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Development of a Low-Cost Integrated 20-kW-AC Solar Tracking Subarray for Grid-Connected PV Power System Applications

Final Technical Report

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TABLE OF CONTENTS

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LIST OF FIGURES

DEFINITIONS

Throughout this report, the following definitions shall apply to the words listed below:

Laminate:	A glass/EVA/cells/EVA/Tedlar encapsulated assembly of discrete PV solar cells with tinned copper terminal ribbons penetrating the Tedlar back sheet.
J-box:	A weather tight enclosure attached to the back of a laminate to provide a junction point between a laminate's terminal ribbons and the PV system's interconnection wiring.
Frame:	A structural element attached to the perimeter of a laminate to provide edge protection and facilitate handling and mounting.
PV module:	A laminate which may or may not be provided with a J-box(es) or frame and is utilized by Utility Power Group in the manufacture of Modular Panels.
Inverter:	A packaged electronic/electrical assembly which converts DC electricity into AC electricity. Often referred to as a PCU or PCS (power conditioning unit or system) when coupled with DC and AC interface and disconnect components.
IPPU:	An integrated power processing unit which performs all PCU functions as well as single axis solar tracking motor control. Also may be known as SIPP (system integrated power processor) or CPPU (central power processing unit)
Modular Panel :	An electrical and structural assembly of PV Modules.
Rail:	A galvanized steel structural element of a Modular Panel to which PV modules are attached.

All laminates, J-boxes, frames, and PV modules described in this report were manufactured and supplied by Siemens Solar Industries, Inc. from their facility in Camarillo, California.

EXECUTIVE SUMMARY

This report chronicles Utility Power Group's ("UPG") successful two-year Photovoltaic Manufacturing Technology (PVMaT) Phase 4A1 work effort which began in July, 1995. During this period, UPG completed design, fabrication, testing and demonstration of a modular and fully integrated 15-kW-ac, solar tracking PV power system sub-array. The two key and innovative components which were developed are a Modular Panel which optimizes factory assembly of PV modules into a large area, field-deployable, structurally-integrated PV panel, and an Integrated Power Processing Unit which combines all dc and ac power collection, conversion and control functions within a single, field-deployable structurally-integrated electrical enclosure. These two key sub-array elements, when combined with a number of other electrical, mechanical, and structural components, create a low-cost and high-performance PV power system. This system, or sub-array, can be deployed in individual units, or paralleled with any number of other sub-arrays, to construct multi-megawatt PV fields.

UPG exceeded its goal of providing a 40% reduction in area-related balance-of-system costs and a 50% reduction in power-related balance-of-system costs by achieving cost reductions of 53% and 52% respectively. The net reduction in the total cost of single-axis solar tracking grid connected PV power systems achieved by UPG was 23.3%. In 1996 and 1997, UPG installed a total of 50 integrated and modular sub-arrays in the United States representing over 700 kW of new PV power systems. When applied to these new systems, UPG achieved a cost reduction resulting in over $1.4 million in savings to UPG's electric utility customers. These customers include the Sacramento Municipal Utility District, Arizona Public Service, and Detroit Edison.

