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Large-Area, Triple-Junction a-Si Alloy Production Scale-Up

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28

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EXECUTIVE SUMMARY

Objectives: The objective of this subcontract over its three-year duration is to advance Solarex's photovoltaic manufacturing technologies, reduce its aSi:H module production costs, increase module performance and expand the Solarex commercial production capacity. Solarex shall meet these objectives by improving the deposition and quality of the transparent front contact; optimizing the laser patterning process; scaling up the semiconductor deposition process; improving the back contact deposition; and scaling up and improving the encapsulation and testing of its aSi:H modules. In the Phase I portion of this subcontract Solarex shall focus on scaling up components of the chemical vapor deposition system for deposition of the front contact, scaling up laser scribing techniques; triple-junction recipes for module production; and metal oxide back contacts. The goal of these efforts is to adopt all portions of the manufacturing line to handle substrates larger than 0.37 m^2.

Task 1: Front Contact Development

Facilitation of a large-area-substrate (>0.56 m^2) chemical vapor deposition (CVD) belt furnace has been completed and designs for injectors are under consideration. A new gas feed system has been designed for both silicon dioxide and tin oxide deposition including dopant delivery and heated exhaust systems. The uniformity of the coating with the current injector over 0.41 m wide substrates was poor (± 26%) on SiO_2, indicating the need for better injector designs. Simultaneously, other smaller CVD reactors are being utilized to optimize the optical and electrical properties of the tin oxide for triple-junction devices.

Task 2: Laser Scribing Process Development

A large-area (>0.56 m^2) laser scribing station has been designed and a preliminary set-up for scribing 0.37 m^2 modules was completed. The active area on these modules with this set-up was over 86% of the aperture area (inside isolation scribe) with future goals of 94% and 96% when scribe widths and spacings can be reduced. An autofocus system has been designed, built and tested for the large-area laser to accommodate glass warpage and improve cutting reliability.

A joint development task between the laser and encapsulation teams has made progress toward developing a method to pass the wet hi-pot requirement for array modules. New scribing techniques and encapsulants have been developed to accomplish this task.

Methods to obtain better coupling between the laser beam and the individual substrate layers are under investigation. Utilizing wavelengths other than the standard green (532nm) has resulted in improved processing speed and more reliable scribes in some applications. Optimization of the parameter space and wavelengths most appropriate for each layer is in progress.

Task 3: Amorphous Silicon Based Semiconductor Deposition Process

The design concept for a five-chamber plasma-enhanced CVD reactor for deposition of > 0.56 m^2 triple-junction modules has been completed. A description of some of the detailed features of this system is included in the body of the text. Improvements in the gas distribution, pumping, electrical and substrate heating systems, based on experience with manufacturing systems, have been designed into this large-area multi-chamber reactor.

Optimization of the triple-junction device recipe has proceeded in a separate reactor capable of depositions on 0.37 m^2 substrates. Initial experiments are underway utilizing 0.093 m^2 substrates to quickly determine the effectiveness of the recipe transfer and examine overall area uniformity with multiple substrates. The spectral response of films made in this reactor has approached that of the smaller research systems; however, optimization of the diode fill factors is still necessary.

Task 4: Rear Contact Deposition Process

The efforts in this task have concentrated on the assembly and test of a large-area magnetron sputtering system to deposit the rear contact. A system was partially assembled to test the magnetrons and system design. Several aluminum films were produced and the remainder of the chambers are being assembled in a similar configuration to provide an oxide-metal capability.

A reactive sputtering process for depositing zinc oxide films is under investigation in a small S-gun system capable of multiple metal depositions. A larger manufacturing system is also being utilized to duplicate research optimized coatings on 0.37 m^2 substrates.

Task 5: Bus/Wire/Encapsulation/Frame

An evaluation of possible commercially available indexing systems to allow scale-up of the frit dispensing system and an indexer was selected which could fulfill the requirements for both contact dispensing and laser scribing of large-area modules (>0.56 m^2).

A new auto-refill frit delivery valve is undergoing tests. This system would allow larger tolerances to substrate flatness without adversely affecting the deposition thickness, position or width of the bus bar. Evaluations of external connection schemes utilizing both commercially available connectors and new designs are also in progress.

The evaluation and selection of improved encapsulants is in progress. The encapsulant must provide protection of a thin film through prolonged outdoor exposure and provide a high dielectric path to ground for high voltage protection. Continuous revaluation, reformulation and accelerated environmental testing have been done to meet these requirements, and even though a potential encapsulant has been selected, further improvement is always necessary.

Task 6: Material Handling

A preliminary equipment layout for a plant with a 10 MW output capacity was completed. The layout was constructed based on input from all task leaders and equipment specialists and is consistent with present practices on our manufacturing line. Vendors of glass handling equipment have been contacted and a manual glass transport system designed.

Task 7: Environmental Test, Yield, and Performance Analysis

Environmental and electrical testing capability of large area modules is under development by the Task 7 team. The development of a light (1-SUN) soak station capable of uniformly illuminating a six-square-foot area at a constant temperature has been completed. Several more light soak stations will be constructed to produce a statistical data base for the measurement of stability of 6-square-foot triple-junction modules.

Test equipment for the measurement of the environmental durability of large-area modules ($\geq 0.56\ m^2$) has been reviewed and maintenanced for optimal test conditions. The equipment currently available includes a hail tester, dry hi-pot tester, humidity-freeze and thermal cycling chambers. A review of the wet hi-pot tester requirements was made with NREL personnel to insure that measurements were consistent. Design of a test station for dry/wet hi-pot and edge insulation testing are in progress. Measurements of the breakdown voltages of triple-junction modules with a silver-oxide rear contact have indicated that slightly lower ($\leq$ 1V) reverse bias voltages can be tolerated to cure small electrical defects. Performance testing of large area triple-junction modules will be accomplished by modifying the fixtures of a standard solar simulator to accommodate both $0.37\ m^2$ (0.41 m x 0.91 m) and $0.56\ m_2$ (0.41 m x 1.83 m) modules.

TABLE OF CONTENTS

Section **Page**

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIXES

1.0 INTRODUCTION

Manufacturing large-area multi-junction devices at low cost requires that all component processes be thoroughly investigated for potential cost reductions, durability and capability. Transfer of multi-junction deposition processes from small single- or multi-chamber systems to larger reactors requires total reoptimization of recipes and increased attention to deposition uniformity. The repeatability of laser processes must be maintained with the same precision over longer distances often at higher cutting speeds. Chemical vapor deposition (CVD) processes require new injector designs to maintain lateral uniformity of electrical and optical properties. New back contact materials deposited with reactive sputtering techniques need to maintain uniformity to insure reliable laser scribing. Encapsulants must be thoroughly tested environmentally and help provide for safe handling of high voltage interconnected panels. Many of these items have not been addressed in the research efforts to provide high efficiency stable amorphous silicon alloy devices. Simultaneously, the processes all need to be scaled up to handle larger size modules if cost efficiency goals are to be achieved.

2.0 TASK 1: FRONT CONTACT DEVELOPMENT

2.1 Introduction

The effort during the first six months of this task have focussed on providing large-area capability for deposition of transparent conductive oxide films and improvement of the existing film properties. Designs of an improved chemical delivery system have been completed for the deposition of both silicon dioxide and tin oxide. New injector designs are in progress to deposit tin oxide films uniformly on substrates up to 0.61 m in width. Current manufacturing and research CVD reactors are being utilized to optimize the tin oxide process parameters for triple-junction devices and investigate alternate materials for transparent oxide films.

2.2 Large-Area Development

The 0.76 m wide belt furnace has been supplied with power, water, nitrogen and a newly designed exhaust system. Belt alignment and programming of the current control system were completed.

Temperature profiling of the heating and cooling zones was investigated by attaching thermocouples to 0.37 m^2 substrates in several locations. Across the belt temperature uniformity was determined as well as the temperatures experienced by the substrate in the direction of travel at various belt speeds.

