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Module Process Optimization and Device Efficiency Improvement for Stable, Low-Cost, Large-Area, Cadmium Telluride-Based Photovoltaic Module Production

Final Subcontract Report
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SUMMARY

Background

This is the Final Technical Report under a three phase subcontract through the National Renewable Energy Laboratory (NREL), #ZN-0-19019.

Photon Energy Inc.(PEI), now Golden Photon (GPI), has been involved with the development of CdS/CdTe devices and modules since 1984. Starting in 1987, a three (3) year subcontract under SERI (now NREL) contributed to progress toward the common objectives between PEI and the Department of Energy(DOE). In mid 1990, a second three (3) year subcontract was begun through NREL in order to further improve the technology base at PEI in order to better address the commercialization issues and objectives of the PEI and DOE photovoltaic goals. PEI was searching for a strategic partner during this same time period in order to accelerate the transition to commercialization.

Independently, the Adolph Coors Company completed the spin-off of its technology businesses to ACX Technologies Company (ACX) at the end of 1992. For many years the Adolph Coors Company developed businesses based on new technologies that were either directly or indirectly related to its primary business - brewing beer. While many of these companies have been very successful, collectively they were perceived and valued by the financial community to be part of a brewing company rather than as stand-alone businesses. The formation of ACX, a completely separate holding company and entity from the Adolph Coors Company, has addressed and resolved that perspective.

In September of 1992, as part of the its new business development efforts, ACX purchased Photon Energy, Inc., located in El Paso, Texas, and subsequently re-named the company Golden Photon, Inc. (GPI). ACX moved immediately to focus the considerable technical and manufacturing expertise it had marshaled to successfully commercialize its other technology-based companies toward the development of new, low cost photovoltaic technologies and manufacturing processes.

Developmental laboratories are operational at the Golden facility and research and development programs have been initiated. Acceleration of these research and development activities will continue as further facility improvements are completed and added.

The GPI objectives in Photovoltaics are covered through continuing advancement in three major areas; specifically, module efficiency, reliability and cost.

The specific objectives of this three-phase program include:
- To achieve active area efficiencies of greater than 14% on small cells,
- To achieve aperture area efficiencies of greater than 13% on 1ft^2 modules,
- To achieve aperture area efficiencies of greater than 12.5% on 4ft^2 modules,
- To achieve greater than 20-year module life (based on life testing extrapolations) with no greater than 10% efficiency degradation.

Small Device Efficiency and 1ft^2 Modules

During the majority of this subcontract, much of the effort was re-focused onto 4ft^2 module output improvement and encapsulation issues; however, several other notable milestones were achieved:
- A 12.7% device with an area of 0.302 cm2 was measured at NREL with 12.7% efficiency.
- Open circuit voltages of 840mV to 846mV on small devices were measured at NREL.
- Short circuit currents of greater than 26mA/cm2 on small devices were measured at NREL.

- The measurement irregularities defined in the Phase 1 annual report have been satisfactorily resolved.
- Aperture area efficiencies of over 8% were achieved on 1 square foot modules. (Average active area efficiencies near 10% were measured on the same modules.)

Four Square Foot Module Results

Significant improvement of 4ft^2 module output and design has been attained within the last year. Through identification and incorporation of improved deposition techniques, total module layer uniformity improved significantly, resulting in notable improvements in overall module output as well as the distribution of module outputs within a batch as substantiated by improved module output distributions.

Historical trends indicate that improvements in average module output were able to be made in a relatively consistent manner as the quality control program evolved. Confirmation of the continuing positive outcome of these efforts has been further validated at NREL by the performance tests of a set of six 4ft^2 modules that were delivered to NREL for baselining and life testing. This set of six modules averaged 25.3 watts (normalized to a pyranometer reading in outdoor tests) with a 3% standard error for the distribution. The average aperture area efficiency of this batch measured 7.5%. The total area efficiency of the best module (26.5 watts) was 7.0%. The aperture area of the best module was 8.0%. The average active area efficiency of the best module was 9.1%. The rather poor utilization of the active/total area of the module is primarily due to the 12-14% optical loss caused by the poorly optimized interconnection methods that have been utilized. In spite of what remains to be accomplished, these confirmed module outputs achieve the initial internal product milestone for GPI.

Reliability Testing

A new design for encapsulation was adopted in late 1992. Qualification testing of the modules manufactured in El Paso appears successful. A number of design iterations have occurred and a great deal has been learned from the qualification testing done thus far. No significant problems are expected to be encountered during such qualification testing of the modules produced in the new 2 megawatt facility.

Initial life testing results of the first generation of the improved encapsulation design show that this improved non-corroding encapsulation design significantly. A number of these first generation modules broke in the field, but subsequent design improvements in the module seem to have resolved this issue and the quality control issues during processing appear to be the only significant remaining issue with reliability. After 175 days of exposure, the outdoor performance for the CdTe modules has remained within 5% of their initial baseline tests.

Environmental and Employee Health and Safety Issues

During Phase 2, a great deal of effort was placed on insuring that methods and policies for Employee Health and Safety were properly evaluated, implemented, and monitored. The equipment specifications and laboratory areas to be utilized in the 2 megawatt facility in Golden, Colorado, included a variety of engineering designs and improvements to insure that the OSHA and environmental regulations are met and greatly exceeded.

Golden Photon has developed a "cradle to cradle" recycling program for handling all of the manufacturing waste materials generated by the two megawatt facility, as well as any modules returned from the field. The establishment of such mechanisms is believed to be necessary in order to insure maximum recapture and recycling of such waste, consistent with the commitment of Golden Photon as a successful, safe, and environmentally friendly, commercial venture.

Summary of Results

The efficiency and stability objectives at GPI on CdS/CdTe modules are being addressed. To summarize:

- Efficiencies of 12.7% have been achieved on small area devices, but work for further efficiency improvement in this area was re-directed to large area development during Phase 2 of this subcontract.

- One square foot modules have achieved over 8% aperture area efficiency (active area efficiency up to ~10%), but work for further efficiency improvement on $1ft^2$ modules was re-directed to $4ft^2$ module output improvement.

- Four square foot modules have achieved 26.5 watt outputs, which calculates to 8.0% aperture area efficiency (9.0% active area efficiency) in Phase 3.

- Consistent prototype production was focused upon and substantially achieved within Phase 2 as evidenced by narrow batch distributions (~3%).

- Life testing at NREL (and GPI) shows no inherent stability problems with the CdTe technology, and the accuracy of module measurement has been satisfactorily resolved.

- A "cradle-to-cradle" recycling program has been initiated based upon the philosophy that the establishment of such mechanisms will be required to insure maximum recapture and recycling of all manufacturing waste materials and/or modules returned from the field.

Progress has been made and advancement is expected to continue as GPI enters a commercial mode.

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1.0 INTRODUCTION AND OBJECTIVES

Background

Photon Energy, Inc. (PEI), now Golden Photon, Inc. (GPI), had been involved in the development of CdS/CdTe photovoltaic modules since 1984. In 1987 a 3-phase, 3-year subcontract through the Solar Energy Research Institute (SERI) was undertaken. The objectives under this former subcontract were primarily directed toward the further development of an improved materials technology and fabrication processes for limited volume production of $1ft^2$ and $4ft^2$ CdS/CdTe photovoltaic modules, with stability and efficiency goals being the most significant milestones. The research and development efforts included improvement and further development in the areas of electroding, encapsulation, doping, small cell as well as 1 ft^2 and 4 ft^2 module performance optimization, and accelerated as well as real time life testing.

Under this earlier 3-year subcontract through SERI (now NREL) starting in 1987, PEI/GPI had succeeded in producing and delivering to NREL a number of significant deliverables. A $1ft^2$ module was measured at NREL with 7.3% aperture area efficiency with a corresponding output of 6.11 watts. During this earlier subcontract the aperture area efficiency on $1ft^2$ modules was increased from 5.4% to 7.3%. Small devices (0.302 cm^2), cut from $1ft^2$ substrates, were produced and delivered to NREL during this earlier subcontract as well. The best of these devices measured 12.3% efficiency, 0.78 volts in open circuit voltage (V_{oc}), 25.0 mA/cm^2 in short circuit current density (J_{sc}) and 62.7% in fill factor. Regarding stability and life testing, an encapsulation system was developed and patented under this subcontract. An early version of this encapsulation system resulted in stable life tests lasting longer than 9 months (the duration of the test at that time) in NREL outdoor life tests [1].

In June of 1990, a second, three-phase subcontract (ZN-0-19019) through SERI (now NREL) was undertaken by PEI/GPI. The objectives were to continue the further development of an improved materials technology and fabrication processes for limited volume production of $1ft^2$ and $4ft^2$ CdS/CdTe photovoltaic modules. The specific milestones relate to small device and module efficiency improvements, module area enlargement, module reliability assessment and improvement, and module cost reduction.

In early 1992, the Adolph Coors Company was preparing to spin-off its technology businesses to ACX Technologies Company (ACX), and it completed this transaction by the end of 1992. For many years, the Adolph Coors Company has developed businesses based on new technologies that were either directly or indirectly related to its primary business - brewing beer. While many of these companies have been very successful, collectively they were perceived and valued by the financial community to be part of a brewing company rather than as stand-alone businesses. The formation of ACX, a completely separate holding company and entity from the Adolph Coors Company, has addressed and resolved that perspective.