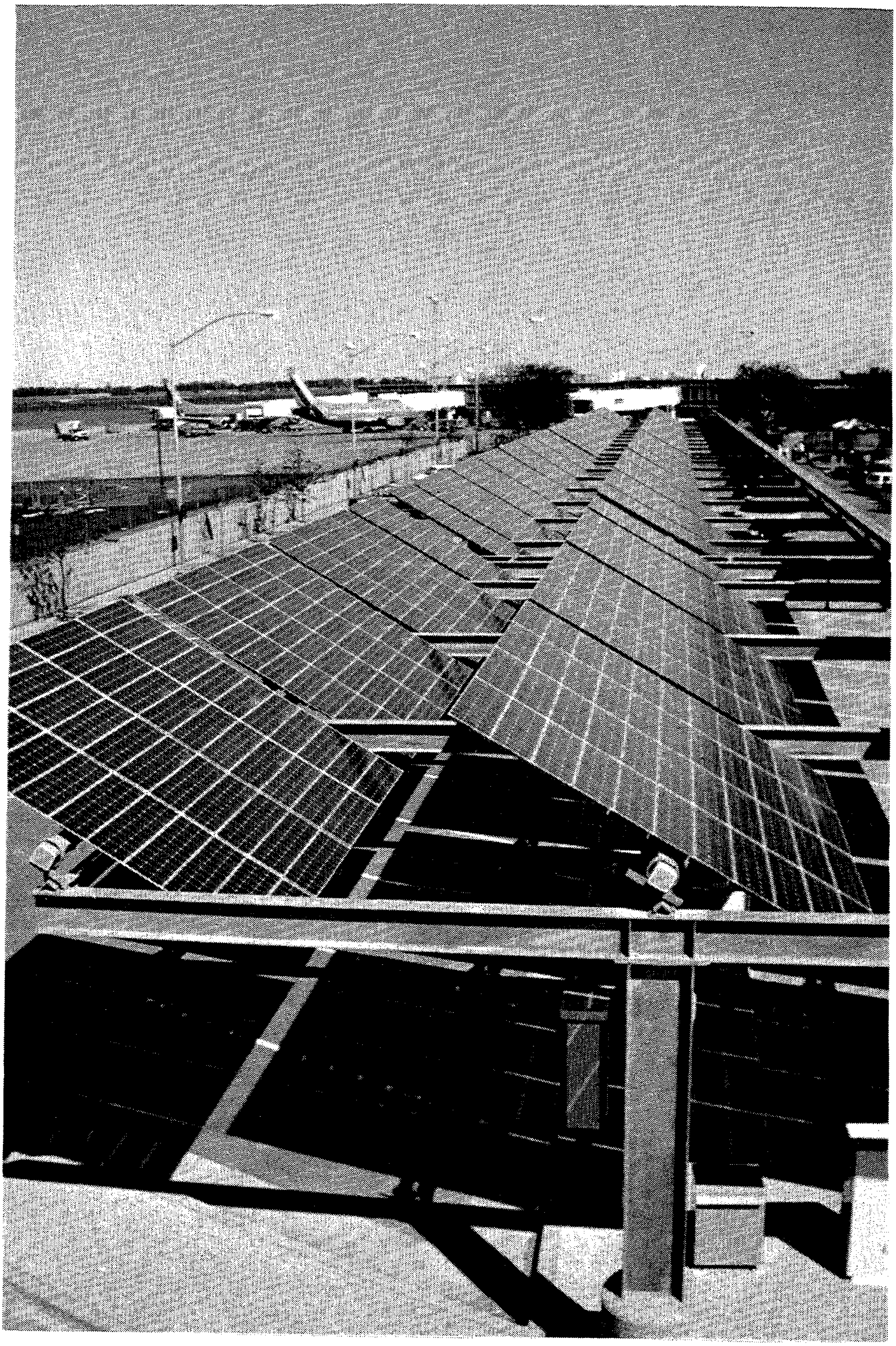

Figure 1. UPG's PVMaT Phase 4A1 Integrated Solar Tracking Sub-Array

INTRODUCTION

The overall goal of this PVMaT Phase 4A1 work effort by Utility Power Group ("UPG") was to substantially reduce the total installed cost of utility-scale grid-connected photovoltaic ("PV") power systems. PV power systems generate electricity via the direct conversion of sunlight into electrical energy and can serve as an environmentally benign and domestically secure source of electricity for utility grid connected peak or intermediate load applications. Considering that almost 700,000 megawatts (MW) of electricity generating capacity exists in the United States alone, PV power systems have only negligibly penetrated the electricity generation market. The dominant factor limiting the use of PV power systems in grid-connected applications today is the capital cost of the total installed system with respect to the annual kilowatt-hours of energy generated.

The two primary PV power system capital cost groups are 1) PV Modules and 2) Everything Else, which is more commonly referred to by the acronym "BOS" (Balance-Of-System). Historically, 60% of the capital cost of typical grid-connected PV systems were allocated to the PV modules while 40% of the costs were allocated to BOS. Technological improvements are the fundamental drivers to cost reduction in both groups, but the cost groups are also greatly affected by production and installation volume which permits standardization, automation, and integration.