A chemical delivery system for the deposition of the SiO_2 diffusion barrier layer using silane, nitrogen and oxygen feedstocks was designed and tested on the 0.76 m wide belt furnace. Temperature profiles and process parameters were determined for SiO_2 film deposition at belt speeds of 0.45 m/min and 0.61 m/min. The thickness uniformity of the films was at best ± 26% on 500Å films over a substrate width of sixteen inches. The large variations in film thickness are directly attributable to warpage of the internal injector parts at process temperatures. Improvements in the internal injector design are necessary to deposit both silicon dioxide and tin oxide films with ±10% thickness uniformity.

Three separate options are being investigated to develop a useable large area injector for tin oxide deposition.

Option 1: Modify Existing Injector

Examine the construction of the experimental injector supplied with the furnace to determine if in-house modifications can be made to insure non-warping injector nozzle plates.

Option 2: Purchase the first prototype of a newly designed injector.

The furnace vendor has developed a new injector design, which is radically different from the injector supplied with the furnace. The cost of this new injector is 250% higher than the original unit. The vendor is examining the design to reduce fabrication costs. However, this would be the first injector made with this design capable of deposition on substrates up to 0.61 m wide.

Option 3: In-House Injector Design

Generate a design based on our experience with current manufacturing systems that would be inexpensive to fabricate and produce uniform coatings. A conceptual design has been completed and arrangements to test a critical aspect of this design using the 0.76 m wide belt furnace have been completed.

The current injector performance tested with the new gas delivery system resulted in nonuniform (± 26%) silicon dioxide films, but tin oxide deposited on these films in the smaller manufacturing furnace showed no change in sheet resistance compared to standard SiO_2 films demonstrating the integrity of the nonuniform SiO_2 as a sodium diffusion barrier. Overall thickness of the SiO_2 layer still needs to be optimized when tin oxide capability is established in the 0.76 m wide belt furnace.

2.3 Film Property Improvements

Designed experiments to study the reaction kinetics of the tin chloride-based tin oxide process were performed on the current manufacturing CVD system. The results of these experiments were then used to optimize the front contact for triple-junction devices.

Improvements in the optical transmission of the tin oxide were obtained with a process based on the reaction kinetics while still maintaining optimal light scattering and electrical properties for triple-junction devices. The poor manufacturability of the new process in the standard manufacturing line furnace would not allow its immediate incorporation, however designs for the large area tin oxide chemical delivery system have incorporated features unique to the new process.

Performance of devices with the improved transmission front contact are still being evaluated. Some initial results are shown in Figure 2.1 with devices deposited on several different types of front contact currently used at Solarex. A significant improvement (~7%) in total current was achieved on the tin oxide deposited with the new PVMaT process.

3.0 TASK 2: LASER SCRIBING PROCESS DEVELOPMENT

3.1 Introduction

Development of the laser scribing effort has been divided into three major areas over the last six months. One area of investigation has focussed on developing large area capability for all triple-junction device scribes (conductive transparent oxide [CTO], silicon, metal, isolation) at production rate scribing speeds. Secondly, a joint effort with the Task 5 encapsulation team to consistently pass wet hi-pot tests is in progress and finally investigations using wavelengths other than the current manufacturing standard of 532nm to scribe each of the film layers in a triple-junction device. Results in each of these areas have been encouraging.

3.2 Large-Area Capability

Development of large-area laser scribing is progressing on two fronts. Elements of equipment design are under investigation in a 0.61 m x 1.22 m capable vertical laser system, and a joint effort with the Task 5 frit team is underway to develop a combined horizontal laser/contact dispense system capable of handling 1.83 m long substrates by at least 0.41 m wide. Indexing fixtures for both the large-area laser systems are in the design stage with preliminary fabrication of some parts started for each system. A real-time autofocus system has been designed and installed on the vertical

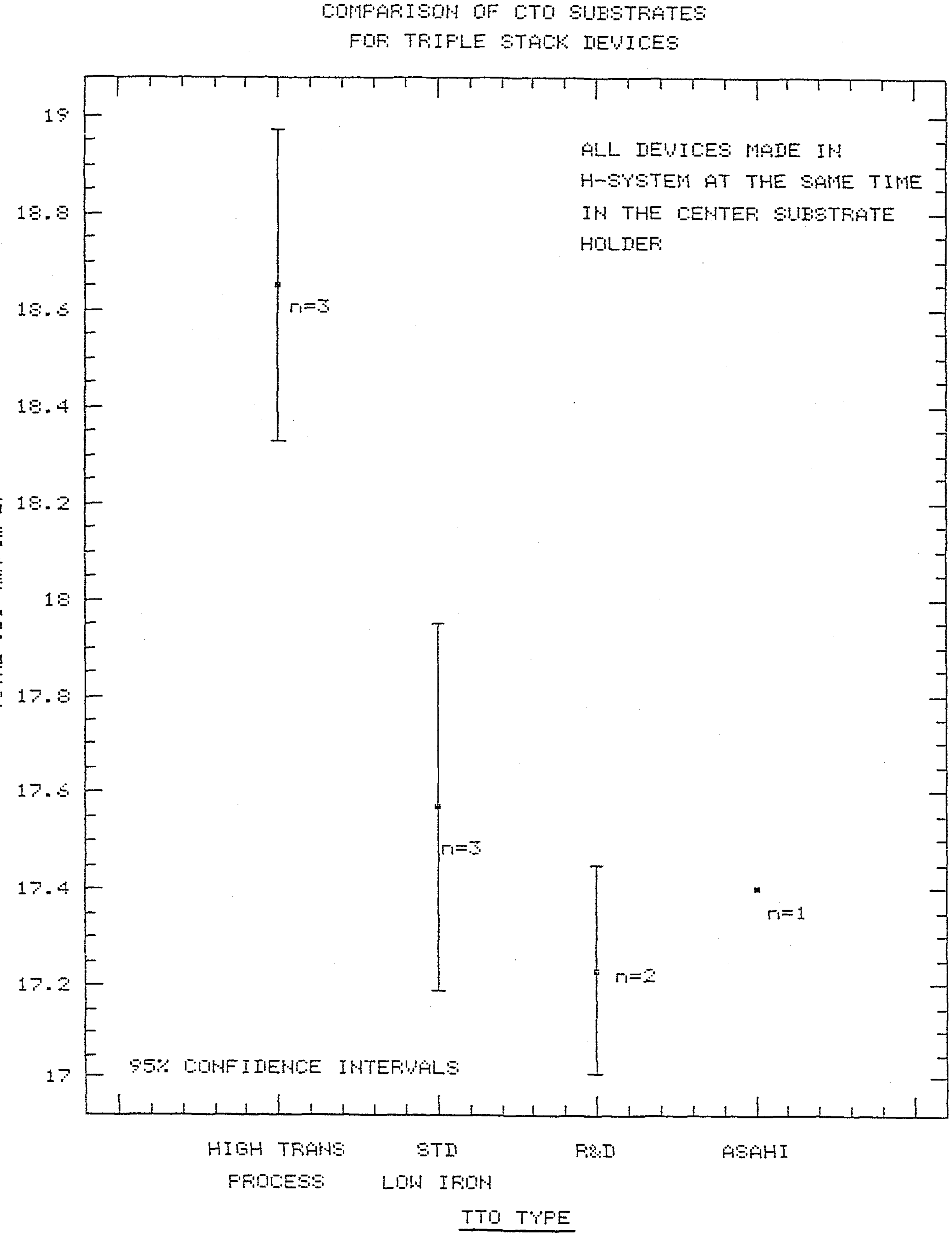

COMPARISON OF CTO SUBSTRATES
FOR TRIPLE STACK DEVICES
ALL DEVICES MADE IN
H-SYSTEM AT THE SAME TIME
IN THE CENTER SUBSTRATE
HOLDER
19
18.8
18.6
18.4
18.2
18
17.8
17.6
17.4
17.2
17
n=3
n=3
n=2
n=1
95% CONFIDENCE INTERVALS
HIGH TRANS
PROCESS
STD
LOW IRON
R&D
ASAHI
TTO TYPE

Figure 2.1

scribing system to maintain optimum cutting despite glass warpage. The first laser scribing deliverable was accomplished on this system with a preliminary fixture. Area utilization on these 0.37 m^2 samples was only about 86% of the aperture area and the cutting speeds were approximately equal to the current 0.09 m^2 manufacturing rate. Investigations on reducing both the scribe width and separation are in progress on this system. Tests have been done on .093 m^2 pieces of thicker glass (3 and 4 mm) to determine the effect on scribing parameters for all these scribes.