As part of its new business development efforts, in September of 1992, ACX purchased Photon Energy, Inc., located in El Paso, Texas, and subsequently re-named the company Golden Photon, Inc. (GPI). ACX moved immediately to focus the considerable technical and manufacturing expertise it had marshaled to successfully commercialize its other technology-based companies toward the development of new, low cost photovoltaic technologies and manufacturing processes.

Status of Facilities

The El Paso facility of PEI/GPI was originally constructed and operated purely as a small-scale photovoltaics research and development facility, with very low-volume manufacturing capability. Subsequent to purchase by ACX, however, the focus of the El Paso facility was significantly re-directed toward the identification and development of the manufacturing processes and equipment that would be required to construct an entirely new two megawatt photovoltaic module manufacturing facility that would utilize Photon Energy's proprietary Cadmium Telluride technology.

After approximately one year of intensive Operations and R&D study, sufficient progress in the definition of process and equipment parameters had been established to begin construction of the new two megawatt facility. All manufacturing activities were suspended at the El Paso facility in September, 1993.

Golden Photon's new two megawatt manufacturing facility is currently being constructed within the existing ACX technology center. It occupies 30,000 square feet of manufacturing space, with specific areas designated for R&D labs, process control, encapsulation and packaging and shipping. With an estimated annual production capacity of approximately 80,000 modules, Golden Photon's new manufacturing facility will produce approximately two megawatts of total power output capacity at currently projected total module efficiency of 6.5 % average during initial phases.

Start-up of the production lines within the new facility is underway. Product is scheduled to be commercially available by mid-year. The first year's total annual production target for the facility has intentionally been set at a conservative 0.7 megawatts.

Limited R&D activities continued in El Paso until late October. Developmental laboratories are presently operational at the Golden facility and research and development programs have been initiated. Acceleration of these research and development activities will continue as further facility improvements are completed and added.

Specific Goals For The Present Subcontract

The specific objectives of this three year subcontract (#ZN-0-19019) were:

- To achieve active area efficiencies of greater than 14% on small cells
- To achieve aperture area efficiencies of greater than 13% on $1ft^2$ modules
- To achieve aperture area efficiencies of greater than 12.5% on $4ft^2$ modules
- To achieve greater than 20-year module life (based on life testing extrapolations) with no greater than 10% efficiency degradation

In order to accomplish the above objectives, the program has been designed to include the following task areas:

TASK I: Windows, Contacts, and Substrates (External device optimization)

o Improved CdS window layers using various methods of deposition, including chemical deposition from solution

o The tin oxide window layer-electrode resistivity and uniformity

o Improved electroding techniques

o Reduction of optical losses due to module division

TASK II: Absorber Material (Internal device optimization)

o The deposition, characterization and evaluation of CdTe alloys

o The characterization, evaluation, and improvement of morphology effects of the CdTe

TASK III: Optimization of Device Structure

o Electronic characterization and modeling of the device

o The development of improved device structures where applicable

TASK IV: Encapsulation

o Analysis and optimization of present methods

o Hermetic sealing techniques

o Isolation of and concentration on long term corrosion issues

<u>TASK V:</u> Process Optimization

- Understanding the diffusion and reaction kinetic issues of the process
- Exploration and improvement of heat transfer issues

TASK VI: Employee Safety Evaluation and Improvement

- Evaluation and improvement (where necessary) of monitoring program for Cd in the workplace
- Evaluation and improvement (where necessary) of policies and practices affecting worker safety in the workplace

The major results of each task are reviewed within the framework of the following criteria:

1) Increasing Cell and Module Efficiencies (Small Device Results)
2) Increasing Module Areas (1ft^2 and 4ft^2 Module Results)
3) Improving Module Reliability (Reliability Testing)

2.0 SMALL DEVICE RESULTS

Device Structure

As reported previously [2], a 0.6-0.9 micron film of tin oxide is deposited onto commercial 3 mm float glass by spray pyrolysis, at a deposition temperature of approximately 480 Celsius. A typical resistivity for the tin oxide film is 4-5 x 10^{-4} ohm-cm, and typical extinction coefficients are 900-1100 cm^{-1}. The tin oxide films generally measure 5-9 ohms per square in sheet resistance and 90%- 95% transmission relative to the glass substrate over the wavelength range from 520 nm to 850 nm, with a variation of 10%-40% in sheet resistance across a $4ft^2$ substrate.

A thin layer of CdS is then deposited on top of the tin oxide. Voltage-biased capacitance measurements, using Schottky diodes deposited on this CdS, indicate a carrier concentration on the order of 1 x $10^{18}/cm^3$. Approximately 6 microns of CdTe is then deposited on top of the CdS; the measured hole concentration of the CdTe is on the order of 1 x $10^{15}/cm^3$. To complete the device, a graphite electrode is deposited on top of the CdTe to a thickness of approximately 10 microns. The top electrode is completed by the evaporation of a tin-based metal contact of approximately 1 micron thickness.

Performance Optimization

Utilizing this structure, a device with an area of 0.302 cm^2 was delivered to NREL and was measured in May of 1991 as 12.7% efficiency [3]. The open circuit voltage (V_{oc}) was measured as 799 mV and the short circuit current density (J_{sc}) was measured as 26.21 mA/cm^2 for this device. The fill factor was low at 60.5%. When the fill factor is raised to 70%, the corresponding efficiency will be ~14.7%.

Several devices from GPI were measured at NREL with over 26 mA/cm^2 for J_{sc}. The highest measured J_{sc} in that set was 26.23 mA/cm^2 [4]. These high currents, and the associated high quantum efficiencies at higher than CdS bandgap energies, became the norm at GPI and have been reported previously [5]. Relative quantum efficiencies in the 85-95% range at wavelengths of 400nm are achieved, at present, on small devices and it is expected that similar quantum efficiencies will be the norm on larger area modules once satisfactory process control has been achieved.

Typical standard-type devices at GPI have efficiencies in the range of 10-12%, J_{sc} values of 24-26 mA/cm^2, V_{oc} values of 770-800 mV and correspondingly low fill factors (54-58%). Improvement of the diode factor is the obvious direction of effort in order to increase the fill factors on typical GPI devices. Improvement of the fill factor to 67-69% would result in efficiencies of 12.4-14.3% using the same values for the other parameters.

Additionally, improvement of the Voc from the approximately 800mV to approximately 850mV would provide another significant improvement in efficiency. As reported earlier [4], voltages provided by the efforts of Dr. T.L. Chu during Phase 1 were typically significantly better than voltages observed with the standard GPI device.

In subsequent experiments at GPI, V_{oc} values of 846 mV were observed on devices made by GPI processing. The indications observed through the solution-grown CdS provided by Dr. Chu at USF were instrumental in helping to direct the activities within the GPI program toward this high voltage milestone. The early attempts at this improved device type result in a different set of parameters from the typical GPI device discussed above: namely higher voltage and high fill factor.

Eff = 10.4%
V_{oc} = 838 mV
J_{sc} = 18.1 mA/cm^2
Fill Factor = 69%

Combining these parameters with a typical J_{sc} value at PEI/GPI of 24-26 mA/cm^2 results in efficiencies of 13.8-14.9%.

Thus, improvement of current on low current, high voltage, high fill factor devices such as these, or improvement of fill factor on low fill factor, high current, average voltage standard GPI devices results in the same range of device efficiencies. Issues regarding advancements on both types of devices and approaches continue to be addressed.

Once the 12.7% device was achieved as a milestone during Phase 1 of this Subcontract, and once the issues related to increasing the efficiency to 14-16% were identified, it was realized that with limited resources the most immediate priority was to demonstrate that a viable commercial entity could exist. Device efficiency improvement, and therefore fill factor improvement, was postponed but will resume again once the GPI laboratories become fully operational.

Solution Grown CdS Layer

During Phase 1 of this NREL subcontract, a lower-tier subcontract, through the University of South Florida (USF), had been utilized for a large part of the device development under the first phase of this subcontract. Dr. T.L.Chu and his group at USF were instrumental in the development of PEI/GPI-USF devices based on "solution-grown" CdS. Part of the USF efforts under this subcontract were to help develop solution-grown CdS for use as our thin CdS layer. Appendix A of the Phase 1 annual report contains the Final Report of USF under this Lower-Tier Subcontract [6].

The major results of the collaborative efforts between GPI and USF are reviewed here. This work pointed the way for GPI to advance toward some of its own voltage and efficiency improvement milestones. Under global AM 1.5 conditions (measured at NREL), the highest efficiency cell under the USF collaboration had a V_{oc} of 0.8384 V, J_{sc} of 23.08 mA/cm^2, and FF of 57.8%, corresponding to a conversion efficiency of 11.2% [7]. One of the experimental iterations resulted in devices which produced devices with over 840mV. It was measured at NREL as 842mV [8]. Dr. Chu and his group had therefore been able to achieve V_{oc} values that were typically higher than the best results at GPI. Typical standard-type devices at GPI had efficiencies in the range of 10-12%, J_{sc} values of 24-26 mA/cm^2, V_{oc} values of 770-800 mV and correspondingly low fill factors (54-58%). The diode ideality factor is typically quite high as measured via the method of Sites [9]. Improvement of the diode ideality factor is the obvious direction of effort in order to increase the fill factors on typical GPI devices. Improvement of the fill factor to 67-69% would result in efficiencies of 12.4-14.3% using the same values for the other parameters. Additionally, combining the high V_{oc} and fill factor values on the devices of Dr. Chu with the high quantum efficiency and J_{sc} values on GPI devices should result in 14-15% efficient devices.

