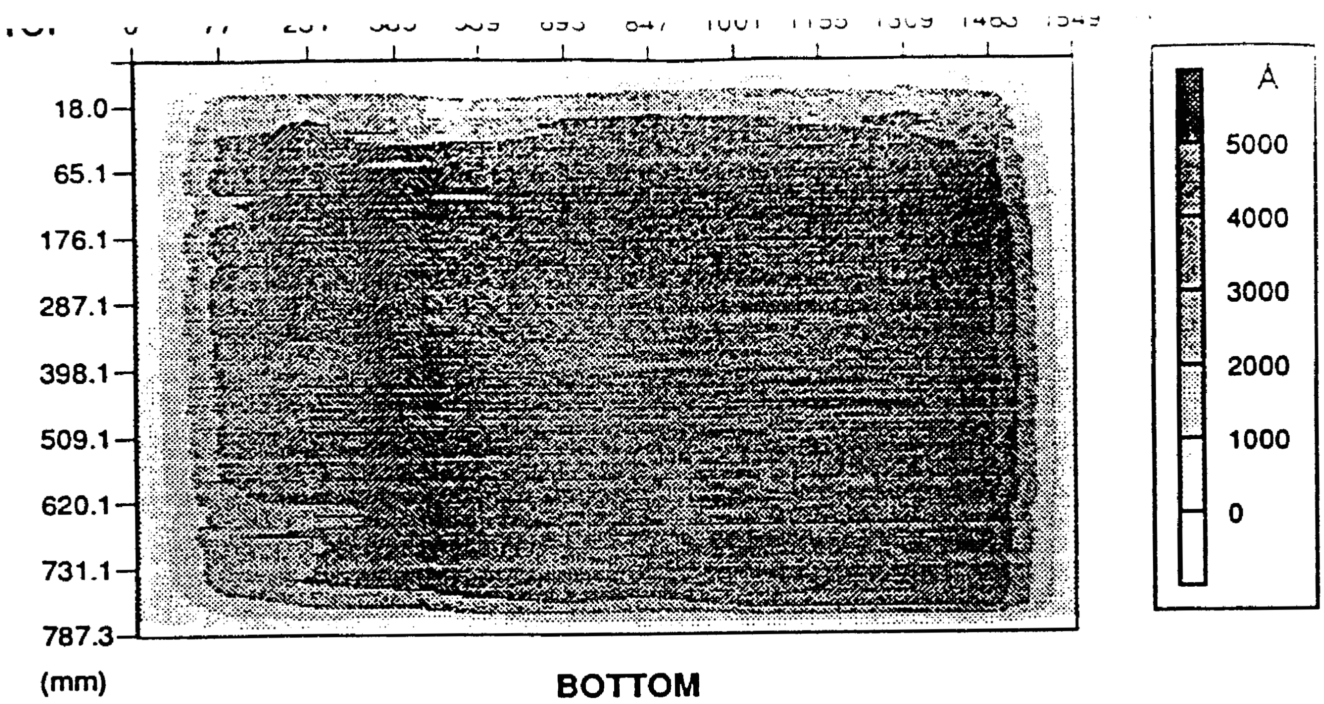


FIGURE 8.   THICKNESS VARIATIONS ACROSS A EUREKA MODULE

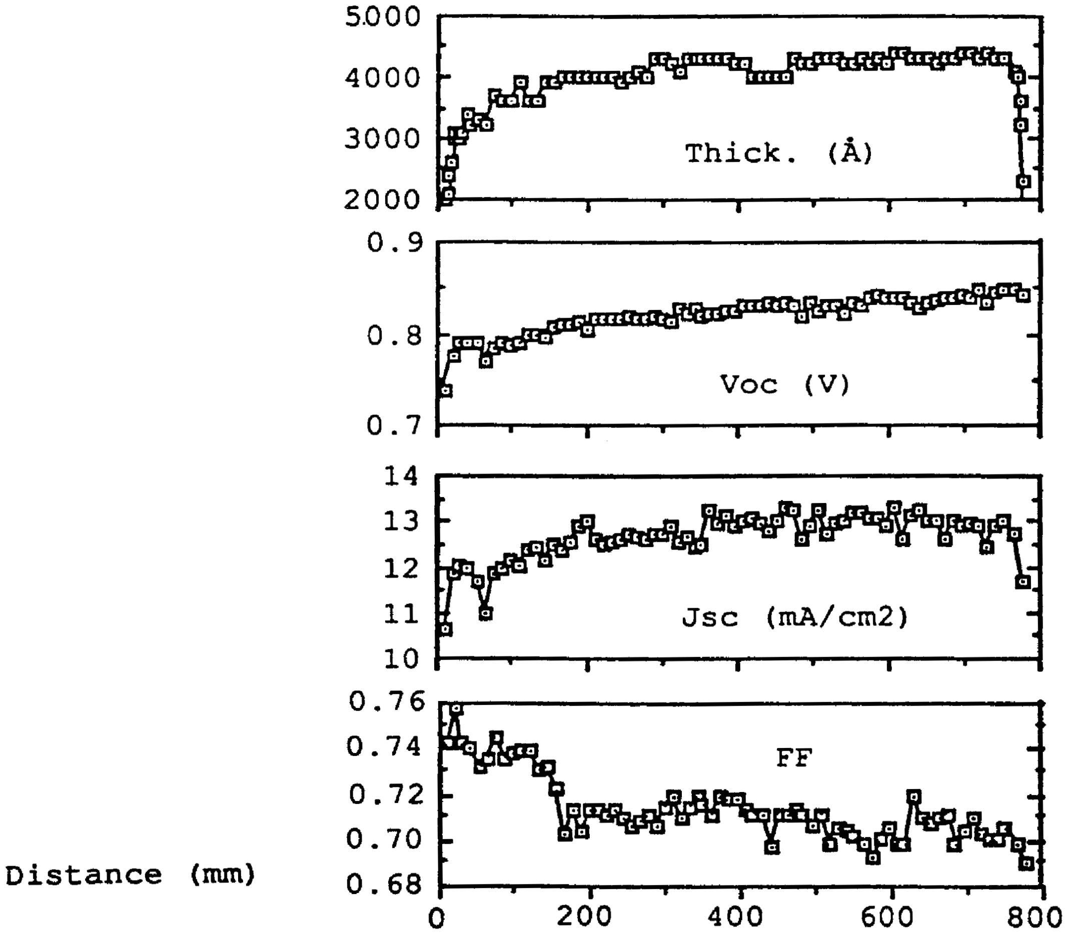


Figure 9. Uniformity of thickness and photovoltaic parameters in Eureka module along the gas flow direction.