The scribing rate becomes more important as the substrates increase in size since the increased number of linear inches of scribes must be done at throughputs similar to smaller area plates. The scribing rate of the metal/oxide combination used on triple-junction devices was standardized to 5 cm/sec to insure high efficiency modules. Under the PVMaT initiative, scribe rates on this metal/oxide combination was increased to 23 cm/sec without affecting electrical performance.

3.3 Hi-Pot Performance

Solarex has chosen a method of combining a laser isolation scribe with a high dielectric encapsulant to insure safe operation of large-area modules at array voltages. This is a cost effective way to protect the modules against the corrosive effects of the outdoor environment while simultaneously preventing current leakage to the front surface of the module.

A new type of isolation scribe has been developed which passes dry hi-pot tests on over 92% of modules tested. This scribe is comprised of four concentric cuts which touch each other along the length but do not cross at the corners. Failures appear to be related to coating defects rather than laser cutting problems. The PVMaT developed isolation scribe without encapsulant increased hi-pot resistance by 27% from an average value of 800 volts to over 1100 volts, while plates with encapsulant can withstand over 4000 volts before breakdown. A method to improve the scribe to obtain 100% reliability is now under investigation.

Several other techniques have been tried to improve hi-pot resistance without success. Edge seaming of glass substrates was done after the deposition of the transparent front contact without improving hi-pot resistance; and a thin film high-dielectric coating on top of the metal back contact layer, and before the encapsulant, did not increase the resistance to high voltage breakdown in the isolation scribe.

Improvements in the scribe have led to better wet hi-pot test performance with the current encapsulants. New methods of paint application as well as alternate materials are under investigation to reduce coating defects that result in point defect failures under wet conditions (Section 6.2).

3.4 Improved Optical Coupling

A third area of investigation under PVMaT Task 2 over the last six months has been to examine the effect of other wavelengths of light to improve the cutting efficiency of each of the laser scribes. Isolation and CTO scribes were done at a wavelength of 1064 nm to determine if reliable segmentation could be done at higher translation speeds. Results indicate that these scribe speeds could be increased by a factor of 4 from 5 cm/sec to 23 cm/sec with equivalent reliability using infrared wavelengths.

An investigation using wavelengths of less than 300 nm to cut various layers is also in progress. The higher energy ultraviolet light can be more tightly focused to provide thinner scribes and increase active area. Efforts have been underway to determine the optimum scribing wavelength for each of the laser scribing techniques so that reliability and scribing speed can be increased for the production of triple-junction modules.

4.0 TASK 3: AMORPHOUS SILICON BASED SEMICONDUCTOR DEPOSITION

4.1 Introduction

Progress was made in the last six months on two separate fronts: The design was completed for a five-chamber, large-area deposition system, and the triple-junction technology was transferred from R&D to a large-area single-chamber system.

4.2 Large-Area Multi-Chamber Deposition System

The five-chamber system will incorporate many improvements over the existing technology at Solarex (See Figure 4.1):

1. **Capability for deposition on large-area substrates.** The new system will deposit films on substrates up to 0.74 m^2, compared to existing manufacturing systems which are limited to just over 0.093 m^2. The size of the cathode, which determines the potential area of deposition, will be about twice the size of existing systems.

2. **Multiple deposition chambers.** The new system will have five deposition chambers, compared to two chambers for the existing manufacturing system. This improvement will allow higher throughput with simultaneous depositions in each chamber (See Figure 4.2).

3. **"Diode" gas distribution system.** A new gas distribution design will be tested, where the gas distribution system will be placed very close to the cathode to prevent a glow discharge in the interval between the plates. In existing systems, there is deposition on the gas distribution system and both sides of the cathode, wasting material and creating sources of a-Si flakes which cause pinhole shorts in modules. The "diode" configuration will be an important precursor step towards a "hollow cathode" configuration for a vertical system.

4. **Six-zone top heater configuration.** This will ensure good substrate temperature uniformity. Existing systems use a three-zone heater configuration, which results in a drop-off in temperature at the substrate edges.

5. **Alternative cathode materials.** All existing systems use molybdenum for cathodes, and many systems employ molybdenum substrate holders. Molybdenum is very expensive and difficult to machine. The use of alternative materials will be explored in the design of the new system.

6. **Symmetrical pumping.** Symmetrical placement of pump ports in the deposition chamber, together with the arrangement of the plenum, gas distribution system, cathode, and substrate, will ensure a uniform distribution of gas flow across the substrate. This is thought to be particularly important in RF deposition. The existing manufacturing system has some uniformity problems caused by asymmetrically-placed pump ports.

7. **RF capability.** All a-Si deposition systems at Solarex now use DC power supplies, with the exception of a few small systems in R&D. Films made with RF have the potential for better gas utilization and longer times between cleaning because there is less deposition on the cathode. The new system will be designed to incorporate both dc and rf deposition techniques.

8. **Easy cleaning.** The cathode and flow isolation shield are designed to be easily removed for cleaning, saving maintenance labor costs. Internal parts have to be cleaned frequently to prevent flaking of built-up layers of a-Si which can also affect the reliability of the modules produced.

9. **Team design.** The design was reviewed by a team consisting of equipment designers, machinists, electricians, process engineers and research scientists. This cross-departmental team approach gave everyone involved in the task input from the beginning of the project. Not all problems can be anticipated, but giving many people input up-front minimizes risks, and allows the best possible design with the materials at hand.