Thus, improvement of current on low current, high voltage, high fill factor devices such as these, or improvement of fill factor on low fill factor, high current, average voltage, GPI standard devices results in the same range of device efficiencies. Issues regarding advancements on both types of devices and approaches will continue to be addressed.

Technical feasibility was shown for solution grown CdS at PEI/GPI. The laboratory results appeared promising due to the potential improvements that may be attained with respect to the scale-ability and the simplicity of such a low-temperature deposition method. The complete question of the economics of solution grown CdS in production at GPI remains to be resolved. A manufacturing prototype has been completed to be able to determine the economics of the method.

Tin Oxide Resistivity Improvement

Specific resistivities of tin oxide produced on large-area substrates have been observed as low as 2.4 x 10^{-4} ohm-cm at PEI/GPI. This occurred on very thick layers of tin oxide (in the range of 1.8 to 2.7 microns). It has not yet proven possible to achieve these values on films with thicknesses in the useful range of 0.2 to 0.8 microns. The typical specific resistivity values which are presently utilized in the interim period are between 4.0 and 4.5 x 10^{-4} ohm-cm.

For most activities at GPI, a tin oxide coated glass substrate with comparable specifications to the above is purchased from Libby-Owens-Ford (LOF) and is designated by them as "TEC-8".

Improved Electroding Techniques

Various dopants and methods of dispersion of dopants into graphite paste electrodes have been evaluated. None have shown improved performance and improved stability at the same time. Efforts continue within this area, but it is felt that the major hindrance to advancement within this area is actually the morphology of the CdTe itself. For evaporated electrodes, the shunt paths caused by pinholes and porosities within the CdTe layer are an issue to be reckoned with in order to proceed with alternative electrodes other than paste electrodes. That is, until the CdTe morphology is improved, alternative electrode development will be postponed. The morphology improvement of the CdTe layer will be pursued at a later time, but the priority is not as high as achieving improved outputs on 4ft^2 modules.

Minimization of Optical Losses Due to Module Division

The interconnection steps of the present process utilize methods which appear inherently limited to approximately 8-10% optical loss. The present normal range in prototype production is approximately 11-14% optical loss. Methods have been conceived at GPI to reduce this excessive optical loss to approximately 3-4% without complete optimization. A program is in place to fabricate prototype modules using these improved methods.

3.0 ONE SQUARE FOOT AND 4 SQUARE FOOT MODULE RESULTS

Milestones and Deliverables Under the Present Subcontract

This subcontract is denoted a "best effort" type contract. The milestones and deliverables were designed to keep close tabs on the improvements in device structure, module design and efficiency that result from the development of superior module-producing technology.

Many of the deliverables were intended for initial measurement and subsequent life testing. With this in mind it was agreed that PEI/GPI should, after an initial delivery of six 1ft^2 modules, deliver four 1ft^2 modules and two 4ft^2 modules every six months of the subcontract to SERI for testing and life testing. These deliverables were accomplished and helped provide, through NREL, the majority of the life testing data developed during this subcontract on PEI/GPI modules.

Under the present contract, a number of the Phase 1, 2 and 3 milestones were either achieved or approached in a best effort manner. During the early part of Phase 3, Golden Photon spent at a rate higher than was originally proposed, in order to accelerate module development. As a result, funding was not sufficient to continue any significant effort under this subcontract in 1994. Even though the contractual moneys have been depleted, GPI has continued and will continue to address the goals and milestones of this subcontract where they align closely with Golden Photon's own goals.

One Square Foot Module Results

In September 1991, two 1ft^2 modules were sent to NREL for output measurement and confirmation. Aperture area efficiencies of 7.6-8.3% and module outputs of 6.4 to 6.8 watts were reported. Average module active area efficiencies of 9.5-10% were also part of these modules. The disparity between active area and aperture area was due primarily to non-optimized optical division losses that totaled approximately 13%. Also, there were a number of issues regarding the accurate testing of larger area modules identified and resolved during the first and second phases of this subcontract. These issues are discussed in the following section, Performance Measurement Issues. The following results are a comparison of tests that were done on a pair of 1ft2 modules prior to a complete resolution of the performance measurement issues.

	GPI	NREL
AAB885B		
P_{max} (un-normalized)	6.4W	6.80W
P_{max} (normalized)	6.4W	6.54W
V_{oc}	21.1V	21.1V
I_{sc} (normalized)	0.590A	0.601A
FF	52%	51.6%
Aperture Area Efficiency	7.8%	7.9%
Active Area Efficiency	8.9%	9.1%

AAC024B		
P_{max} (un-normalized)	6.87W	6.59W
P_{max} (normalized)	6.84W	6.30W
V_{oc}	21.5V	21.3V
I_{sc} (normalized)	0.605A	0.597A
FF	52%	49.5%
Aperture Area Efficiency	8.3%	7.6%
Active Area Efficiency	9.4%	8.7%

Aperture area on both of these modules is 825 cm^2. The active area for AAB885B is 719 cm^2 and for AAC024B is 724 cm^2 [10].

In spite of the measurement variation, it was concluded that GPI has attained aperture area efficiencies on modules between 7.6% and 8.3% on 1 ft^2 modules. Active area efficiencies are rather high, due to poor utilization of module area (non-optimized interconnection losses). Active area efficiencies on modules have additionally been observed at PEI in the range of 9.4-9.9%. Interconnection optimization, uniformity across the modules and improvement of the fill factor (through improvement of the diode ideality factor) should result in significant improvements in module output for the near term. As these issues are further resolved, the originally-projected milestone goal for aperture area efficiencies of 10% should be realized and exceeded.

In late 1991, a reassessment of the 1ft^2 module efficiency goals within this subcontract was undertaken. The major goals of PEI/GPI as well as the U.S. Department of Energy (DOE) are primarily concerned with low cost commercialization of photovoltaics. In that light, the result of that reassessment indicated that module sizes at least 4ft^2 in area were necessary in order to achieve reasonable economics for successful commercialization. 1ft^2 module aperture area efficiencies had already been demonstrated in the 8% range. Extrapolating the 1ft^2 module results to the 4ft^2 modules resulted in projected 4ft^2 module outputs that were acceptable from a market entry standpoint. That is, 24 watt, 4ft^2 modules appeared to be satisfactory for a market-entry product from both a performance and economic standpoint. Therefore, by the end of November, 1991, all available efforts were re-directed toward reproducing on 4ft^2 modules the efficiencies observed on the 1ft^2 modules.

Performance Measurement Issues

As described in the Phase 1 Annual Technical Report, there are a number of issues associated with the accurate measurement of PEI/GPI modules. The pulse simulator typically utilized for large area module testing does not appear to be a satisfactory means of testing PEI/GPI and other modules that have a significant time constant for readjusting the internal bias due to the existing bias condition.

Through a number of 1ft^2 and 4ft^2 module tests, it has been shown that the LAPSS (Pulsed Simulator), normally utilized for large area module measurement, is not presently acceptable for measurement of the present GPI module. The LAPSS tests on a number of modules varied between 14.7% low to 20.7% low [11]. This large variation itself precludes the use of the LAPSS for testing or life testing use at the present time.

Even on the continuous Xenon artificial sun source at NREL, one has to insure that pre-biasing of the device at other than the maximum power point is minimized or avoided. As an example of this sensitivity to pre-biased condition, Fig. 3-1 shows a device test (0.30 cm^2) with 10 seconds under illumination at 2.0 V forward bias prior to acquiring the current-voltage (I- V) performance curve. Fig. 3-2 shows the same device tested after pre-biasing at 0 V (short circuit) for 30 seconds prior to testing without a maximum power point soak before measuring the I-V curve of the device. Fig. 3-3 shows a repeat test of Fig. 3-1 to indicate the reversibility of the effect. Fig. 3-4 shows the proper testing sequence utilizing a 10 second maximum power point soak prior to running the I-V curve for the device. Fig. 3-5 is the same device tested 15 minutes later, after the sample has re-equilibrated to room temperature. A positive-temperature coefficient for the fill factor is readily observed here. The rate of ramping through the voltages during acquisition for these devices was approximately 40mS per point, points taken in steps of ~10 mV. The V_{oc} is affected by temperature to the extent of ~2 mV per degree Celsius and the temperature rise of the substrate is estimated to be less than ~10 degrees Celsius.

It becomes apparent that these devices do not immediately adjust to their instantaneous bias condition. Since this is the case, it is necessary to incorporate a maximum power point tracking algorithm into the testing sequence in order to obtain accurate, repeatable, and realistic device efficiencies.