The focus of UPG's work effort was on BOS component manufacturing technology, which essentially involved all PV power system engineering, manufacturing, assembly and construction tasks from the receipt of a PV module to the delivery of grid-connected electricity. Working with Siemens Solar Industries (Camarillo, California) to optimize the design of PV modules for power systems applications, UPG's goal was to obtain and demonstrate significant cost reductions in the installed cost of PV power systems. Single-axis solar tracking, which provides over 20% more energy in a typical year than a fixed-axis PV system, was selected as the optimum array configuration upon which the overall design was based.

As a leading provider of PV system engineering and construction services, UPG was able to quickly transfer any such cost reductions into the PV power system marketplace. As a result of the success of this Phase 4A1 PVMaT contract, UPG received orders from electric utility customers to manufacture and install over 50 integrated, single-axis solar tracking sub-arrays. They are scheduled for completion in 1997 and 1998. The novel systems-design approach utilized by UPG will be described in the following sections, but can be summarized by the word "integration". Full system integration is the key to obtaining the lowest cost and highest performance PV power systems.

BACKGROUND

Utility Power Group was formed in 1985 by a team of dedicated and experienced engineers and scientists to commercialize photovoltaic (PV) electricity generation technologies in grid and non-grid connected electric utility applications. From 1985 to 1992, UPG's primary focus was on developing advanced thin film PV module manufacturing technology. From 1992 onward, the company's focus shifted to providing PV power system design, engineering, construction, installation, operation and maintenance services to electric utilities, as well as to Government and commercial organizations. In 1993, UPG provided the Sacramento Municipal Utility District with a "turn-key" 200-kW PV power system at the Hedge Substation in Sacramento, California .

In 1994, UPG installed a 100-kW PV system in Fort Davis, Texas for Central and South West Services' Solar Park which required a total of fifty-one separate electrical enclosures to provide dc combining, conduit/wire routing, tracker control, disconnect, and inverter functions. Over 2,200 PV modules were individually field installed on the array structures. A single inverter provided dc to ac power conversion, and a single tracker, motor controller, provided solar tracking commands.

Upon completion of this project, UPG personnel analyzed the costs associated with the construction of grid-connected PV power systems to determine the potential for, and identify the barriers to, future cost savings. To summarize these analyses, it was determined that a shift in philosophy from "constructing" PV power systems to "manufacturing" PV power systems would have the greatest impact upon BOS cost reduction.

The construction approach to providing PV power systems has historically required obtaining a site specific design package, procurement of various equipment, components and materials from a wide range of vendors, and field installation of these equipment, components and materials in as efficient a manner as possible. The problem with this approach is that there is no opportunity nor incentive for the contractor to combine or integrate equipment, components and materials in the design phase. Additionally, the contractor typically performs all activity in the field where labor efficiency is adversely effected by weather, site conditions, and travel.

A manufactured approach to providing PV power systems would require the development of standard design packages with integral involvement of the vendors of equipment, components and materials. Through intelligent mechanical and electrical integration of PV modules, array structure, and power conversion electronics, the number of discrete systems parts could be reduced and several field installation tasks could be shifted to a more efficient factory environment.

UPG's desire to shift from a construction approach to a manufactured approach dovetailed with a recent trend in the PV industry in which the PV module manufacturers are not directly involved in the sale of the PV power system. Viewing the module as a component of the complete system rather than as the controlling basis of the system will allow the contractor or supplier of the system to take advantage of a number of cost reductions related to design integration.

Having identified the development of a modular PV panel and an integrated power processing system as the most important elements in a PV power system cost reduction program, UPG received cost shared funding under Phase 4A1 of the Photovoltaic Manufacturing Technology project in July, 1995. The two year sub-contract from the National Renewable Energy Laboratory ("NREL"), enabled UPG to develop technologies to "manufacture" grid-connected PV power systems thereby significantly reducing the capital costs of such systems and accelerating the commercialization of this important technology.