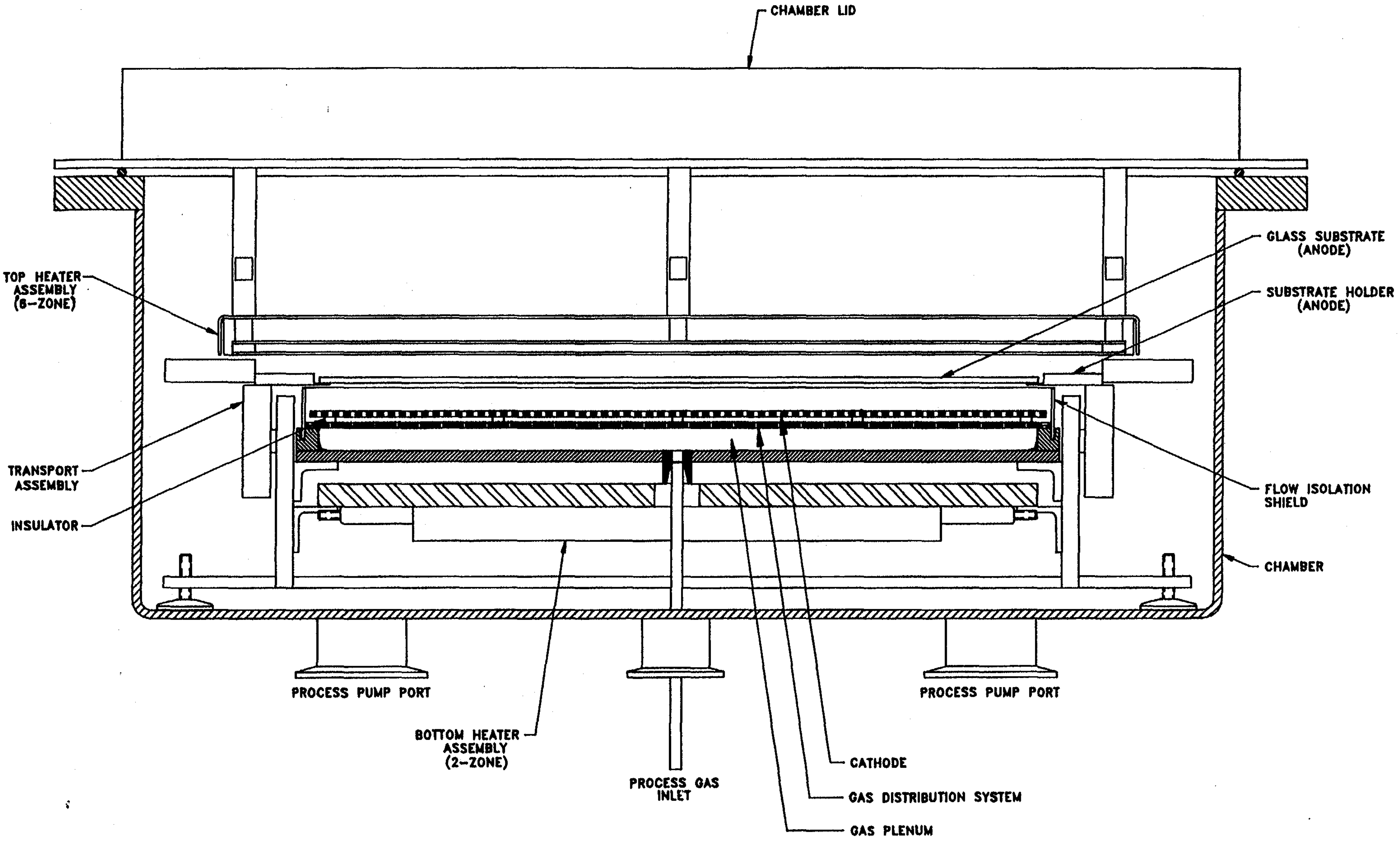
4.3 Transfer of Triple-Junction Technology

The triple-junction technology developed in R&D was transferred to a manufacturing deposition system capable of depositing silicon over 0.37 m^2, compared to about 0.093 m^2 for the R&D systems. This system was formerly used for batch-line manufacturing and was converted to make triple-junctions by expanding the gas-delivery manifold from six gases to nine. Holders have been designed for (0.41 m x 0.91 m) substrates (present holders take three 0.3 m x 0.33 m substrates).

Work over the first several months focused on matching the best R&D efficiencies for small-area devices. Much time was spent optimizing the thickness and transmission of the non-current-generating p- and n-layers, in order to maximize current generation in the intrinsic I-layers. A new process had to be developed using diborane in helium as a feedstock gas for p-layers, replacing diborane in silane, which is no longer supplied by gas vendors. Small-area devices with initial efficiencies of 9-9.5% have been achieved (see Figure 4.3).

Several batches of 12" x 13" modules have been made. The best module aperture-area efficiency thus far is 8.3%.