The J_{SC} values appear from these curves to be independent of the pre-biasing sensitivity condition. The V_{OC}, and therefore the calculated parameter of fill factor, appears to be quite dependent on the pre-biasing condition. The only parameters that can then be properly determined from a standard I-V curve on this type of device are the J_{SC} and the maximum power point (assuming a maximum power point tracking algorithm is utilized). In order to attain accurate V_{OC} and fill factor values, the V_{OC} of the device (or module) must be taken after relatively long term equilibration (at a constant temperature) using a standard intensity (with a standard spectral content) light source with a fixed-value high-impedance meter. An accurate V_{OC} will then be measurable and an accurate fill factor can then be properly determined.

In a study of this effect conducted at Colorado State University [12], the major conclusions were:

- The voltage effect is real and reversible.
- The voltage effect is dependent on voltage history, not illumination history.
- Physically, the effect is almost certainly the result of changing the occupation of traps at the junction.
- This voltage effect is expected to be significantly reduced as the junction quality is improved (lower diode ideality factor).

An attempt was made to measure the decay constants of the maximum power point output under various biasing conditions. A part of the results of this experimental work by K.Emery are shown in Fig. 3-6 [13]. Notice the slowness of the response re-equilibration after each change in pre-biasing condition. Also notice the reversibility of this effect.

A significant amount of measurement difficulty and uncertainty had arisen on the GPI modules due to the above described testing issues. For module sizes larger than ~4" x 6", there has been considerable question regarding accurate measurement of PEI/GPI module outputs. The pulse simulator typically utilized for large area module testing does not appear to be a satisfactory means of testing modules such as ours which have a testing sensitivity to the prior-biasing condition of the module.

NREL has implemented a methodology that was mutually worked out between NREL and PEI/GPI. This method includes maximum power point tracking (a minimum of 10 seconds, preferably as long as 30 seconds of more) to minimize voltage bias deviation from the actual maximum power point in order to minimize this response error. After the determination of the maximum power point, the IV performance curve is produced by scanning from high voltage to low voltage to help minimize the effect. The method also attempts to minimize the temperature rise of the module in an outdoor test and utilizes a similar reference standard calibrated at NREL in addition to the pyranometer reading that is usually utilized for normalizing outdoor tests. This second reference is intended to grant the ability to throw out data points when the references do not agree with each other within a certain allowable range since these references are constructed with the same device structure as the module being tested. The Power Output and the Isc values are believed to be accurate within an error of approximately 3-5% of the value obtained.

Four Square Foot Module Results

$4ft^2$ Module Efficiencies and

A $4ft^2$ module from PEI/GPI was tested at NREL in late 1991 measuring 21.3 watts when normalized to 1000 W/m2. During the entirety of Phase 2, the overwhelming majority of R&D effort was focused upon improvement of the output of $4ft^2$ modules. Figures 3-7, 3-8, and 3-9 show the trend line of module output early 1992 showing poor control and little progress. Figure 3-8 is a snapshot from mid to late 1992 showing some progress and numerous setbacks. The variability of results from batch to batch and within batches is a testament to a basic lack of process control. Such conditions are typically found in any start-up prototype line and the El Paso facility proved to be no exception. During Phase 2, a considerable amount of process understanding was attained, and poised GPI for more rapid advancement within Phase 3. Figure 3-9 is another snapshot that ends at the completion of Phase 2 (April, 1993). The trends in this figure show that the module outputs continue to improve in a consistent manner. To further substantiate the issue of process control improvement, Figure 3-10 shows the distribution of modules within the batch of 9 designated as #7 in Figure 3-9. Once the trash modules in the lower output range are thrown out as a yield loss, the remaining distribution is nearly Gaussian in form and it appears to have a total spread (2-3 standard deviations) of less than 0.5 watts out of 22 (or approximately 2.5%). Even though module outputs were lower than desired, there was significant improvement and process control also improved. The understanding of the process leading to process reproducibility & improved output was invaluable.

Significant improvement of 4ft^2 module output and design has been attained within the last year. Through identification and incorporation of improved deposition techniques, total module layer uniformity improved significantly, resulting in notable improvements in overall module output as well as the distribution of module outputs within a batch. Figures 3-11 and 3-10 show an early and a more recent module output distribution to substantiate the improvements that have also been made in process control.

A large part of the module output improvements observed in Figure 3 was due to uniformity improvement.

As an example, Figure 3-12 and 3-13 show uniformity profiles of efficiency over an early, non-uniform module (Figure 3-12) and a later, much more uniform module (Figure 3-13). This type of analysis and process feedback has been found to be invaluable in improvement of module output. It is clear that a large improvement in uniformity has occurred. It is primarily this type of information feedback that has supported process control that allowed these consistent trend lines to be achieved.

The historical trends shown in Figures 3-7, 3-8, and 3-9 indicate that improvements in average module output were able to be made in a relatively consistent manner as the quality control program evolved. Confirmation of the continuing positive outcome of these efforts has been further validated at NREL by the performance tests of a set of 6-4ft^2 modules that were delivered to NREL for baselining and life testing. This set of six modules averaged 25.3 watts (normalized to a pyranometer reading in outdoor tests) with a 3% standard error for the distribution. The average aperture area efficiency of this batch measured 7.5 %. The total area efficiency of the best module (26.5 watts) was 7.0%. The aperture area of the best module was 8.0%. The average active area efficiency of the best module was 9.1%. The rather poor utilization of the active/total area of the module is primarily due to the 12-14% optical loss caused by the non-optimized interconnection methods that have been utilized. In spite of what remains to be accomplished, these confirmed module outputs achieve the initial internal product milestone for GPI.

4.0 ENCAPSULATION, QUALIFICATION, & RELIABILITY TESTING

Qualification Testing

Qualification testing of the prototype modules manufactured in El Paso resulted in a number of generation of module designs. Modules produced from the new Golden facility will employ the IQT qualification test protocol. No significant further problems are expected to be encountered during such qualification testing of the modules produced in Golden since all the tests including long term humidity exposure have been done in some fashion on the El Paso modules.

Several tests above and beyond the standard qualification tests are in the process of being evaluated for their ability to discern quality control problems before the module is deployed in the field. This is an important area requiring significant attention in order to be able to properly warranty a long life photovoltaic module.

Reliability Testing

The life testing data from NREL is meant to form an integral part in the achievement of the reliability objective under this program. That is, the ability to extrapolate life testing data to determine what amount of degradation (if any) will occur after 20 years' exposure in the outdoor environment. In order to be able to extrapolate life testing data accurately, one must assure narrow error bars exist. As mentioned above, the difficulties associated with this accurate measurement are substantially resolved, so that measurement issues related to reliability projections should no longer be limiting.

Encapsulation and module design are the lynch pins of reliability for photovoltaic modules. There have been a number of sets of modules in a variety of stages of development delivered to SERI and NREL by PEI/GPI in the past several years. A number of the early sets were meant to serve as "proof-of-concept" indications that no initial degradation occurs and that CdTe is not inherently unstable. A number of the earliest attempts were presented for life testing at NREL without sufficient weatherproofing. The result has been that after several years the encapsulation system on a number of these modules has failed [14]. As the encapsulation system and weatherproofing has advanced, these types of failures have been reduced as well. As progress in module design and quality assurance continue, these types of field failures are expected to be reduced to insignificance.

Quality control issues related to encapsulation have been determined to be responsible for most if not all of the dramatic failures in the field. It was earlier concluded that $1ft^2$ modules had water vapor permeability's of 2mg to 50mg per year per linear foot of module edge[15]. Thus, as long as the assembly of these encapsulated modules proceeds properly, the performance of the encapsulation system is quite good. Testing of the encapsulation quality is not trivial, and development of acceptable methodology for this quality control step has lagged. As this quality control improves, however, it is expected that such failures will be reduced significantly.

Figure 4-1 shows the NREL life testing data on an early module design toward the end of Phase 1 of this subcontract. The most recent life testing data presented by NREL are shown in Figure 4-2. There modules were delivered to NREL in December of 1992, and are constructed of a first-generation improved encapsulation design based on a glass-to-glass format. This figure shows the initial life testing results of the first generation of the improved encapsulation design implemented in late 1992. With this non-corroding encapsulation design improvement, the quality control issues during processing appear to be the only significant remaining issue with reliability. A number of these first generation modules broke in the field, but subsequent design improvements in the module seem to have resolved this issue. This should be able to be substantiated in the relatively near future by not only accelerated testing, but also by actual field tests. After 185 days [16], the outdoor performance for the CdTe modules has remained within 5% of their initial baseline tests. More sets with the non-breaking design are scheduled to be deployed in the near future.

The fact that a number of modules have shown no significant degradation indicates that there is probably no inherent degradation problem associated with CdTe modules. As further improvements to the encapsulation system and module measurement techniques continue to be made, reliable module lifetimes are expected to become more homogeneous and likely show excellent ongoing reliability on both real time and accelerated life tests.

A reliability milestone for this subcontract and for GPI is: "To achieve indications of less than 10% degradation of modules extrapolated to 20 years." Given the life testing results already in hand, the design improvements that are being conceived and tested, and the reduced measurement error bars, this milestone is likely to be met in the near future.