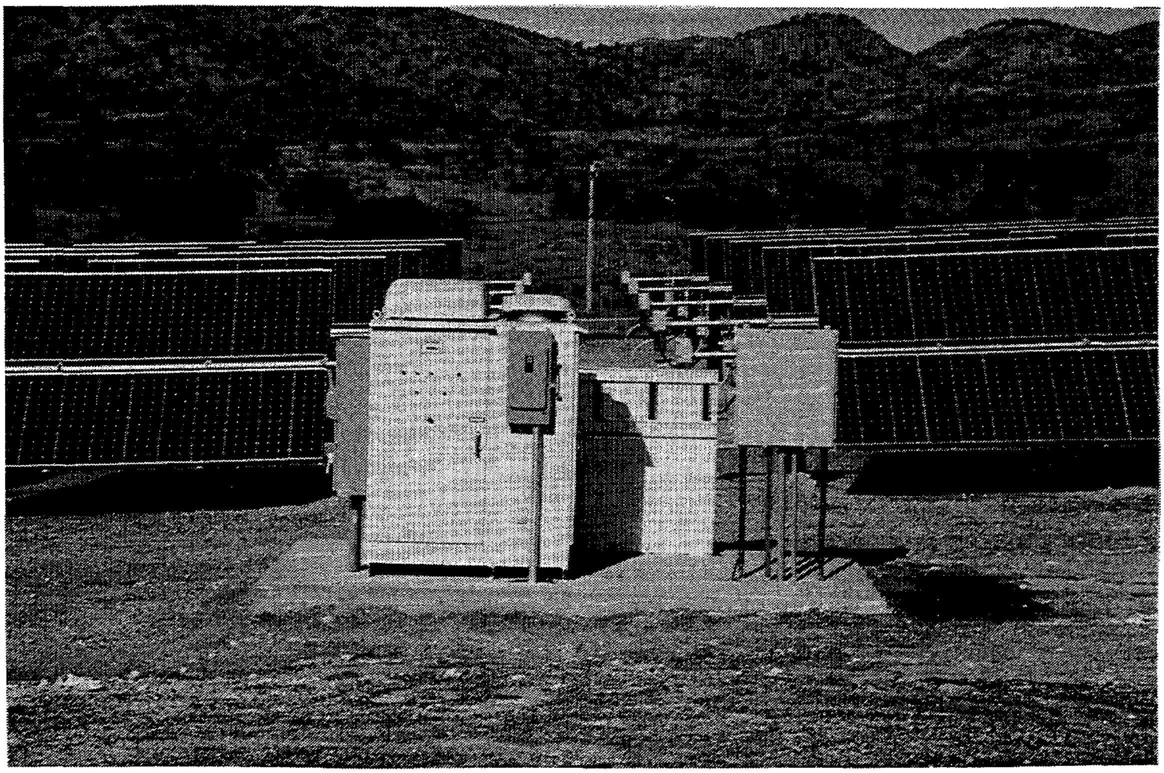

Figure 2. Photograph of 100 kW PV power system in Fort Davis, Texas.

Although the PV system in Fort Davis, Texas was based upon UPG's lowest cost single axis solar tracking array design at that time, it was not optimized for BOS cost reduction. Figure 3 provides an approximate percentage breakdown of the cost items within the BOS cost group.

COST ITEM	% of Total
Design	**8**
Power Related	**24**
Inverter/Data Acquistion	20
Transformer	3
Disconnects	1
Area Related	**68**
Structure	26
Labor & Project Management	15
Tracker Drive	10
Foundation	5
Site Expenses	5
Electrical Enclosures	5
Wire & Conduit	2
TOTAL	**100**

Figure 3. BOS cost group breakdown.

UPG's PVMaT Phase 4A1 work effort directly targeted the BOS cost group and affected each of the listed cost items. Modularity and integration of array components significantly reduced the number of discrete field construction and installation operations required, simplified the design and construction documentation, and permitted standardization of equipment, components, and materials.

OBJECTIVE

The overall objective of UPG's two-year, two-Phase PVMaT Phase 4A1 effort was to achieve greater than a 20% reduction in the installed cost of PV power systems. With UPG's focus on the BOS cost group, which had typically represented 40% of the total cost of a PV power system, the overall objective could be re-stated as seeking to achieve a 50% reduction in BOS costs.

TECHNICAL APPROACH

The technical approach utilized by UPG in pursuit of the above objective was based upon the following lessons learned during the construction of multiple PV power systems by UPG in 1992 and 1993:

- Factory assembly of BOS components provides cost savings over field assembly.
- Reducing the number of discrete BOS components reduces installation cost.
- Standardization of design reduces the cost of BOS components and materials.
- Reduction of discrete tasks reduces the cost of BOS construction labor.