a–Si Deposition Chamber



END VIEW

fig. 4.1

a-Si Deposition System

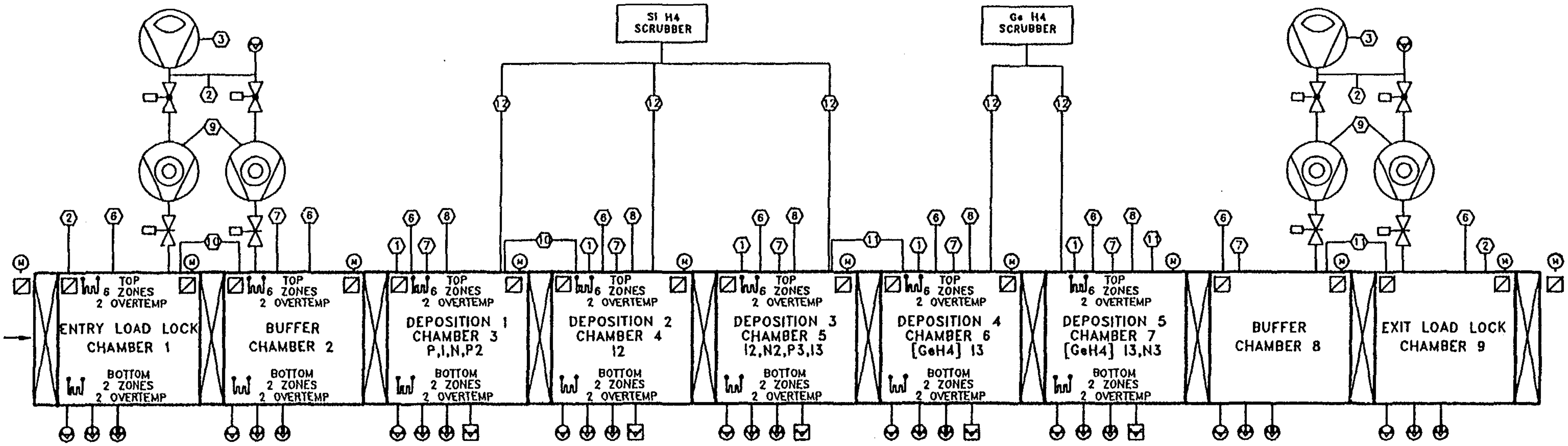


Figure 4.2a

Symbol Legend

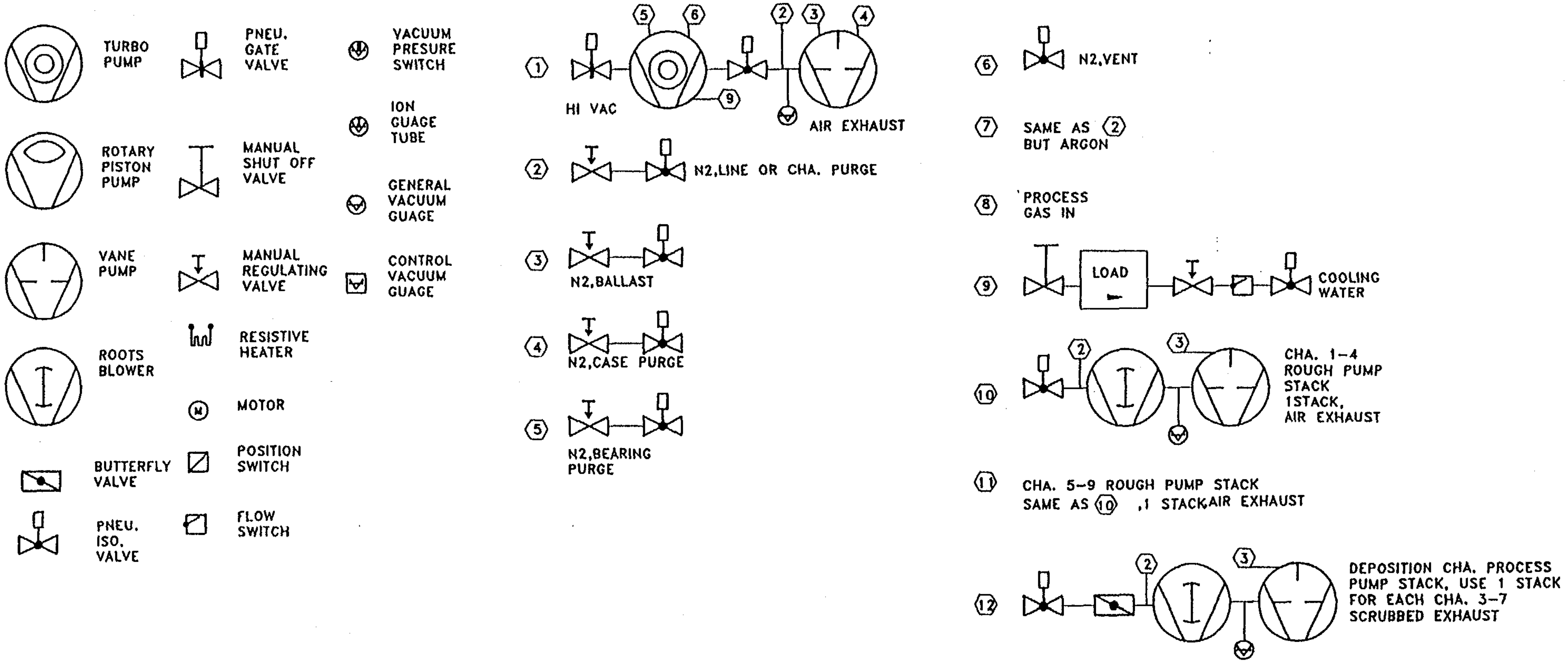
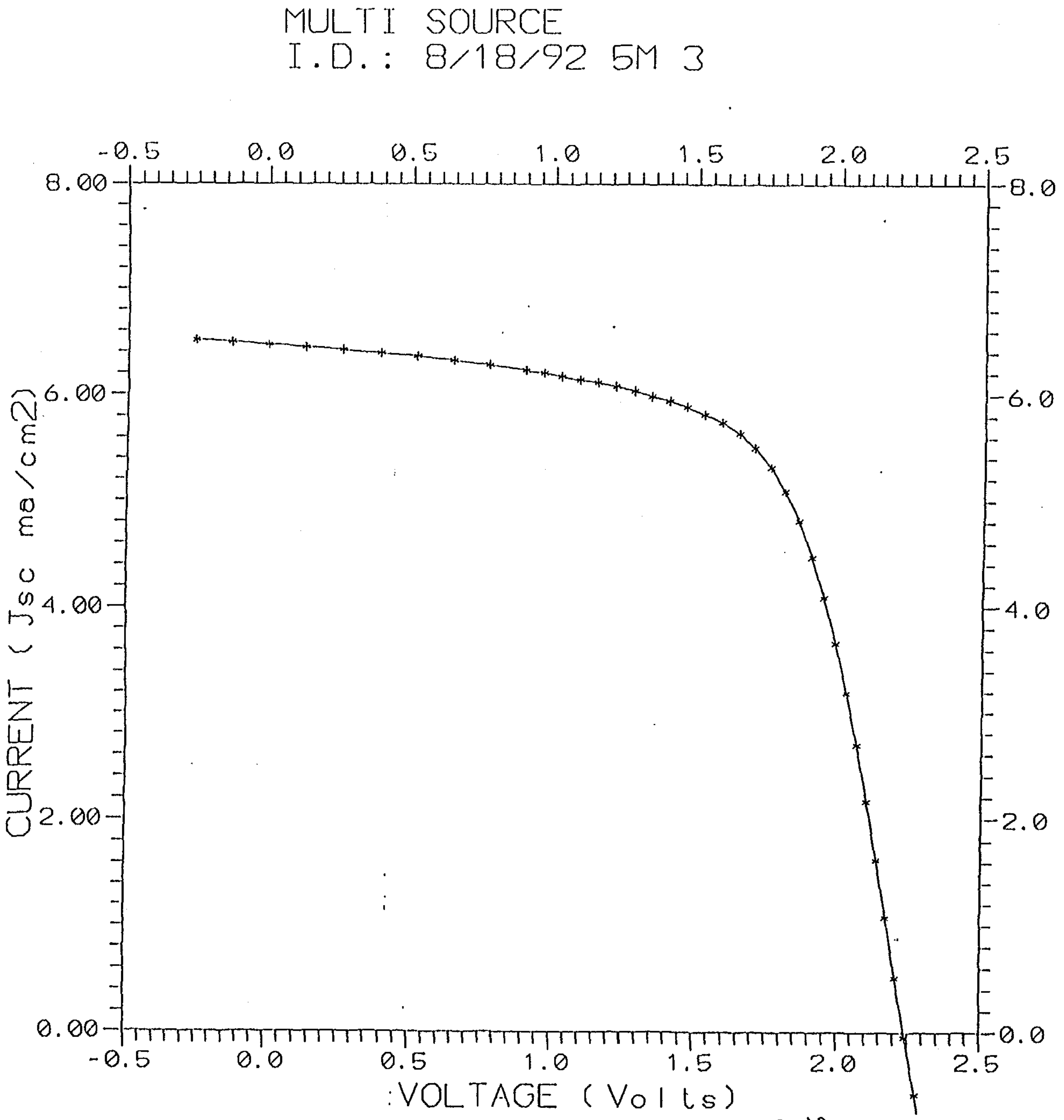


Figure 4.2b

Figure 4.3: Small-area triple-junction device made in large area system



Voc : 2.242 Volts
Jsc : -6.5 ma/cm2
F. F. : 64.5 %
Eff : 9.4 %

Isc : -1.746 ma
Pmax : 9.352 mw/cm2
Imax : -1.485 ma
Vmax : 1.700
Jmax : -5.500 ma/cm2
Rs : 62.78 ohm-cm2
Rsh : 5.64E+03 ohm-cm2

Intensity (Xenon) : 100.7 mw/cm2
Intensity (Infra.) : 98.2 mw/cm2
Temp : 29.1 C
Cell Area : 0.270 cm2
Segment : 1
Total Area : 0.270 cm2

DATE : 10-08-1992
TIME : 13:26:20

5.0 TASK 4: REAR CONTACT DEPOSITION PROCESS

5.1 Introduction

Three separate sputter deposition systems are being used to study the metallization process for triple-junction devices: A small sputter-gun system to evaluate materials and the reactive sputtering parameters on small area diodes, an in-line magnetron system to provide back metallization for modules up to 0.37 m^2 and to test the materials properties of the silicon system and the quality of laser scribes. A large area six-chamber system will provide state-of-the-art metallization for modules up to 0.56 m^2 and allow testing of manufacturing capability for large-area modules.

5.2 Materials Evaluation

Triple-junction modules are currently metallized with a ZnO/silver contact compared to the manufacturing practice of bare aluminum on single-junction devices. The bulk of the environmental data has been established on aluminum backed devices with the current encapsulant. An experiment was undertaken to quantify the performance differences between silver-and-aluminum-backed triple-junction devices. A comparison of efficiency, current generated in each layer and quantum efficiency at 800 nm is illustrated in Table 5.1.

COMPARISON OF ZnO/ALUMINUM AND ZnO/SILVER REAR CONTACTS

			I-Layer Current (mA/cm^2)			Quantum Efficiency
Rear Contact		Efficiency (%)	Front	Middle	Back	at 800 nm
ZnO/Aluminum	#:	34	9.0	9.0	9.0	9.0
	$\bar{x}$:	8.29	6.06	5.47	4.87	0.164
	σ_x:	.43	0.11	0.07	0.14	0.008
ZnO/Silver	#:	33	7.0	9.0	9.0	9.0
	$\bar{x}$:	9.46	6.05	5.57	5.72	0.237
	σ_x:	.48	0.12	0.06	0.09	0.009
Ratio of $\frac{\text{Aluminum}}{\text{Silver}}$		0.88	1.00	0.98	0.85	0.69

Table 5.1

The cells made with the ZnO/aluminum rear contact had significantly lower efficiencies than cells made with the ZnO/silver contact because of lower current generated in the back I-layer. The a-Si deposition recipe used in this experiment was optimized for ZnO/silver. If the recipe was optimized for ZnO/aluminum, the loss in efficiency would be less--how much less is not known.