Thickness non-uniformity effects the overall current as the 69 cells are connected in series, hence, effects to a lesser degree the overall voltage, in a round about way. As one can see in Figure 9, a current of 13mA/cm^2 has been achieved over a large area of the panel but yet the average is still around 12mA/cm^2 due to the current limiting cells at the top. One can also see that 850mV per cell is also possible since an average of 820mV is caused again by the cells at the top of the panel. Solving the uniformity problem would give 850mV and 13mA/cm^2 at the top portion of the panel, as well, resulting in the panel voltage of 58.6V and the panel current of 2048mA. There is also a non-uniformity in the front-to-back direction (see Figure 8). We have not yet quantified the variations of the photovoltaic parameters along this direction. However, it is believed that the non-uniformities along this direction affect to a lesser degree the overall power output of the panel.

The non-uniformity in RF power absorption from chamber to chamber effects thickness uniformities from plate to plate. This results in a greater standard deviation in the power output of panels. This in turn decreases the total power output of the facility. Thickness variation from chamber to chamber and to certain extent sputtering induced defects such as spitting are responsible for the approximately 3% standard deviation in the panel power output of a given run. We believe that reducing these loss mechanisms would enable us to reach 1% standard deviation level.

Defects caused during sputtering such as spits and flaking result in lower fill factors, this combined with more efficient laser isolation due to uniformity improvements should increase average fill factors from 68% to 71%. These results coupled with the increase in V_{OC} and J_{SC} produce panels of 85 watts average.

3.5.2 Active Area Utilization

Approximately 5-7% of the active thin film layers are lost due to three laser scribing stages involved in making the monolithic device. With the appropriate control systems it should be possible to minimize the loss to 3% with the direct increase of panel efficiency by 2-4%.

3.5.3 Defects

Defects of concern here are primarily film imperfections that cause shunting in the solar cell. The module power output is reduced by such shunting, and minimization of such losses is considered here, defects in the microscopic structure of the silicon, such as those influencing device performance and/or the Staebler Wronski effect are not considered here. Defects in the spatial uniformity of layers are not considered directly, but are considered in the way non-uniformities affect the occurrence of shunting defects.

The structure of large area solar cells manufactured at APS is Glass/TCO.a-Si:H/Aluminum, where TCO denotes the transparent conductive oxide at the front of the cell, and a-Si:H denotes the amorphous silicon hydride semiconductor device material. These cells are connected in series within a module by means of the standard lasered three-scribe configuration, and with such interconnection, there are three paths by which shunted power can be lost from the cell: 1) aluminum to TCO, 2) Aluminum to Aluminum, and 3) TCO to TCO.

The shunting defect status of a module fabricated on an APS SnO_2:F coated superstrate is given in Table 3. A shunt identification chart is also attached, more details on the classification system used here is included in Section 4.5.2. Module 41, although a 75Wp plate experiences significant shunting, mainly due to poor isolation at the edge isolation scribe, laser induced shunting in its bottom half, and isolated (but severe) pin holes throughout.

Using the tabulated isolation resistances for each cell, which were measured near the power point voltages of the cell (about 0.7 volts) we calculate a shunt quality , $Q_S = 96\%$. Thus, according to our modelling, the unshunted module power output would be 75/0.96 - 78Wp.

Shunt quality on our standard product varies from 85-98% on average hence efforts spent addressing the various causes of shunting will significantly influence the power output of a module, without incurring any additional direct costs.

ET21901H-41	Voc	Isc	FF	Pw	Eff	Rs	T
(Normalized)	56.2	> 1994	< 66.8	74.9	7.2	---	25

Cell #	R_i (Ω)	Defect Type And Comments	Cell #	R_i (Ω)	Defect Type And Comments	Cell #	R_i (Ω)	Defect Type And Comments
1	7.0	ISO, DA	24	13	P	47	17	
2	0.7	ISO, DA	25	29		48	29	
3	21	ISO	26	29		49	20	
4	18	ISO	27	20		50	26	
5	23	ISO, Sp	28	9.0	Sp, $L_{c,r}$	51	9.6	$L_{c,r}$, ISO_l
6	20	ISO, Sp	29	8.3	L_r	52	15	$L_{c,r}$, ISO_l, P_c
7	14	ISO, Sp	30	9.4	L_c, ISO_l	53	10	$L_{c,r}$, ISO_l
8	11	ISO, Sp	31	8.7	L_c, ISO_l	54	22	
9	2.2	ISO, Sp, B	32	8.2	L_c, ISO_l	55	61	
10	25	ISO, Sp	33	8.0	L_c, ISO_l	56	53	
11	13	ISO, Sp, 3P	34	7.8	L_c, ISO_l, $3P_c$	57	80	
12	16	ISO, P	35	7.5	L_c, ISO_l, P_c	58	42	
13	14	ISO, P	36	6.6	L_c, ISO_l, P_c, P_l	59	29	
14	32	ISO, P	37	8.4	L_c, ISO_l, P_l	60	95	
15	10	ISO, L	38	7.6	L_c, ISO_l	61	45	
16	40		39	9.0	L_c, ISO_l	62	5.9	B_l, P_l
17	12	ISO, L	40	6.0	L_c, ISO_l, LL_c	63	15	Sp_c
18	11	P	41	8.2	L_c, ISO_l, P_c	64	55	
19	20		42	5.9	L_c, ISO_l, $2P_c$	65	35	
20	20		43	6.0	L_c, ISO_l, DA_r	66	25	
21	21		44	6.0	L_c, ISO_l, DA_r	67	84	
22	26		45	8.1	L_c, ISO_l, Sp_c	68	20	
23	20		46	26		69	5.8	DA_a

ote: See text for explanation of defect type code
- Multimeter 200 Ω Range overload