These lessons, and a desire to shift from a "constructed" systems approach to a "manufactured" systems approach, led UPG to select modularity and integration as the two primary design criteria to be utilized. A modular, alternating current ("ac") sub-array design would simplify the generation of PV system design packages and reduce incremental administrative and project management costs. Redundancy and reliability are PV system operational cost factors which benefit from modularity and from the reduced number of components associated with increased functional integration.

Based upon the above lessons learned and design criteria, UPG began development of an integrated and modular ac sub-array which became the foundation for the PVMaT Phase 4A1 work effort described in this report.

The two key sub-array elements developed and demonstrated by Utility Power Group over the two-year program were:

- A Modular Panel (MP) which was factory assembled and tested by Utility Power Group utilizing production optimized and reliability tested PV laminates manufactured by Siemens Solar Industries.

- A Integrated Power Processing Unit (IPPU) which was factory assembled and tested by Utility Power Group and combined all sub-array electrical functions including power collection, system protection, direct current ("dc") to ac conversion, solar tracking, and switching into a single field deployable unit.

The foundation BOS cost item was not addressed in this development effort due to the marginal opportunity for cost reduction as compared to the other cost items. Although UPG pioneered the use of wood poles in a center supported single-axis solar tracking array configuration, many other foundation designs can provide cost effective module and panel support when properly designed.

UPG's work effort was segmented into a series of tasks with associated subtasks to facilitate NREL's monitoring of UPG's performance-to-goals and to provide UPG with a clear framework upon which to conduct an efficient development program. Figures 4 and 5 provide a list of these tasks for Phase I (Year 1) and Phase II (Year 2), respectively.

TASK 1 MODULAR PANEL DESIGN
Design review of SSI's PV modules and laminates.
Design/specify module(s)/laminate(s) for the Modular Panel ("MP").
Design/specify bus bar and interconnect devices within the MP.
Design/specify shipping containers for laminates and MP's.
Design/specify MP structural elements.
Analyze MP cost.
Complete MP fabrication/assembly drawings.
TASK 2 IPPU DESIGN
Analyze functional groups within the IPPU.
Design/specify IPPU enclosure and field mounting procedure.
Develop plan and criteria to select IPPU manufacturer.
Design/specify IPPU functional group sub-assemblies.
Develop test plan for IPPU.
Analyze IPPU cost.
Complete IPPU fabrication/assembly drawings.
TASK 3 PROTOTYPE MODULAR PANEL FABRICATION
Fabricate PV modules/laminates.
Fabricate shipping containers for modules/laminates and MP's.
Fabricate bus bar and interconnect devices.
Fabricate structural elements.
Fabricate prototype MP.
Develop test plan for MP.
TASK 4 PROTOTYPE IPPU FABRICATION
Fabricate sub-assemblies and interconnects.
Fabricate enclosures.
Assemble prototype IPPU.
TASK 5 PROTOTYPE MODULAR PANEL TESTING
Qualification test of module/laminate.
Mechanically test MP.
Electrically test MP.
TASK 6 PROTOTYPE IPPU TESTING
Bench test sub-assemblies.
Bench and field test prototype IPPU.
Select IPPU manufacturer.

Figure 4. Phase I Tasks

TASK 7 PRE-PRODUCTION IPPU FIELD TESTING AND DEMONSTRATION
Bench test sub-assemblies.
Bench and field test pre-production IPPU.
Submit IPPU design to Underwriter's Laboratories for evaluation.
Select IPPU manufacturer.
Submit pre-production IPPU to SNL for independent testing.
Start-up and test pre-production IPPUs in Solarport PV system.
TASK 8 PRE-PRODUCTION MP TESTING AND DEMONSTRATION
Qualification testing of Models 11M55 and 7SP75 Panels.
Start-up and field test 744 Model 11M55 Panels at Yuma Proving Grnd.
Install 270 Model 7SP75 Panels at SMUD Rancho Seco site.
TASK 9 DESIGN MODULAR PANEL MANUFACTURING SYSTEM
Analyze prototype modular panel assembly fixtures.
Develop assembly procedure.
Specify manufacturing system throughput, flexibility, and tolerances.
Design manufacturing system.
TASK 10 TESTING AND EVALUATION OF MP MANUFACTURING SYSTEM
Start-up and de-bug system.
Test trial panels.
Assess results of initial production run of panels.