5.3 Large-Area Development

A six-chamber metalization system will be used to deposit the oxide/metal layers required for the back contact on triple-junction modules. All of the chambers have been cleaned in preparation for assembly. One chamber required extensive modification to be used as a deposition chamber for the oxide materials. Eight sputtering cathode positions are available for each of the magnetron chambers. The heater configuration and placement in the system has been decided requiring some additional modifications.

The large-area six-chamber system was facilitated to test the magnetron cathodes in a single chamber. Several aluminum films were deposited on 0.41 m wide glass substrates and measured for thickness uniformity. The remaining chambers are being assembled using the heater assemblies currently available to eliminate additional design time.

These heaters have been cleaned, refurbished mechanically and rewired to improve reliability. All six chambers have been connected together and their transport mechanisms aligned to permit substrate holder travel through the system. Vacuum plumbing and electrical wiring are currently in progress.

The bulk of the effort on Task 4 over the last six months has been devoted to preparing a system capable of sputter deposition of an oxide/metal rear contact on large-area substrates.

6.0 TASK 5: FRIT/BUS/ENCAPSULATE/FRAME

6.1 Introduction

The effort on Task 5 has been concentrated in two areas. The development of reliable external contacts to large-area substrates and the encapsulation of large-area substrates for corrosion protection and hi-pot reliability. Several coatings have been screened and the best ones selected for further testing and improvement will be used for passing hi-pot test requirements.

6.2 External Module Connection

Evaluation of an appropriate system to dispense a conductive frit pattern was completed. The three primary considerations were between an X-Y-Z controller by Anorad or Camelot and modifications to in-house equipment. Approval was received from the Project Management Group to proceed with the purchase of an Anorad controller system, which would be used as a shared system for large area bus/bar application and laser scribing for 0.41 m x 1.83 m modules.

A design review of an indexer concept for the Anorad system was held. The concept is an edge holder design which supports the substrate on all four sides on a non-metallic delrin type material mounted on rails. The indexer would have the flexibility to accommodate various size substrates by means of a slide rail adjustment. The indexer would, also, have some adjustability on the edge rails to maintain a flatness of +/- 0.25 mm. This indexer design is currently being transferred to AUTOCAD in preparation for detailing.

Work with a new auto-refilling valve system for characterization and optimization is continuing. Operational limitations were noted with the ultrasonic valve sensor used to activate the pump for refilling. Sensitivity to position, pressure and frit condition were found to be potential causes for failure. Due to these problems, other methods of level sensing in the cartridge system are being considered.

Initial valve characterization indicates a much wider window for snap-off distance (distance from valve tip to substrate surface) could be tolerated. Experimentation indicates less line width sensitivity to substrate flatness at set points greater than 0.75 mm. Further work has been directed to variations in volumetric flow rates and sensor performance concerns. Capacitive proximity sensors are being evaluated as an alternative to ultrasonic sensor. Initial response is encouraging. Work is in progress to determine best mounting position and sensor location. Data from initial characterization must be reconfirmed once sensor parameters have been established.

A low-temperature-fired conductive material has been received for evaluation. Initial qualification of this conductor has been completed. This will lower the peak temperature requirement by ≈ 30°C by using lower melting temperature glass frit. The average range on pull test after firing was 10-14 kg which compares favorably with current high temperature frits. Post processing effects still need to be evaluated.

In addition, sample plates have been sent out to investigate the possible use of flame solder processing for current busing as an alternative to high temperature processing.

Connector research is still continuing. Single/lug type connectors were designed to be consistent with current module design. Acceptance testing of these connectors with respect to pull testing and thermal stressing is in progress. Also, J-Box designs are under evaluation.

6.3 Encapsulation

Extensive maintenance and repair work was required in order to get an in-house .61 m x 1.22 m spray coater system operational. Orders were placed for paint components of experimental formulations.

Experimental formulations to be evaluated were polyester/urethanes, acrylic/urethanes, UV curable Acrylate and UV curable urethane acrylate. Initial test runs of all experimental formulations were completed for preliminary screening tests.

Evaluations of these coating formulations were performed by using the following testing methods:

1. **Water Immersion Test** per Solarex procedure water immersion at 50°C +/- 2°C, illuminated (ELH light source) for five days.

2. **Thermal Cycling - 200 Cycles**
   -40°C to +90°C @ 50% RH and cycle period not to exceed six hours.

3. **Wet Hi-Pot Test** as per NREL (SERI/TR-213-3624)

4. **UL 1703 Cut Test** for hardness

5. **UV Exposure - 1000 hrs.**
   QUV 60°C UV/40°C condense

Initial coating tests were made to achieve coating thicknesses of .025mm and .038mm. At this thickness, surface defects and incomplete surface coverage were apparent by visual examination. Evidence of pinholing was also noted. Measures were taken to reduce air-born particulates through laminar hoods and minimizing handling. Complete surface coverage and significant reduction in surface defects was achieved at approximately .075mm - .09mm coating thickness. At this thickness, dielectric strength was enhanced and positive results were noted in hi-pot testing.

The polyester group exhibited some sensitivity to the drying profile. This resulted in coating pull back, and was most problematic with formulation No. 38. An unlevel oven chamber contributed to this pull back and also to a non-uniform coating thickness. Drying profile temperatures were reduced to eliminate pull back. Further optimization of the drying profile is required. Pinholing is still evident and is a contributing factor to wet hi-pot failures. The acrylics, however, had good fast curing films even at heavier applications. Defoamer additives were used to reduce surface tension and eliminate pinholing significantly.

6.3.1 <u>Environmental Testing Results</u>

Of these three polyester/urethane formulations, No. 40 was superior. Water immersion testing after five days showed evidence of corrosion only on a small number of pinhole areas and in obvious surface contaminated areas. The cut test (UL 1703) resulted in no exposed metal. QUV exposure after 1000 hrs. showed discoloration of all three formulations and microscopic examination showed corrosion.

Acrylic formulation No. 43 out performed No. 42. Water immersion testing of No. 42 had large areas of corrosion and No. 43 showed corrosion over contaminated areas (i.e., oily fingerprints) only. Formulation No. 43 appears to have better hardness properties and UL 1703 cut test only scratched the coating surface. A 15 cm x 33 cm module coated with No. 43 successfully passed wet hi-pot after submitting to UL 1703 cut test. QUV testing for 1000 hrs. exhibited no obvious coating discoloration, but microscopic examination showed evidence of the onset of corrosion (See Table 6.1).

PRELIMINARY COATING - TEST RESULTS						
Formulation	**Water Immersion**	**Thermal Cycling**	**Met Hi-Pot Testing**	**UL1703**	**QUV (1000 hrs.)**	**Processing Concerns**
No. 38	good; minimal corrosion, small pinholes	adhesion good	pass at 2250V t = ≈ 3 mils	exposed alum.	film yellowing corrosion at alum.	pull back; not completely cured pinholes.
No. 39	large number of pinhole corrosion	adhesion good	failed dry hi-pot	exposed alum. across majority of travel	film yellowing corrosion at alum.	incomplete curing pinholes
No. 40	good; minimal pinhole corrosion and areas of surface contamination	adhesion good	pass at 2250V t = ≈ 3.5 mils	scratched film; no exposed alum.	film yellowing corrosion at alum.	incomplete curing pinholes
No. 42	large corrosion areas	adhesion good	failed dry hi-pot	alum. exposed	no discoloring	curing good; application good
No. 43	good; minimal corrosion at areas of surface contamination	adhesion good	pass at 2250V t = 4 mils	scratched film; no exposed alum.	no discoloring	rapid drying; good curing, application good
No. 378	spotty areas of corrosion; air line corrosion	film discoloring	-	-	-	rapid curing (UV) single component
No. 393	large corrosion areas	film discoloring	-	-	-	rapid curing (UV) single component

Table 6-1

The UV curable coatings No. 378 and No. 393 were spray applied by hand. These film thicknesses were .084mm and .050mm respectively. Water immersion testing was performed on both coatings. Coating No. 393 showed signs of water permeability and corrosion within 48 hrs. The acrylate hybrid No. 378 performed much better. Spotty signs of hairline corrosion and water permeability were noted on some units after five days of water immersion. Further testing of the No. 378 acrylate with additional additives was pursued based on these encouraging results. These tests are ongoing. Subsequent thermal cycling tests indicate that both formulations No. 378 and No. 393 have discolored and lost adherence.