TABLE 3. DEFECT STATUS OF A EUREKA MODULE

Shunt Identification Code

B	Bridge, from aluminum to aluminum
Bu	Burnish, a mechanical abrasion apparently caused by a blunt instrument.
DA	Defect Area, a region of concentrated shunting (further explained in text).
ISO	Isolation Scribe problem.
IPH	Isolated PinHole, usually large isolated shunt.
LL	Local Laser shunt (probably induced by other than laser parameters).
LPH	Large PinHole
PH	PinHole, or PinHoles, ut fairly isolated from one another.
S	Spit, probably produced by aluminum sputtering.
Sc	Scratch, a mechanical abrasion apparently caused by a sharp instrument.
Sm	Smoky area, powdery appearance, origin not known, usually small.
Sp	Speck of something, perhaps a spit, or scratch, or other, but too small to identify further.
2,3...	Number of appropriate defects.

Subscripts

a	All area.
c	Center of module.
l	Left side of module. for off # modules, left side is front of chamber; for even # modules, left side is back of chamber.
r	Right side of module.

4. Task 3. Problems impeding the achievement of those potentials.

A wide range of problems must be investigated and solved if the potential benefits defined in Section 3 are to be achieved. Due to the diversity of the problems being confronted, from solid state physics, mechanical engineering, production engineering to quality control, a multi-disciplinary team of expertise is required.

APS will allocate adequate resources to address the four areas that we expect to deliver the maximum benefits for improved performance, reduced manufacturing costs and significantly increasing production.

4.1 Product Design

Detailed market intelligence information must be acquired before the photovoltaic module or panel can be efficiently specified, in terms of electrical performance, encapsulation requirements, mechanical specifications, etc., and the design phase can begin.

With the "Eureka" facility operating in its most efficient fashion, in terms of usage of processed square feet of photovoltaic panels, with a mixture of products ranging from power modules to "sub-modules" and consumer products it is essential that APS can establish the pertinent specification rapidly.

It is likely that representatives of APS Sales and Marketing functions will conduct a detailed thin film (a-Si based) study to obtain the relevant information to overcome this impediment.

With the idealized specification in place the products can be designed with the aid of CAD. At the earliest possible stage design reviews will be held to establish the critical manufacturing and quality issues that must be defined and subsequently solved to enable the product to be assembled in an efficient, cost effective, reliable fashion. Design tolerances for each component must be defined and the relevant controls put in place to enable the yield of the product to be maximized with the generation of the minimum of non-uniforming product.

4.2 Encapsulation

The potential manufacturing improvements in encapsulation, as defined in Sections 3.3, could be achieved if the problems in the four following areas can be successfully solved.

* Simplification of module design

* Reduction in organic [EVA] requirement in modules.

* Reduction in active area loss due to encapsulation

* Develop encapsulation lamination process for large area glass modules.

4.2.1 Simplification of Module Design

By critical examination of the components incorporated in manufacturing the module or sub-modules cost reduction can be expected (value engineering) and if the product is designed to take advantage of automation the labor content of the encapsulation process can be minimized. By adopting a simplified automated approach to this step of the manufacturing process, a cheaper more reliable product will be the outcome.

4.2.2 Reduction in Organic [EVA] Requirement in Modules

With 18 mills of EVA, as used in the APS 50 Wp (stabilized) power modules, contributing to approximately a quarter of the total direct encapsulation material cost it is important that for cost reduction purposes that this costly polymer is either used in smaller quantities or a cheaper replacement material is found.

This demanding task must be addressed if the very aggressive cost target is set in Section 3.3 are to be met. Problems associated with the electrical isolation and mechanical adhesion properties of thinner layers of EVA and the possibility of replacing EVA with an inorganic [e.g. Si_3N or SiO_2]/polymer multilayer where the polymer does not require the insulating properties that exist in the costly EVA must be addressed.

4.2.3 Reduction in Active Area Loss Due to Encapsulation

Processes that enable the removal of relatively small area of conductive material at the edge of the module and yet may leave a highly insulating perimeter to the product will have to be developed for implementation into the manufacturing process. The loss of active area due to conductive bus bar attachment will also need to be solved by an alternative method to that being employed in the existing APS power module.

4.2.4 Develop Lamination Process for Large Area Glass Modules

The vacuum laminator process presently being employed in the "Eureka" manufacturing line was designed specifically for use in crystalline and polycrystalline module encapsulation. It is not appropriate for use in a high volume thin film on glass manufacturing line. The "clam shell" style of laminator commonly used in crystalline module lamination works in a batch mode and typically has a cycle time of 8-12 minutes. Due to the thermal mass of the "Eureka" glass laminate this process can prove to be difficult to control and at 8-12 minutes is exceedingly time consuming in comparison with the other aspects of the encapsulation process. As it is the rate limiting step in the encapsulation process flow this entire process requires a great deal of attention.

Some key problems that require to be addressed center on equipment and process design of an EVA laminator which is specifically designed for large area glass modules. The ideal machine would be "in-line" and, hence, would enable lamination process to be sped up and hence more extensive use of automation could be justified.

4.3 Automation

As the control aspect of automation has a significant impact on the introduction of real time process and quality control into the manufacturing environment, we shall discuss the problems associated with both of these topics in the following section.