Figure 5. Phase II Tasks

The fundamental sequence of design, fabricate, factory test, and field test was performed for both the Modular Panel and Integrated Power Processing Unit. Secondary sequences of re-design, re-fabricate, and re-test were performed as required whenever improvements in performance or reliability could be obtained. The refinement of these products and their manufacturing processes was a continuous effort as could be expected within any new technology.

MODULAR PANEL DEVELOPMENT

The factory assembled and modular PV panel developed by UPG and Siemens Solar Industries (SSI) provided cost reduction to the PV module cost group and the structure cost item as shown previously in Figure 3. These cost reductions were achieved through:

1. Elimination of aluminum structural frames mounted to the perimeter of each module.
2. Elimination of mechanical fasteners to attach the aluminum structural frames to a panel support member.
3. Elimination of single-use packing materials through utilization of re-usable bulk packaging for PV modules.
4. Standardization of manufacturing based upon a large-area module.
5. Simplification of the Modular Panel support member and its torque tube attachment means.
6. Simplification of shipping containers for Modular Panels.

UPG and SSI reviewed a number of SSI's commercially manufactured and prototype module designs to determine the optimum configuration for the Modular Panel ("MP") with the intention of developing a new PV module specifically designed for assembly into large area modular panels for high voltage power system applications such as those served by UPG's single axis solar tracking sub-array.

Figure 6 lists the primary design criteria utilized by UPG and SSI to evaluate and select the module design for the MP.

ELECTRICAL	MECHANICAL	MODULE MANUFACTURING	PANEL ASSEMBLY
Voltage	Length	Cell Size	Module Size
Current	Width	String Length/Yield	Sub-Array Interface
Diodes	Terminal Location	Terminal Location	Terminal Location
UL	UL	UL	UL
NEC	Weight	Circuit Size/Yield	NEC
Wire Size	Mounting	Module Size/Yield	Mounting
Area Efficiency			

Figure 6. Modular Panel design criteria.

SSI's model M55, M72, M110, and SP75 PV modules formed the baseline for this investigation, and were compared and contrasted to a number of prototype module design concepts. The key results of this analysis were not entirely expected and can be summarized as follows:

- Increasing laminate size much beyond that of the 20.5 inch (521 mm) x 47.0 inch (1194 mm) SP75 module did not offer additional incremental cost benefit due to increased yield losses and increased manufacturing equipment capital costs.

- Low voltage modules (paralleled strings) connected in parallel at the MP level via a bus bar approach did not offer cost benefit due to the cost of the higher current MP junction-box (J-box) and wiring components which would be required.

- Optimization of a low-cost single J-box designed for module attachment at SSI and produced in high volumes provided the best opportunity for cost reduction.

- Utilization of a UL listed PV module significantly reduces the cost and time required to obtain UL approval of the Modular Panel.

- Lower costs were obtained by utilizing high volume commercially manufactured PV modules rather than a lower volume module designed specifically for use in the MP.

These results led UPG and SSI to the conclusion during Phase I that the unframed version of the M55 module was the optimum choice for use in the prototype MP. In Phase II Siemens Solar Industries introduced the SP75 PV module, which with an increase in size, power output and an optimized single junction box ("J-box") would result in the manufacture of a superior Modular Panel for most applications.