The two encapsulants selected for continued development are #40 and #43 since they show the most promise for passing hi-pot and environmental tests.

7.0 TASK 6: MATERIALS HANDLING

7.1 Introduction

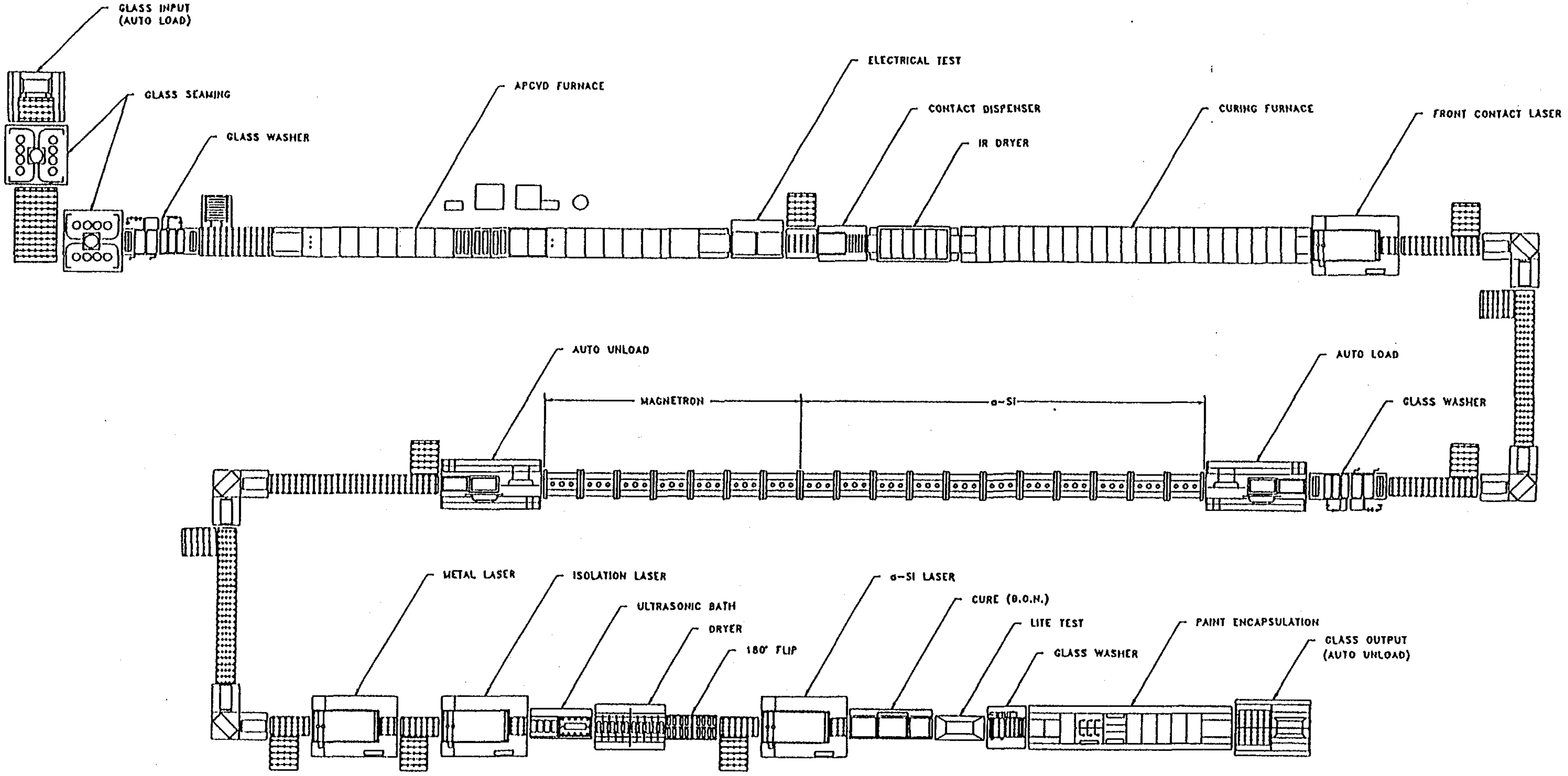
This team's efforts were directed at completing a layout of equipment, based on current processing techniques, which would be capable of producing ten megawatts of multi-junction thin film photovoltaic modules. Individual pieces of equipment will now be analyzed to determine facilitation, incoming materials and effluent handling requirements for producing a volume of 10 megawatts of large-area high efficiency multi-junction modules.

Interim manual materials handling techniques to produce prototype large-area modules have been under investigation over the last six months.

7.2 Ten Megawatt Plant Layout

The equipment layout for a prototypical thin film multi-junction photovoltaic module plant was completed (See Figure 7.1). Inputs from each of the PVMaT task teams as to their equipment requirements was gathered by the Task 6 team and a possible equipment layout was designed based on their current level of experience.

10 MW PLANT LAYOUT



APPROXIMATE AREA REQUIRED– 265 FT. X 150 FT. (39,750 SQ.FT.)

Figure 7.1

8.0 TASK 7: ENVIRONMENTAL TEST, YIELD AND PERFORMANCE ANALYSIS

8.1 Introduction

The task activities during this initial phase of the manufacturing technology program have emphasized the design and development of environmental and electrical testing capabilities and an electrical cure processing station for large-area triple-stack a-Si modules. The greatest emphasis has been placed on the design and fabrication of a large-area light soak station which was the first task milestone and which has been completed. In addition, progress has been made in developing capabilities for environmental testing, electrical testing and the electrical cure of triple-stack devices.

8.2 Light Soak Station

Evaluating the susceptibility of large-area modules to light induced effect is of primary concern as new processing methods are developed over the course of the program. The assembly of an appropriate light soak station early in the program, then, is essential.

Considerations in the design and fabrication of the light soak station in addition to size include the type of light source and its spectral content relative to absorption in the individual junctions of the triple-stack structure. The station has been sized to accommodate up to a 0.74 m^2 panel (0.41 m x 1.83 m) as may be eventually provided by the processing equipment.

Investigations were made of potential available light sources which might closely approximate the solar simulator. A review of several papers in the literature provided little direction on the use of light sources to soak triple-stack devices. Some stage lights with temperatures near 5500°C may be available but are judged to be expensive in operation and maintenance. DC argon arc lamps are also high cost and still have a spectral content which is not ideal. Sodium vapor lamps which have been used for indoor light soaking of single-junction a-Si have a high spectral content in the yellow and potentially would imbalance the middle junction in the triple-stack structure.

A separate study has been conducted comparing the light-induced effects of triple-stack panels exposed outdoors against similar panels exposed on sodium vapor lamps. The results of this investigation show that there are some differences in light-induced effects between the two methods; however, the differences are not as great as would have been expected and at longer exposure times on the order of 1000 hours or greater, they were only a few percentage points apart.[1] As a result of these data, the decision was made to proceed using the sodium vapor lamp as the light source for the large-area light soak station.

The light-soak station design evolved following this analysis is comprised of eleven high-pressure sodium lamps arranged in an array to illuminate the eight-square-foot area of interest under a support structure for the panels. The standard GE lamp reflectors were coated with a Kodak white reflectance coating to enhance the uniformity of light intensity across the array. The height of the support structure above the lamps was adjusted to provide a nominal light intensity of one sun. The panel support structure itself is comprised of a steel base and side rails on which glass panes are placed. Module temperature control is achieved using two large fans to circulate air over the unit.