The process that will significantly impede scientists and engineers at APS in achieving the desirable manufacturing potentials described in Section 3.2 and 3.4 an can be subdivided into a series of categories as follows:

- Equipment design and implementation
- Defining critical control parameters and implementing effective SPC
- Monitoring and control system design and implementation
- Software and additional computing hardware design and implementation
- Staff quality and process control awareness

4.3.1 Equipment Design and Implementation

With a great deal of equipment used in photovoltaic manufacturing being either custom designed or non-standard systems there is a pressing need for strong equipment design expertise supported by extensive use of CAD systems.

In a fully automated facility or a facility tending towards full automation, it is essential that equipment is designed to fulfill a specific task in the most efficient fashion with all the relevant monitoring and control systems designed into the equipment at the earliest part of the design phase, not designed to just replace people. Unfortunately, as a significant number of sections of the existing generation of manufacturing facilities are just "scale-ups" from the laboratory insufficient attention has been paid to manufacturing equipment design. APS, Inc. is not an exception to this mistake in the design of manufacturing equipment. A typical example of poor automated manufacturing equipment design , as far as "Eureka" scale panels is concerned is the I-V solar simulator in the APS "Eureka" production line. The schematic in Figure 10 indicates the very inefficient method of glass motion in the testing system/annealing section of the manufacturing line. With the panel needing to be in a vertical orientation for testing two additional translation stages are required, at not an insignificant cost, however, possibly of greater importance, is the fact that moving a 20 lb. piece of glass on a 3mm wide edge is undesirable due to the possibility of chipping or breaking the superstrate. Chipped glass can result in the panel being scrapped for module application and the resulting debris can reduce the up-time of the equipment.

A significant amount of effort must therefore be applied to identifying the manufacturing "bottle necks" and through careful design in a CAD/CAE environment solve these problems. Detailed design documentation should be kept for future equipment manufacture and for up-grading systems at the minimum cost.

4.3.2 Defining Critical Control Parameters and Implementing Effective SPC

In order to fully utilize plant automation and gain the benefits of an integrated control system, it is essential to define exactly what parameters need to be monitored and, in turn, held to defined specific tolerance ranges. A system must then be put in place to allow the required sharing of information between individual "stations" with accessibly useful information been available to the pertinent staff. The aspect of the system integrated will be covered in Section 4.3.4.

Critical control parameters will be defined as a result of R&D work in the laboratory and development work on the line. Control parameters not only must significantly affect the manufacturing process but also be readily implemented in line. The defining of control parameters which meet the above criteria is a very demanding task. A illustration of the difficulties involved in monitoring the a-Si laser scribe quality "in line" can be sub-divided into the following series of tasks.

- define method of defining scribe quality - eg. CCD, camera to view scribe lines.