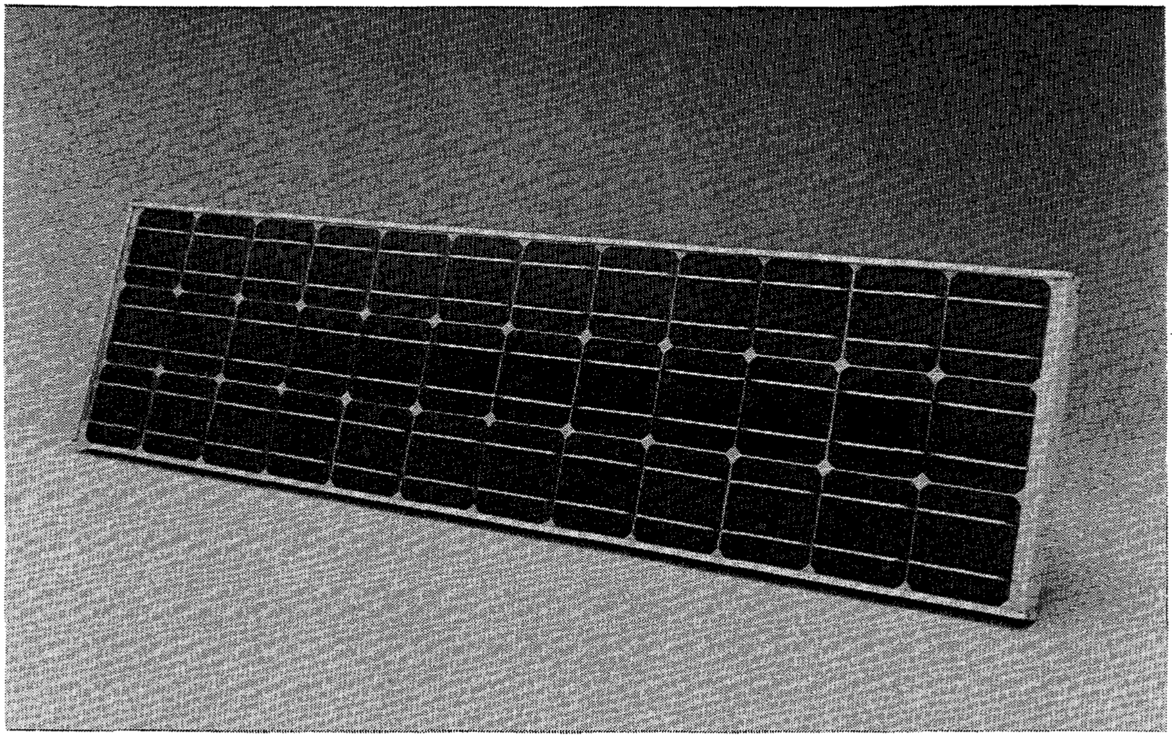

Figure 7. SSI M55 PV Module.

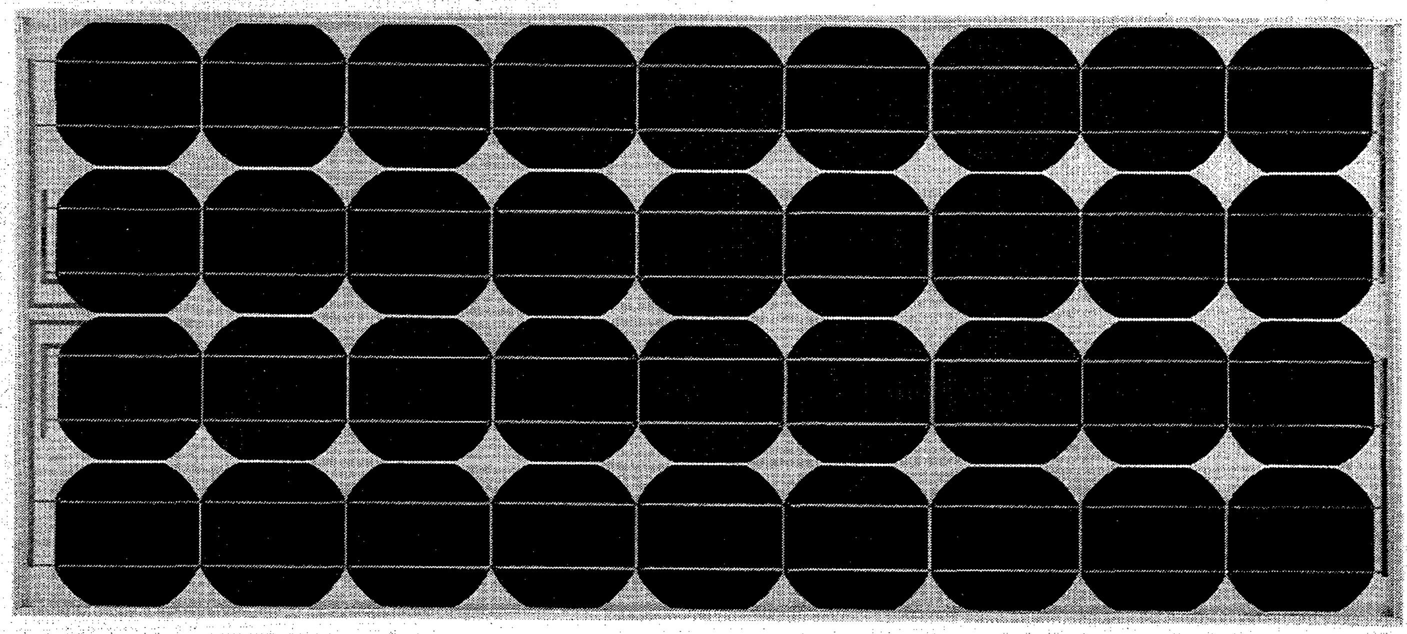

Figure 8. SSI SP75 PV Module.