Figure 8.1 shows the lamp configuration along with temperature and illumination mapping of the station. In designing the station, objectives of maintaining the temperature at less than 50°C and the light intensity within 30% of one sun were adopted. As shown on this figure, these objectives were met. The illumination was mapped using the short circuit current of an 20 cm x 20 cm a-Si reference module as measured on a Spire simulator. The illumination values shown on the figure are normalized relative to this measured short circuit current. The temperatures were measured by placing six 30 cm x 33 cm modules with thermocouples attached down the center of the illuminated area. The temperatures were recorded after 60 minutes of illumination.

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[1] Newton, James A., "Comparison of Amorphous Silicon Degradation Under Various Light Sources," NREL Photovoltaic Performance and Reliability Workshop, Golden, CO, September 1992.

8.3 Environmental Test

Efforts have been initiated to provide the capability for environmental testing of large-area triple-stack modules to meet the requirements of the Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules. This test capability will attempt to follow the interim plan explicitly except that a static load mechanical test capability will be provided in place of the dynamic mechanical load test.

The testing capability available to date for the testing of large-area modules of at least six square feet in size was reviewed and checked for functionality. Those available at this reporting period include the following:

- Thermal cycle
- Humidity freeze
- Dry hi-pot
- Hail test

A review of the requirements and design considerations for wet hi-pot testing has been made including a visit to the NREL test laboratories to observe their test equipment. Design activities for the test station to include both wet and dry hi-pot testing and edge insulation tests is in progress at this time .

Designs for the remainder of the interim test regime will be prepared over the next two quarters.

8.4 Electrical Test

The light sources available which might be used for electrical testing of triple-stack a-Si modules have been examined and continue under review. Pulse simulators such as LAPS units require large areas to set up and are expensive to purchase and maintain. In addition, the experience with thin-film modules is that special adaptations need to be made to compensate for capacitive reactance of the modules which affects the measured output curve during the very short duration of the light pulse. Spire simulators which are available at Solarex and NREL have been used to test a number of triple-stack submodules with reasonable results. It appears at this time that with proper reference cells and calibration, a Spire-type simulator would be adequate for large-area a-Si modules.

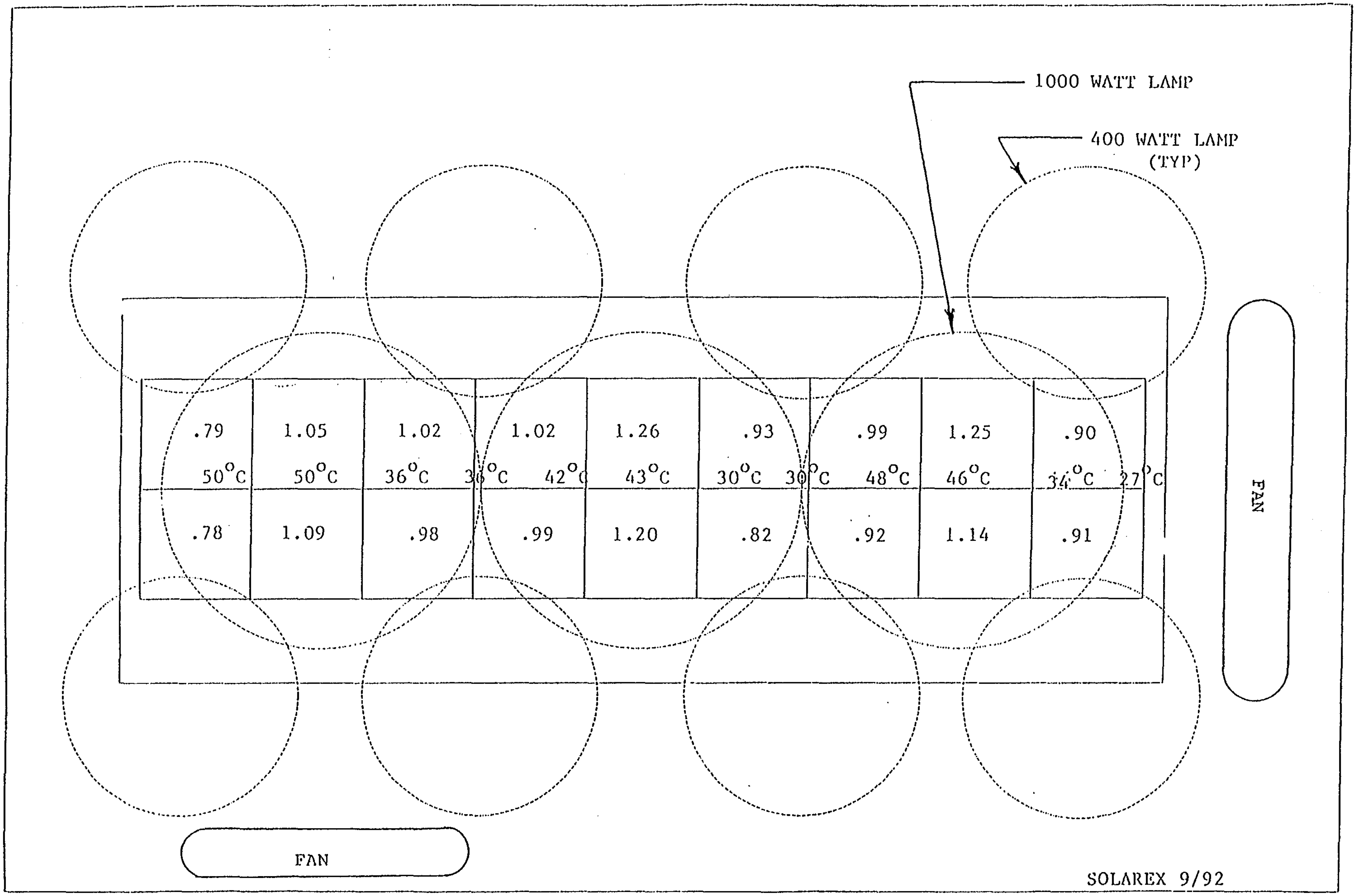
With the Spire simulator available at Solarex, the plan is now to proceed with fixturing and slight adaptations of this unit to demonstrate the manual testing of modules >0.56 m^2. The information derived from this activity will be used to design the automated electrical tester in later phases of the program.

8.5 Electrical Cure

The application of reverse bias electrical voltage to thin film a-Si diodes to "cure" minor film defects has been a common practice, and a beneficial one, on single junction modules. The object in the current program is to determine the reverse bias electrical parameters that apply to large-area triple-stack modules from a processing view point and design the process to implement them. Available triple-stack 30 cm x 33 cm submodules fabricated in at least three different deposition systems are being evaluated for necessary and tolerable reverse bias voltage and current requirements. Measurements recorded to this point indicate voltage tolerances for the triple-stack modules with silver back contact metal may be on the order of one volt lower than for single-junction modules with aluminum back contact metal.

Design of fixturing for manual curing of large-area modules has been initiated. This fixturing is to be mounted on a machine base which will be the framework to mount the electrical equipment for curing and, in later phases, the mechanics to automate the process.

LARGE AREA LIGHT SOAK STATION LAYOUT



SOLAREX 9/92

FIGURE 8.1

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16. Abstract (Limit: 200 words)

This report describes Solarex's work to advance its photovoltaic manufacturing technologies, reduce its a-Si:H module production costs, increase module performance, and expand the Solarex commercial production capacity. Solarex will meet these objectives by improving the deposition and quality of the transparent front contact; optimizing the laser patterning process; scaling up the semiconductor deposition process; improving the back-contact deposition; and scaling up and improving the encapsulation and testing of its a-Si:H modules. In the Phase 1 portion of this subcontract, Solarex focused on scaling up components of the chemical vapor deposition system for deposition of the front contact, scaling up laser scribing techniques; triple-junction recipes for module production; and metal-oxide back contacts. The goal of these efforts is to adopt all portions of the manufacturing line to handle substrates larger than 0.37 m^2.

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