5.0 ENVIRONMENTAL AND EMPLOYEE SAFETY AND HEALTH

Safety in the Workplace

During Phase 2, a great deal of effort was placed on insuring that methods and policies for Employee Health and Safety were properly evaluated, implemented, and monitored. This is especially necessary since GPI has been in a preparatory mode for operating the 2 megawatt facility in Golden. In late 1992, the amended OSHA standards for airborne cadmium of 5 micrograms/cubic meter went into effect. Proper monitoring plans were implemented and proper procedures, engineering designs and controls were evaluated and implemented for the existing process is El Paso in order to achieve these regulations. Additionally, the equipment specifications to be utilized in the 2 megawatt facility in Golden, Colorado, included a variety of engineering improvements over those in El Paso to insure that the OSHA regulations are met and exceeded many-fold.

Environmental Issues

In 1965, the Adolph Coors Company invented the aluminum can, and subsequently initiated and aggressively pursued the concept of recycling/reclaiming the valuable raw materials contained in these cans. Consistent with this commitment to recycling, and as a fundamental approach to doing business, Golden Photon has developed a “cradle-to-cradle” program for handling all of the manufacturing waste materials generated by the two megawatt facility, as well as any modules returned from the field. This program consists of agreements currently in place with primary cadmium producers and refiners, as well as the incorporation of return/recycle agreements with utility customers purchasing Golden Photon’s photovoltaic modules. Additionally, a consumer/distributor rebate program is being developed to assure the recapture of the maximum amount of material possible.

Additionally, the expertise available to Golden Photon through ACX has been applied toward the resolution of all the environmental issues related to each process step. The effort in this area has been significant and all permitting issues have been resolved for the Golden facility.

6.0 COMMENTS, CONCLUSIONS, AND FUTURE PLANS

The development of the equipment design and process parameters for the new 2 megawatt facility resulted from the recognition that a significant improvement in the ability to identify issues and control each step in the manufacturing process was required over that which was initially in place at the El Paso facility. Accordingly, implementation of Statistical Process Control procedures within the operation resulted in dramatic improvement in panel uniformity and batch distributions. Notable improvements in overall module output were the results of these efforts.

As stated in the Deliverables section, in August of 1993 a set of six 4ft^2 modules was delivered to NREL for baselining and life testing. This set of six modules averaged 25.3 watts (normalized to a pyranometer reading in outdoor tests) with a 3% standard error for the distribution.

These module outputs achieve the initial product milestone for GPI. The average aperture area efficiency of this batch measured 7.5 %. The aperture area of the best module (26.5 watts) was 8.0%. These module efficiencies are expected to improve further in the near term by improved module interconnection and encapsulation design as well as improved quality control and process control measures.

Summary of Primary Subcontract Results

The efficiency and stability objectives at GPI on CdS/CdTe modules have been addressed. To summarize:

- Efficiencies of 12.7% have been achieved on small area devices, but work for further efficiency improvement in this area was redirected to large area development during Phase 2 of this subcontract.

- One square foot modules have achieved over 8% aperture area efficiency (active area efficiency up to ~10%), but work for further efficiency improvement on 1ft^2 modules was redirected to 4ft^2 module output improvement.

- Four square foot modules have achieved 26.5 watt outputs, which calculates to 8.0% aperture area efficiency (9.0% active area efficiency) in Phase 3.

- Consistent prototype production was focused upon and substantially achieved within Phase 2 as evidenced by narrow batch distributions (~3% standard error).

- Life testing at NREL (and GPI) shows no inherent stability problems with the CdTe technology, and the accuracy of module measurement has been satisfactorily resolved. Some residual packaging problems remain but are likely to be certifiably solved in the near future.

- A "cradle-to-cradle" recycling program has been initiated based upon the philosophy that the establishment of such mechanisms will be required to ensure maximum recapture and recycling of all manufacturing waste materials and/or modules returned from the field.

Progress has been made and advancement is expected to continue beyond this subcontract as GPI moves into the commercialization phase.

The most important areas for future development efforts are:

- Continued efficiency improvements (both active area and aperture area) on 4 ft^2 modules.

- Continued efforts in encapsulation design and the quality control steps of the encapsulation assembly and qualification sequence.

- Continued and expanded life testing at both NREL and GPI to insure quality and longevity.

- Continued evaluation of the development of efficiencies on small devices.

7.0 ACKNOWLEDGMENTS

We at GPI would like to acknowledge the efforts of the NREL administrators, monitors, and technical support teams as well as other NREL subcontractors who have contributed to the efforts and advancement at GPI under this Subcontract.

8.0 REFERENCES, PUBLICATIONS, AND AWARDS

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16. L. Mrig, Personal Communicate, Aug.-Sept., 1993.

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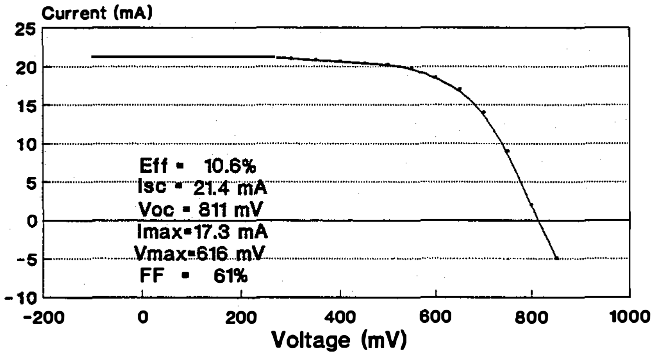
- Annual Technical Report, Phase 2, of Subcontract #ZN-0-19019-1, November, 1993.

Awards

A national award was jointly granted to GPI and SERI during this past year. This R&D 100 award is given to the 100 most important breakthroughs in the world on a yearly basis. GPI is proud to share this honor with NREL for the continuing developments on CdS/CdTe-based photovoltaic modules.

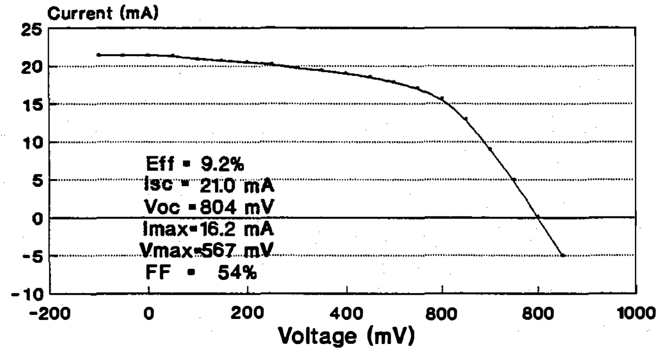
TESTING VARIATIONS TO DEMONSTRATE
Effects of Pre-Bias Conditions
(10 secs at forward bias of 2.0V)



1/19/92
Device #719A-22C#2; Area = 0.302 cm2

Fig. 3-1

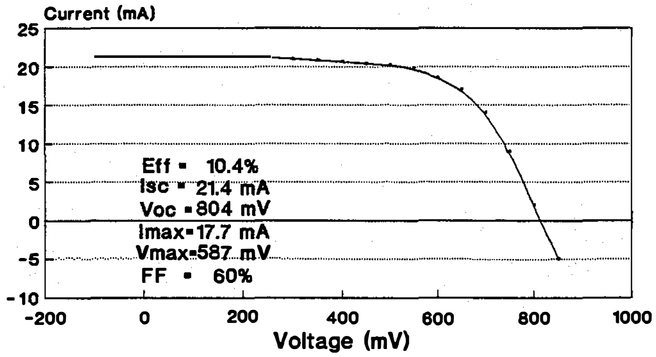
TESTING VARIATIONS TO DEMONSTRATE
Effects of Pre-Bias Conditions
(30 secs shorted and illuminated)



1/19/92
Device #719A-22C#2; Area = 0.302 cm2

Fig. 3-2

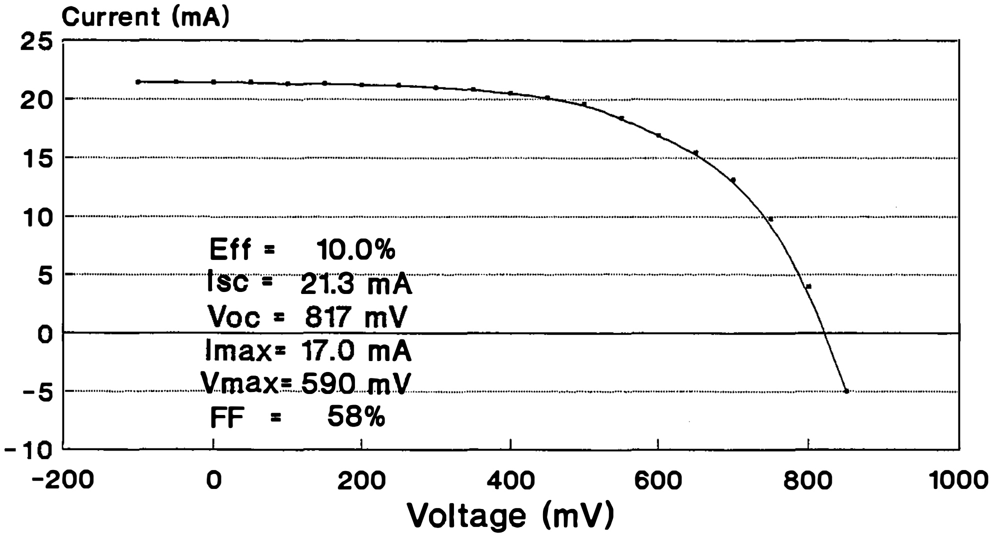
TESTING VARIATIONS TO DEMONSTRATE
Effects of Pre-Bias Conditions
(10 secs at forward bias of 2.0V)