- design and implement hardware and control software

- define SPC control set points

- design and implement corrective action sequence to avoid down time on the line

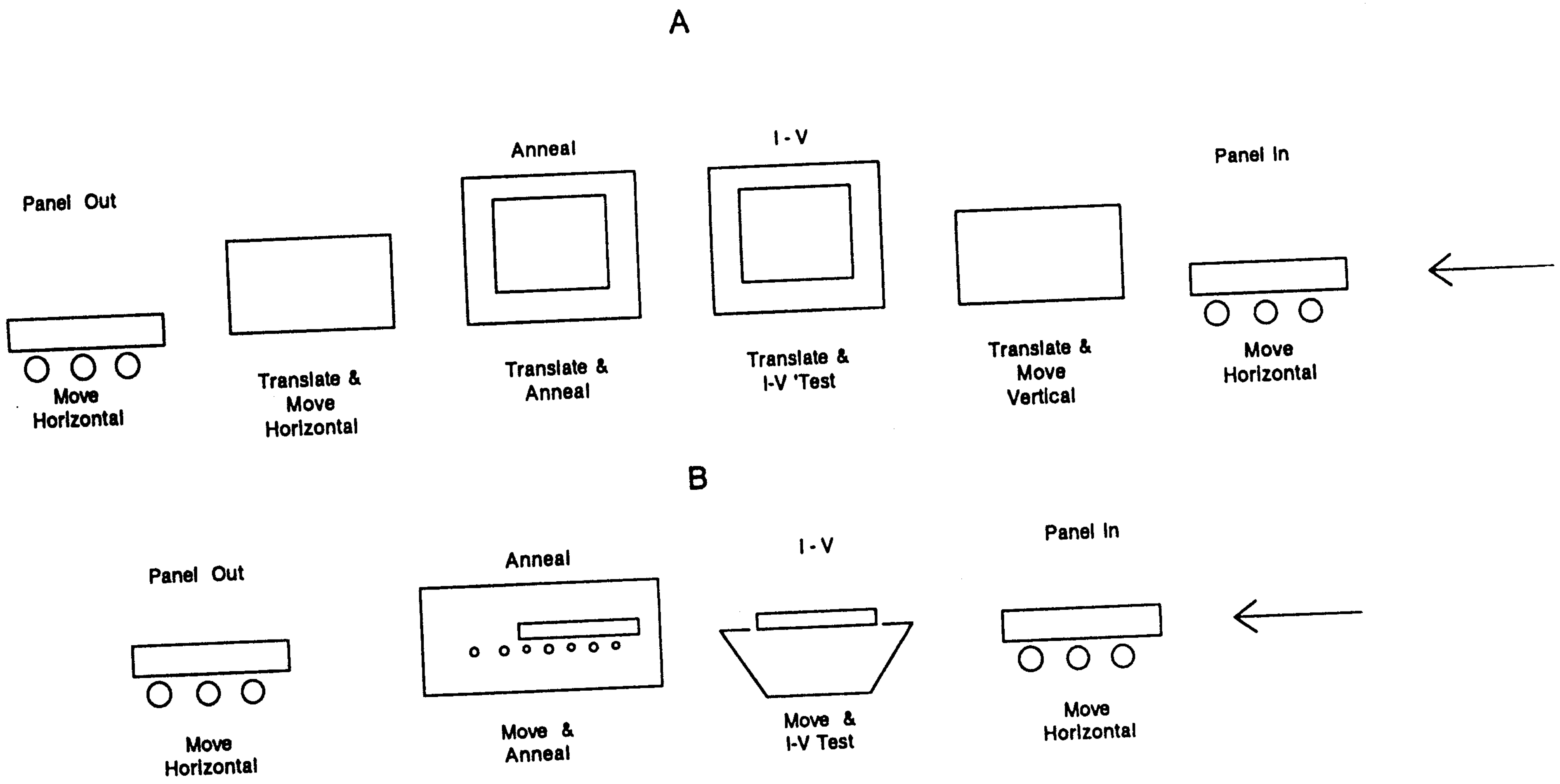


Figure 10
Schematic process flow from Al laser unload to after panel anneal.
A) Poor design.
B) Good design for automated manufacturing environment.

Members of both the Research and Development Groups and Quality Control will be involved in determining the relevant parameters to be monitored and controlled. As we expect the program of work to be progressive, we expect the problems to be addressed sequentially as below:

- define control parameters 1 -eg. SnO_2
- monitor, control and act upon parameter set 1
- define more advanced control parameters 2
- monitor, control and act upon parameter set 2
- etc.
- etc.

This evolutionary process of development of the Eureka facilities control parameters and the associated SPC system is a pragmatic approach to this key area of development of the plant.

4.3.3 Monitoring and Control System Design and Implementation

As mentioned in Section 4.3.2, once the critical parameters have been defined and the level of parameter control has been defined the design and fabrication of the monitoring hardware can be implemented. Typically, monitoring equipment will be designed "in-house" using mechanical, electrochemical and electrical/electronic staff. When considering the monitoring and control problems that will be addressed it is essential to ensure that the information generated can be assessed in the integrated system LAN, hence, equipment must be designed accordingly.

4.3.4 Software and Additional Hardware Design and Implementation

The "Eureka" facility has been designed to use a local area network system (LAN) using the IEEE CSMA/CD specification (carrier multiple access with collision detector). The network will use a Ethernet configuration with a Novell operation system environment. The automated integration of the facility, will use this network which will have the functions of sharing resources, sharing information and coordination of distribution functions.

Both hardware and software development will be required to bring the system into a useful network. Once the network has been constructed, a considerable amount of effort will be required in defining the information required for various functions, for example SPC, stock control, maintenance, etc., and software will have to be developed to meet these needs.

4.3.5 Staff Quality and Process Control Awareness

To fully utilize the monitoring and control aspect of the automation within the facility for quality and process control purposes expertise in SPC or a similar discipline is essential. APS at present has insufficient staff with this expertise and therefore this absence of the required human resources must be addressed.

This particular problem could be solved by recruiting one person with a detailed understanding of statistical process control followed by the training of staff who are skilled in other areas of expertise to enhance their set of skills and, hence, offer a team of SPC aware participants in quality and process control.

4.4 Reduction in Loss Mechanism

The problems that we felt needed to be addressed to achieve the potential described in Section 3.5 are as follows:

4.4.1 Non-Uniformity of Layers

We believe that flow non-uniformities if they exist in the amorphous silicon "plasma box" do not contribute to the observed thickness non uniformities in the a-Si layers simply because at our utilization levels of around 30% the film thicknesses should not depend strongly on the flow rates. Thickness non uniformities over a panel can be understood by investigating the response of the unit plasma box to the RF power input. This is an electromagnetic wave propagation problem that can be solved based on the electrical model of the unit plasma section as shown in Figure 11. We observe thickness non-uniformities along two difference directions, as is shown in Figure 8. The first is the non-uniformity along the 5 foot length of the panel. This is mainly due to the RF voltage depression at the injection point (i,e, lower left hand corner in fig. 8). The extent of this depression is a function of the length of the panel over which the RF signal propagates. Thus, as a first attempt, we can move the injection point to the center of the panel, so that the RF signal propagation length is reduced by a factor of two. However, this solution complicates seriously the mechanical and/or electrical design of the system and as such needs to be carefully evaluated in terms cost/benefit issues. Actually the second non-uniformity which is along the width of the panel is what reduces the overall panel output the most. It is clear from fig. 8 that the thickness gradient at the top to the panel is shallower then at the bottom. Because our cells are along the 5 foot length, we have at least 2 or 3 cells at the top which limit the overall current. The solution of this problem lies in our quantitative understanding of the dependence of the RF voltage

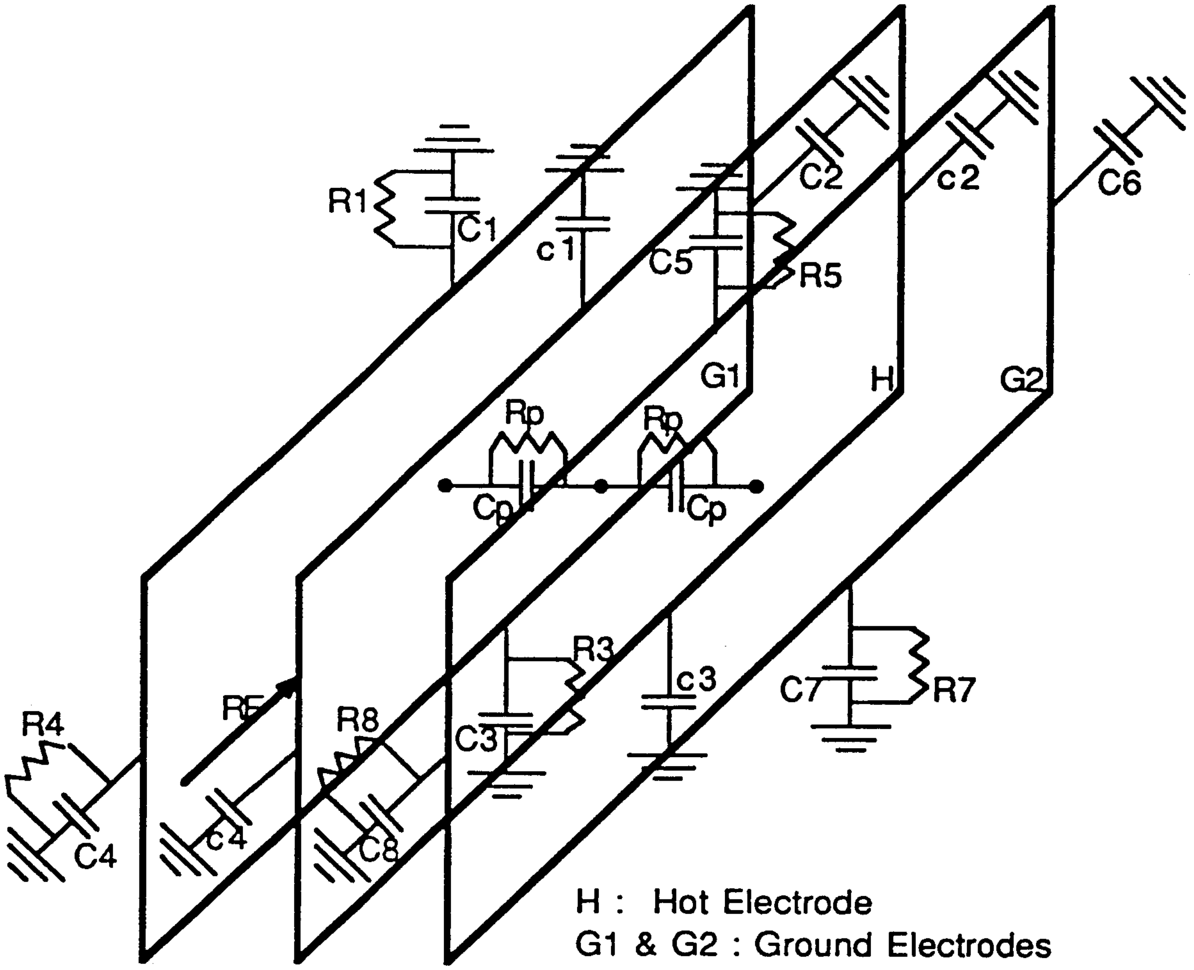


FIGURE 11. ELECTRICAL MODEL OF THE UNIT PLASMA SECTION.

distribution across the panel to the boundary conditions as defined by the values of the capacitances C_i and c_i and the resistances R_i. We believe that by an appropriate choice of these capacitive and resistive elements the top-down non-uniformity could be reduced to acceptable levels.

Thickness non-uniformities from chamber to chamber can best be reduced by implementing accurate measurement and control process for power absorption in the individual plasma sections.

The problems associated with compositional variation required quantative compositional studies, to be carried out in the laboratory, and in line monitoring of gas chemistry in the reactor to evaluate the fashion these variations influence the photovoltaic parameters.

4.4.2 Active Area Utilization

To approach the goal of approximately 3% loss of active area due to the three laser scribing steps we must solve two serious problems. Firstly, the mechanical indexing of the laser beam relative to the edge of the panel and from beam to beam and secondly, the control circuiting required to achieve this at high speed, as the target for full scribing operations in "Eureka" is less than 100 seconds per plate. As it is more difficult to maintain tolerances at high speed the combination of these problems is very challenging indeed for the engineers who would be working on this topic.

Considerable effort will have to be applied to the appropriate design of the mechanical aspects of the laser systems and sophisticated control circuitry to which though the local PC's will have access.

4.4.3 Defects

Following classification of the critical types of defects, section 4.4.3.1 defines some of the most commonly observed defects, the possible source of the problem and possible preventative steps or courses of action that could be taken to avoid the defects. Effort will have to be applied to prioritized the significant defects and carry out a program to eradicate, or minimize the key problems.

As a significant number of defects can be attributed to cleanliness and control of equipment, for example the power and shape of a laser beam, it is anticipated that the activities of personnel working in this area will be strongly lined with aspects of 4.3

4.4.3.1 Defect Classification

1. Bridge (B)

   Description:

   Small shunting connection from aluminum of one cell to that of another cell or from TCO of one cell to that of another cell; incomplete isolation of aluminum of TCO during laser patterning. Width of bridge is often only a fraction of a millimeter.

   Source:

   Usually caused by debris or glass scratches in laser beam path.

   Prevention:

   Maintain clean environment and proper module handling.

   Elimination:

   Reverse bias treatment[2] usually effective. Electrochemical etch[2] effective.

2. Burnish (Bu)

   Description:

   A mechanical abrasion apparently caused by a blunt instrument on one or more thin films of the cell. Shunting is usually from aluminum to TCO, through the s-Si:H.

   Source:

   Improper handling of module.

   Prevention:

   Careful and/or automated module transport.

   Elimination:

   Reverse bias treatment moderately effective. High temperature anneal[2] may be effective.

3. Defect Area (DA)

   Description:

   A distributed region of shunting between aluminum and TCO. Most likely contains closely spaced pinholes in a-Si:H. Deposition of aluminum over affected areas causes aluminum/TCO contact. Regional extent may be over several square centimeters, and when present, presents serious levels of shunting.

   Source:

---

[2] Reverse bias treatment involves momentarily subjecting the cell to a reverse bias with the purpose of eliminating shunts. Electrochemical etching is a partially developed process that effects the chemical break-up of shunting paths. High temperature heat treatment involves heating the modules at elevated temperatures for sufficient time in order to effect desired changes.