1/19/92
Device #719A-22C#2; Area = 0.302 cm2

Fig. 3-3

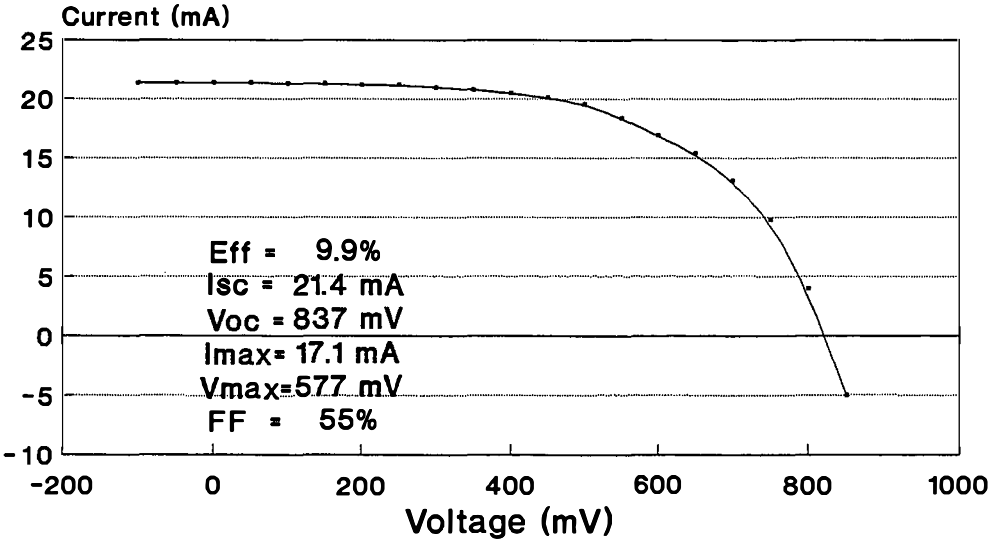
TESTING VARIATIONS TO DEMONSTRATE
Effects of Pre-Bias Conditions
(10 secs max power point soak)



1/19/92
Device #719A-22C#2; Area 0.302 cm2

Fig. 3-4

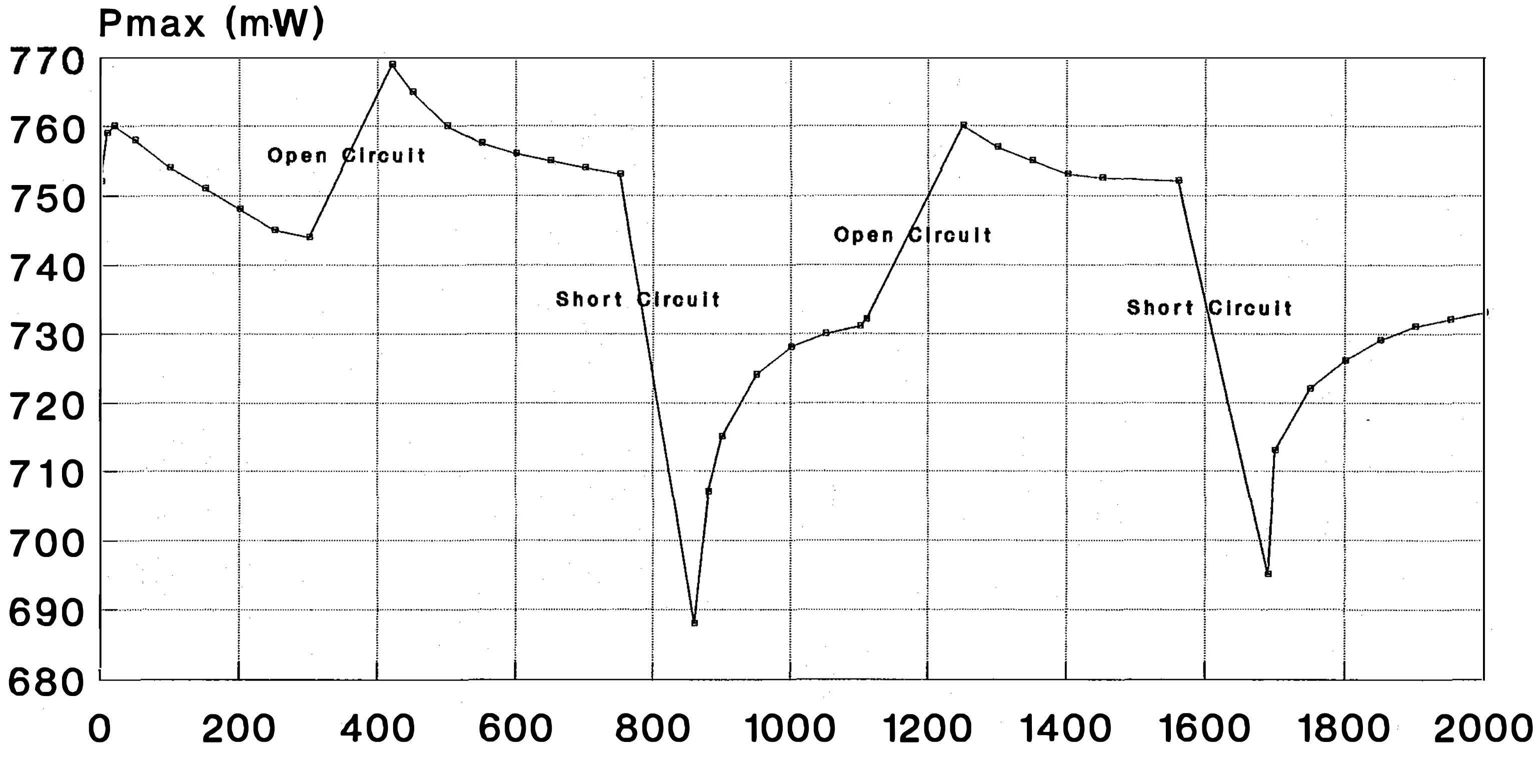
TESTING VARIATIONS TO DEMONSTRATE
Effects of Pre-Bias Conditions
(10 secs mpp soak, After 15 min)



1/19/92
Device #719A-22C#2; Area = 0.302 cm2

Fig. 3-5

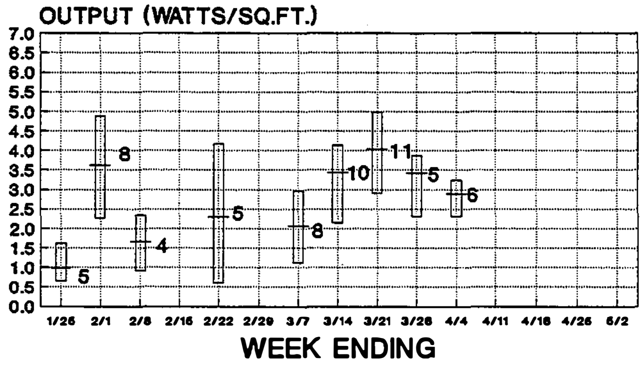
Effects Of Pre-Bias
Sample "Upper"



8/19/91

Relaxation Curves
Fig. 3-6

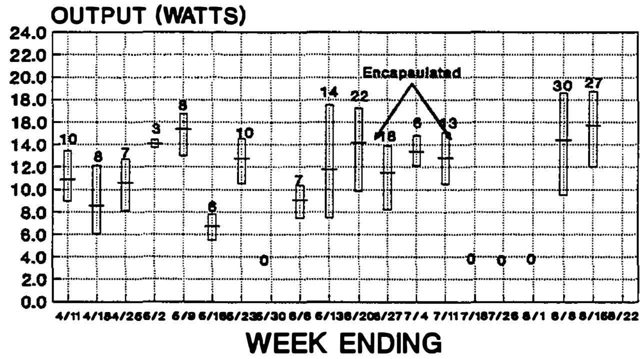
Trend Lines Showing
Outputs of Testable Modules



# Indicates # of Modules Tested
1992

Figure 3-7

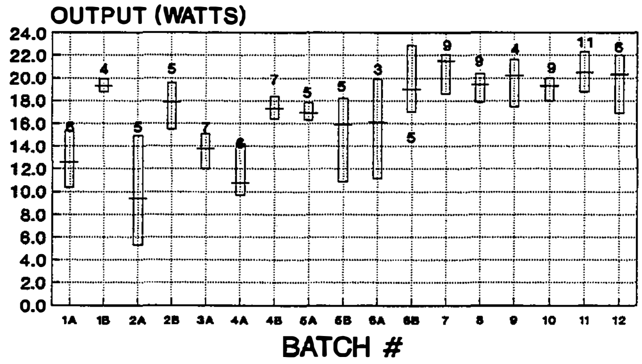
Trend Lines Showing
Outputs of Testable Modules