Believed at least in part due to glass shard debris resting on glass/TCO during a-Si:H deposition. Other sources of debris are possible.

Prevention:

Use wet swiping process (instead of dry process) and/or thoroughly clean glass after swiping. Maintain clean environments.

Elimination:

High temperature annealing may be helpful. Reverse bias treatment only sometimes effective and sometimes may worsen shunting. Electrochemical etching may be effective, though method requires further research.

4. Extended Improper Laser Isolation

Description:

Most commonly appears as shunting between aluminum and TCO along much of the aluminum isolation arise. such defects usually contain a high level of shunting.

Source:

Unoptimized laser operation parameters, extraordinarily thin a-Si:H, TCO that is very granular or excessively hazy (diffusive), aluminum that does not adhere well to the a-Si:H, severe nonuniformities in thin film layers, etc.

Prevention:

Optimize laser parameters, TCO specifications, and cell fabrication techniques in general.

Elimination:

High temperature annealing and reverse bias treatment may eliminate some shunting. Electrochemical etch perhaps effective.

5. Flaky aluminum scribes (F)

Description:

A particular example of Defect Type (4), only affected region may be on the order of a centimeter. Scribe appears flaky.

Source:

Most often caused by laser operation with too little power. Laser energy is insufficient to completely remove aluminum from scribe. condition may be coupled with other aspects of laser operation, as well as with properties of films being scribed.

Prevention:

Optimize laser operation; Quality control of film depositions.

Elimination:

Reverse bias and anneal treatments only partly effective. Electrochemical etch perhaps more effective.

6. Local Laser Shunt (LL)

Description:

Localized shunting in laser scribe wherein aluminum contact TCO. Extent is often only microscopic, but sometimes up to about a centimeter in length.

Source:

Usually not due to maligned laser operation. Often caused by imperfections in thin films (e.g., mechanical abrasions) or by dirty surfaces (e.g. fingerprints) on which films are deposited.

Prevention:

Quality control of thin film depositions and proper transport of modules during fabrication.

Elimination:

Reverse bias and high temperature anneal somewhat effective.

7. Pinhole (P)

Description:

Highly localized shunt between aluminum and TCO, through a small pore in a-Si:H layer. Usually microscopic, and even then, usually visible under transmitted light only. some pinholes can be seen by the naked eye through the use of back lighting. Most likely contains aluminum that has been sputtered to TCO. Some pinholes are closely spaced to others (within millimeters), and some are well isolated. defect Areas (see above) may in fact be many small pinholes very closely spaced.

Source:

Debris that persists on glass/TCO during a-Si:H deposition. Debris is then disturbed prior to aluminum deposition, resulting in aluminum/TCO contact upon subsequent aluminum deposition. some pinholes can also be caused when cells having extraordinarily rough TCO are subjected to a surface under pressure.

Prevention:

Clean process environment and the elimination of powder and flakes during a-Si:H deposition; quality control of TCO deposition; proper module handling.

Elimination:

Reverse bias and anneal treatments somewhat effective. Electrochemical etch appears significantly effective.

8. Spit (aluminum) (S)

Description:

Speck of aluminum resting on a-Si:H. Shunting occurs between aluminum and TCO.

Source:

Caused by small drops of aluminum during aluminum sputtering. Hot metal forms an electrically conducting alloy in a-Si:H.

Prevention:

Routinely clean deposits in sputtering apparatus.

Elimination:

Neither reverse bias of high temperature anneal treatments very effective. Effectively removed by electrochemical etch.

9. Scratch (Sc)
    Description:
        A mechanical abrasion, apparently caused by a sharp instrument. Damage could be to TCO, a-Si:H or aluminum. Usually appears as shunting between aluminum and TCO.
    Source:
        Improper module handling prior to encapsulation.
    Prevention:
        Proper module handling.
    Elimination:
        Reverse bias treatment significantly effective. High temperature anneal may be effective. Electrochemical etch significantly effective.

10. Extraordinarily hazy TCO (H)
    Description:
        Extraordinarily hazy appearance to TCO in confined regions. The condition often produces laser-induced shunting between aluminum/aluminum or aluminum/TCO.
    Source:
        Nonuniform TCO deposition; non-optimum laser performance results.
    Preventions:
        Quality control of TCO deposition.
    Elimination:
        Electrochemical etch may be effective.

11. Speck (Sp)
    Description:
        Minute (fraction of a millimeter) blemishes in thin films, of various origins, not all identified.
    Source:
        Miscellaneous scratches, burnishes and debris.
    Prevention:
        Proper module handling during processing and maintaining a clean environment.
    Elimination:
        Reverse bias, anneal, and electrochemical etching all have varying degrees of effectiveness.

5. Task 4. Costs and other requirements in overcoming the problems in manufacturing technology.

To date the considerable scientific and engineering resources that have been applied to the Eureka manufacturing line have addressed the basic establishment of the initial production process and the product design rather than improvements in the manufacturing efficiency. As much of the key equipment that constitutes the Eureka plant was custom built, either by APS engineers or by outside vendors to our specifications, it is not surprising that significant resources have been applied to make the individual parts of the plant run to their initial design specifications. Only now when majority of the equipment is in place and operational is it feasible to focus resources on the overall efficiency of the manufacturing process. The outline resource plan for the 3 year project to enhance the efficiency of the Eureka manufacturing process is estimated to require approximately 23 people. In addition to existing process scientists, this new phase of work would rely heavily on additional production specialists that have not been required to this point on the Eureka project. The manpower resources allocation to the various individual tasks would be as follows:

Task	Scientists	Engineers	Technicians	Est. Total Cost per annum $k
1		1		180
2		3	5	1120
3	1	1	2	600
4	1	2	2	790
5	2		3	710
Total	4	7	12	3400

Given the likely materials usage and the addition of specialist consultants the total project cost per annum with appropriate overhead would be approximately $3.4 million per annum.

In view of the overall magnitude of the efficiency improvement tasks it is envisaged that the level of project cost will be somewhat constant throughout the 3 year program with the emphasis within the individual tasks changing as the project progresses. For example, the product design task would be expected to address a number of differing products throughout the time period in sequence. While each individual product will take into account the specific requirements of the target markets each of the products will reflect the distinctive characteristics of the evolving amorphous silicon production process. Thus, the Task 1 3 year project would be expected to thoroughly address up to 6 different product designs fully optimizing the designs to enhance overall manufacturing efficiency. The automation task is the largest single activity planned within this overall project. To a large extent the effective implementation of the automation within the Eureka plant will involve redesigning some sections of the process equipment recognizing the ultimate automation goals. Some elements of the existing Eureka plant have been designed as larger versions of equipments used within previous batch processes rather than fully recognizing that the automation goals may well require radically different process elements.

While the identified process steps are undergoing redesign for better automation other parts of the process will be further automated by the inclusion of appropriate PC systems. Finally, towards the end of the three year project all of the individual control PC's for the various process steps will be fully networked to enable the relative throughput rates of the individual process steps to be optimized to achieve the most efficient performance for the overall plant.

This overall task can be expected to require the skills of mechanical, electrochemical and production engineers with the emphasis changing as the project progresses towards the ultimate networked system.

The current encapsulation system is based on the use of vacuum lamination, a process which had been developed for the crystal silicon products rather than automated thin film production. Recognizing the vastly different cost structure of an amorphous silicon manufacturing process as compared with the cell assembly requirements of a crystalline line automation of this stage of the Eureka process may require more fundamental reevaluating of the encapsulation.

Emphasis to date has quite obviously been focused on the development of an encapsulation that will enable a large area thin film module to pass the required high reliability test regime. That requirement having been met with the module currently passing the PVUSA qualification testing the focus can move to a more fundamental reevaluation of an encapsulation appropriate for automated thin film photovoltaic production. The extent to which some aspects of the encapsulation can be achieved as an extension of the current sputtering process will be assessed. It would be surprising if the use of a relatively thick EVA layer in a process designed primarily for the crystalline product is eventually selected as the optimal encapsulant for an automated thin film PV line. Thus, the phases of task 4 will initially involve the fundamental encapsulation process evaluation followed by assessment of the various more automated options and the eventual installation and optimization of the selected process.

The real time process and quality control task will initially involve the identification and selection of the various key process parameters that can be used within the control system,. Given the area of the individual panels and the planned high volume throughput of the plant, the number of key parameters will likely be greater than previously identified in thin film batch lines and the need for timely process corrections significantly more acute. This particular task will rely heavily on the improvements made in automation. Once the individual process step is controlled by a local PV and the key process parameters identified the emphasis will be focused on the installation of appropriate monitors to measure the selected parameters. It is apparent that several of the bulk parameters can be readily measured such as sheet resistance of the conductive oxide, however, other important parameters such as effectiveness of laser scribing or the grading of the semiconductor junction will be significantly more difficult to monitor.

Once the parameters are selected and the monitors designed and installed the emphasis of this task will move to defining the control limits appropriate for the individual parameters. Inevitably, this process will be somewhat tentative. In addition to the equipment development and installation, this task will necessarily require significant training for the individual process stage engineers. Typically, we would plant to use external training expertise to fulfill this considerable and important need.

Loss of mechanism can be thought of as two distinct types. Losses of active cell area resulting from the current panel design for example laser line widths or isolation boarders and unintentional losses introduced by either dust within the system or variations in process elements such as the RF power in deposition. Work on avoiding the unintentional losses such as point defects will involve stringent planned maintenance and cleaning schedules. While the loss of active area introduced by the existing design will involve modification to the encapsulation and possibly to the individual cell design.

While each of the 5 tasks will be structured with their own individual objectives, time lines and resource plan, it is apparent that for the whole manufacturing efficiency improvement to be successful that progress on each task will significantly influence other associated tasks.

Document Control Page	1. NREL Report No. NREL/TP-411-5018	2. NTIS Accession No. DE93000026	3. Recipient's Accession No.

4. Title and Subtitle

Photovoltaic Manufacturing Technology Phase 1

5. Publication Date

October 1992

6.

7. Author(s)

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Chronar Corporation
195 Clarksville Road
Lawrenceville, NJ 08648

10. Project/Task/Work Unit No.
PV250101

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

(C) XC-1-10057-16

(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 1991 - 10 May 1991

14.

15. Supplementary Notes
NREL technical monitor: R.L. Mitchell

16. Abstract (Limit: 200 words)

This report describes subcontracted research by the Chronar Corporation, prepared by Advanced Photovoltaic Systems, Inc. (APS) for Phase 1 of the Photovoltaic Manufacturing Technology Development project. Amorphous silicon is chosen as the PV technology that Chronar Corporation and APS believe offers the greatest potential for manufacturing improvements, which, in turn, will result in significant cost reductions and performance improvements in photovoltaic products. The APS "Eureka" facility was chosen as the manufacturing system that can offer the possibility of achieving these production enhancements. The relationship of the "Eureka" facility to Chronar's "batch" plants is discussed. Five key areas are also identified that could meet the objectives of manufacturing potential that could lead to improved performance, reduced manufacturing costs, and significantly increased production. The projected long-term potential benefits of these areas are discussed, as well as problems that may impede the achievement of the hoped-for developments. A significant number of the problems discussed are of a generic nature and could be of general interest to the industry. The final section of this document addresses the cost and time estimates for achieving the solutions to the problems discussed earlier. Emphasis is placed on the number, type, and cost of the human resources required for the project.

17. Document Analysis
a. Descriptors
manufacturing ; photovoltaics ; solar cells ; amorphous silicon

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

50

20. Price

A03

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