# Indicates # of Modules
1992

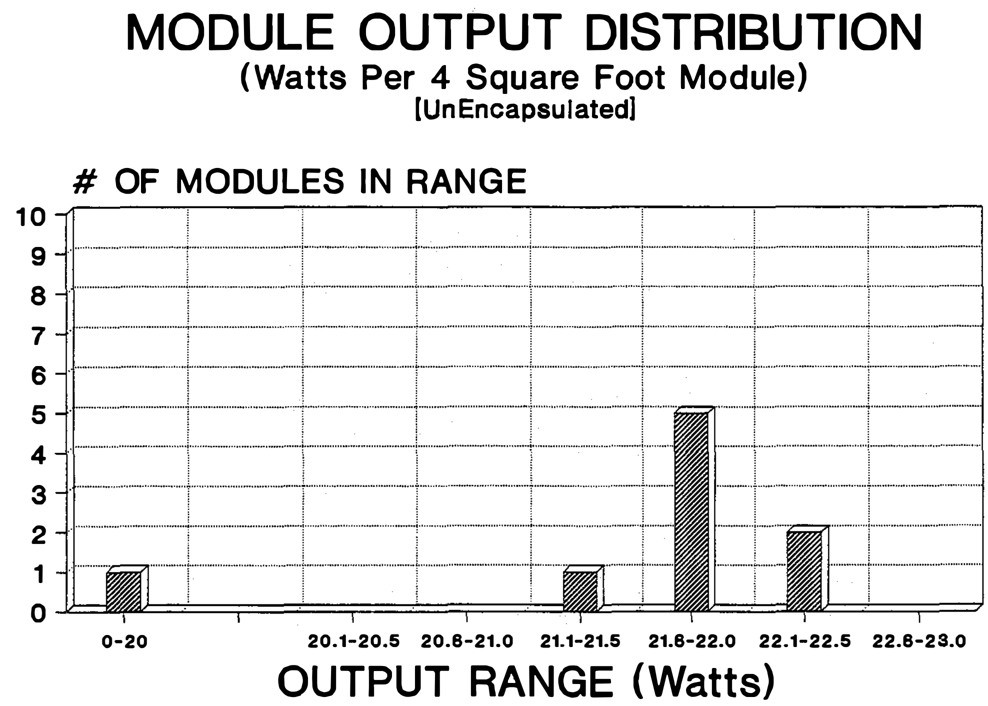
Figure 3-8

Trend Lines Showing
Outputs of Testable Modules



# Indicates # of Modules
1993

Figure 3-9

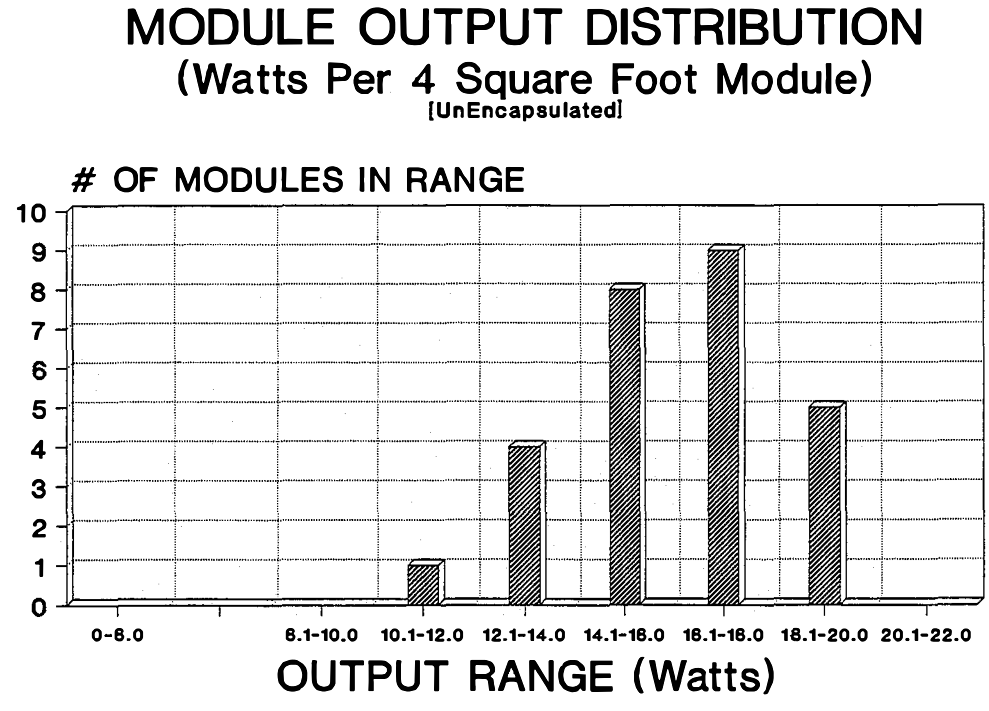

MODULE OUTPUT DISTRIBUTION

(Watts Per 4 Square Foot Module)

[UnEncapsulated]

MODULES TESTED = 9
Batch 7

Figure 3-10


MODULE OUTPUT DISTRIBUTION

(Watts Per 4 Square Foot Module)

[UnEncapsulated]

MODULES TESTED = 27
8/15/92

Figure 3-11

UNIFORMITY TESTING ON MODULES
cEFFICIENCY

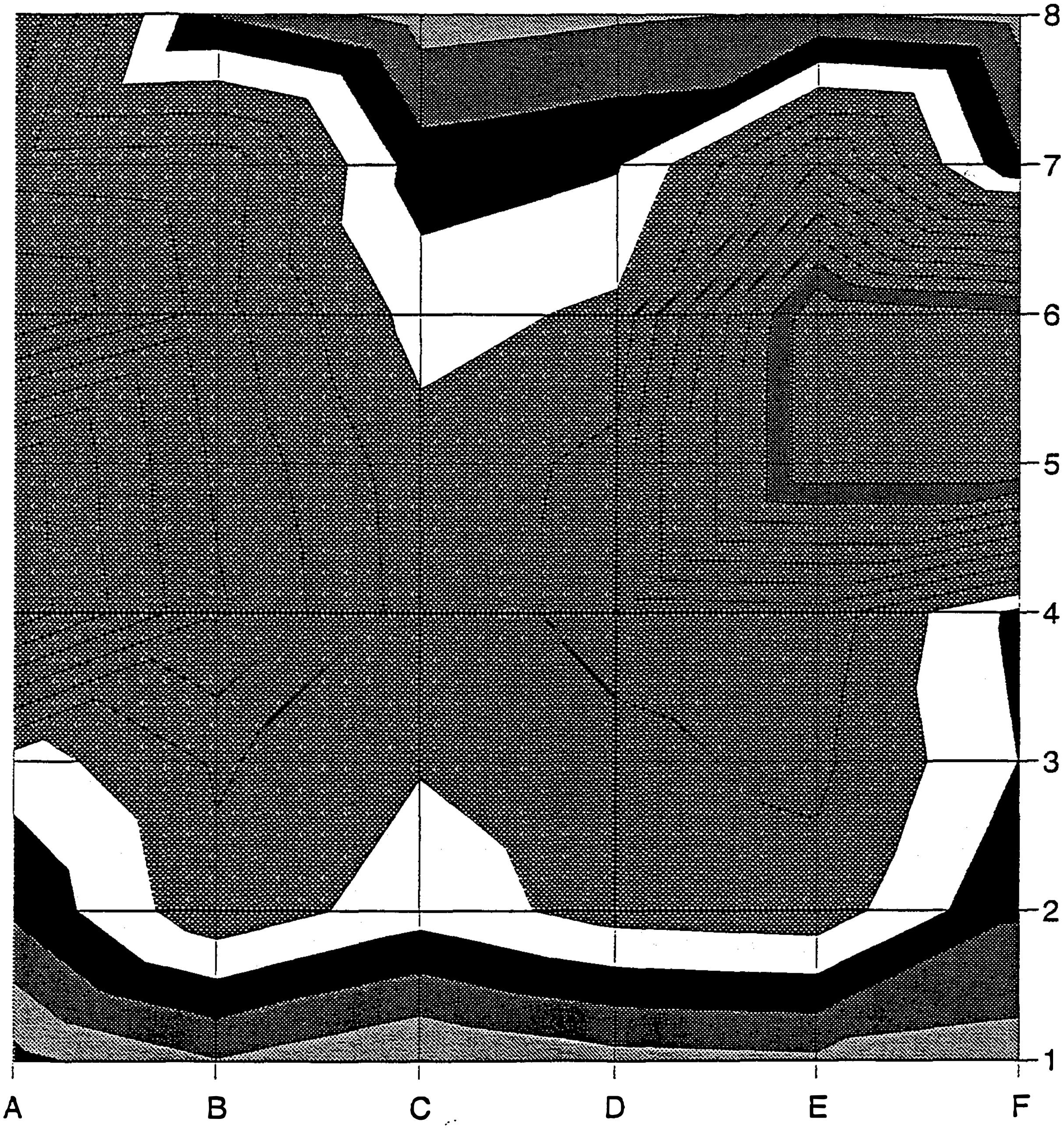


Fig. 3-12

UNIFORMITY TESTING ON MODULES
cEFFICIENCY

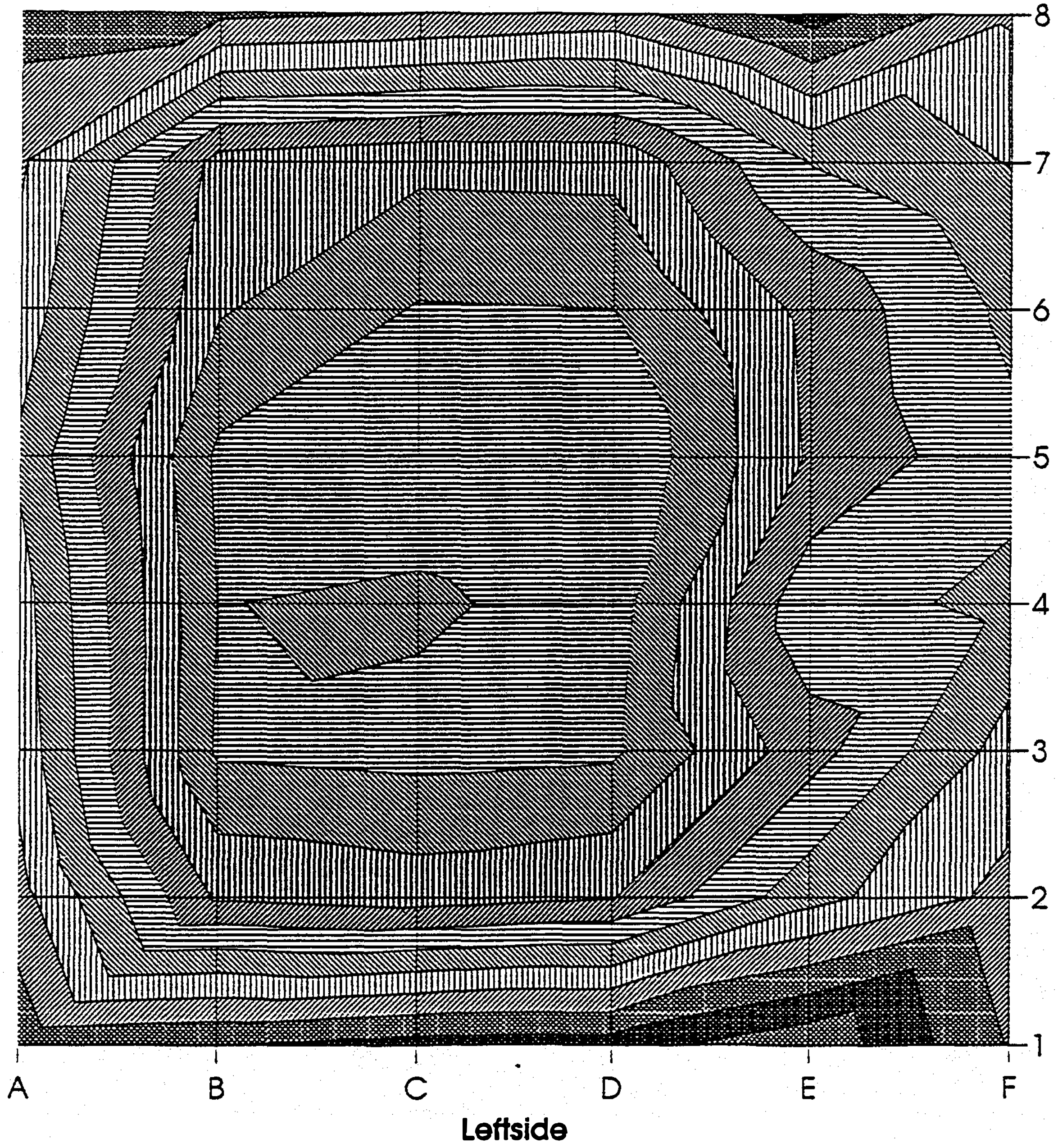
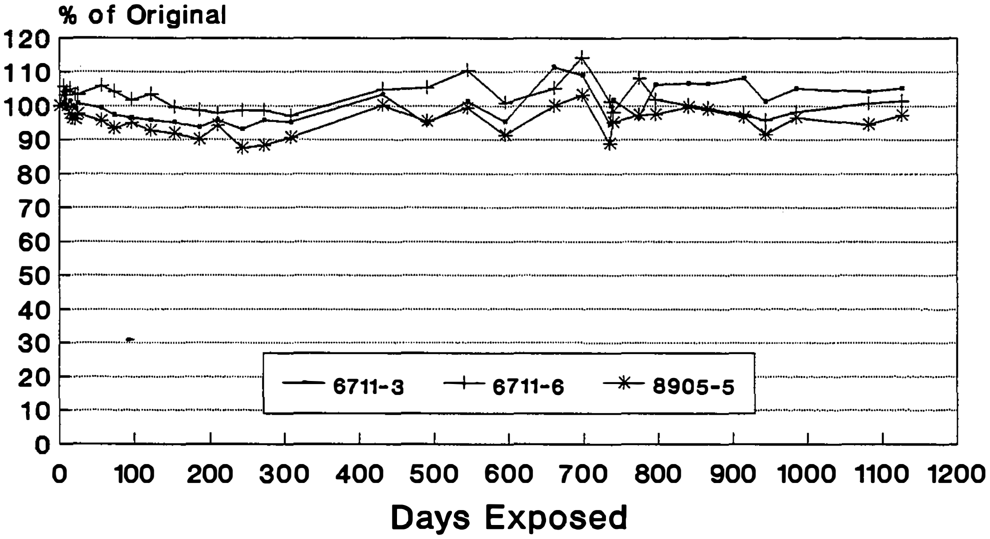


Fig. 3-13

Life Test Data

For 6711-3,6711-6,8905-5

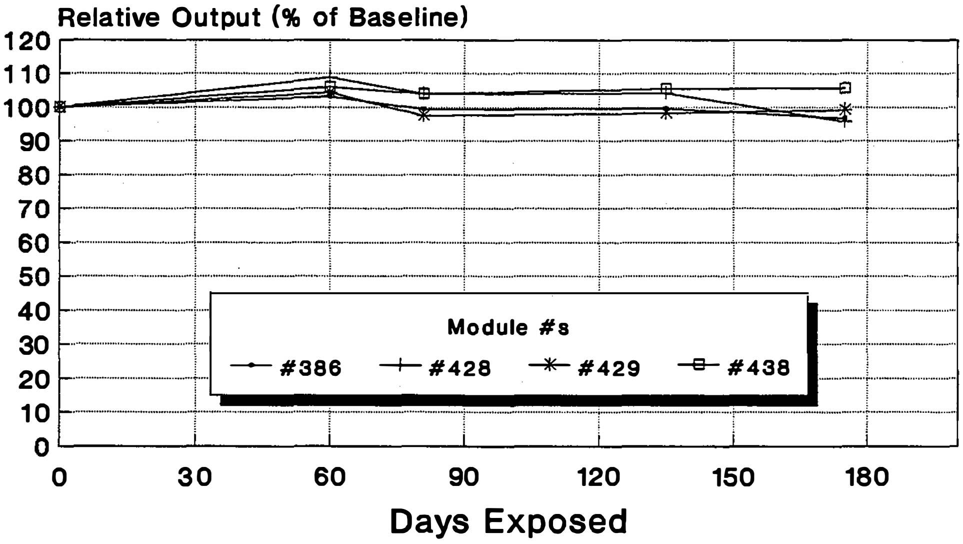


Deployed July '89

Figure 4-1

STABILITY RESULTS

Golden Photon CdTe Modules



Depoyed December 1992

Figure 4-2

REPORT DOCUMENTATION PAGE

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5. FUNDING NUMBERS

C: ZN-9-19019

TA: PV431101

6. AUTHOR(S)

S.P. Albright, S.X. Johnson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Golden Photon, Inc.
Golden, Colorado 80401

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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

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NREL Technical Monitor: H.S. Ullal

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12b. DISTRIBUTION CODE

UC-270

13. ABSTRACT *(Maximum 200 words)*

This report describes work performed under a three-phase subcontract. The objectives of the program include (1) achievement of active-area efficiencies of greater than 14% on small cells; (2) achievement of aperture-area efficiencies of greater than 13% on 0.09 m^2 (1 ft^2) modules; (3) achievement of aperture-area efficiencies of greater than 12.5% on 0.37-m^2 (4 ft^2) modules; and (4) achievement of greater than 20-year module life (based on life testing extrapolations) with no greater than 10% efficiency degradation. The results obtained and described herein include the following: (1) efficiencies of 12.7% were achieved on small-area devices; (2) 0.09-m^2 (1 ft^2) modules achieved greater than 8% aperture-area efficiency, but work for further efficiency improvement was redirected toward the 0.37-m^2 (4 ft^2) modules; (3) 0.37-m^2 (4 ft^2) modules achieved 26.5-W output, which calculates to 8.0% aperture-area efficiency; (4) consistent prototype production was focused on and substantially achieved within Phase 2; (5) life testinc at the National Renewable Energy Laboratory showed no inherent stability problems with the CdTe technology, and the accuracy of module measurement was satisfactorily resolved; and (6) a "cradle-to-cradle" recycling program was begun based upon the philosophy that the establishment of such mechanisms will be required to ensure maximum recapture and recycling of all manufacturing waste materials and/or modules returned from the field.

14. SUBJECT TERMS

module ; efficiency ; cadmium telluride ; production ; photovoltaics ; solar cells

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17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

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