Based upon the selection of un-framed M-55 and SP75 modules as the lowest cost options for the MP, the task of designing and specifying interconnect devices was greatly simplified. Although several novel approaches were considered, including a bus bar assembly spanning the length of the panel, the modules' use of a small J-box provided UPG with the least cost option. The J-box was designed to facilitate in-series wire insertion and connection, and therefore a single conductor, UL-approved seven-strand copper USE-2 cross-linked polyethylene-insulated, interconnect wire was utilized between module J-boxes.

Once the modules to be utilized in the manufacture of Modular Panels was determined, electrical and structural issues served to determine the panels' physical design size. Due to shipping, handling, and wind load considerations for the existing solar tracking support structure, UPG determined that the length of the panel should not exceed thirteen feet. To optimize materials and sub-array area utilization, the panel should not be less than nine feet in length. Electrically, the series voltage derating requirements of UL Standard 1703 and the 1996 NEC limits the open circuit voltage of a series sub-circuit to the equivalent of twenty-two (22) M-55 modules or fourteen (14) SP75 modules. These issues combined to indicate that a MP should contain either eleven (11) M-55 modules or seven (7) SP75 modules connected in series. A sub-circuit would then be created by connecting two M-55 panels or three SP75 panels in series. UPG established 11M55 and 7SP75 as the model numbers for the prototype Modular Panels based upon the Siemens Solar Industries Model M-55 and SP75 PV modules, respectively.

Structural components fabricated from both aluminum alloys and steel were evaluated for use within the MP with consideration given to weatherability, strength, cost, and galvanic compatibility. Superior in all areas of importance, steel was selected as the material of choice for the primary structural component to combine modules into a unitized panel.

The simplest and lowest cost panel structural configuration centers the modules side by side over two parallel steel section lengths, or rails. UPG selected a thin section "C" structural shape for the rail based upon its high strength to weight ratio and the ease with which holes can be located along its length. Galvanized sheet steel was selected for its corrosion resistance and galvanic compatibility with the primary solar tracking sub-array support structure. The rail as designed was quite similar to a standard structural "2x4 stud" widely used throughout the construction industry. The use of high volume commercially available materials was found to significantly reduce the costs of the MPs' structural components and reflects UPG's overall design philosophy to use commercially available standard components wherever possible.

The goal of elimination of module frames dictated that the only means available for module attachment to the panel rails were clips, adhesives, or a combination of both. UPG's analysis indicated that there were advantages and disadvantages associated with each of these approaches and that there was not a significant cost differential between them. Having utilized structural adhesives in a previous array constructed in 1989 at PVUSA, UPG selected a two component adhesive system in which one component provides initial adhesion to facilitate factory assembly of panels, and the second component provides long term high strength adhesion to withstand wind loading under a wide range of environmental conditions.

Siemens Solar Industries produced several hundred M55 and SP75 sample modules which were utilized in testing the adhesive systems to meet the requirements of UL 1703 as well as UPG's supplemental environmental standards. In addition to a number of single module test sections, over twenty five prototype Modular Panels were fabricated and structurally stressed and tested utilizing these sample modules.

Assembly of the 11M55 and 7SP75 Modular Panels required the design, fabrication, and testing of a specialized manufacturing system. UPG conducted several iterations of this development sequence prior to acceptance of a semi-automatic panel manufacturing system with sufficient flexibility to handle a number of different module and panel configurations. The manufacturing system not only provides rapid and reproducible alignment of each PV module within a panel, but also provides independent pressure control to each module to compensate for module-to-rail surface irregularities. Specialized panel handling fixtures and adhesive dispensing equipment was also developed to support the panel manufacturing system.

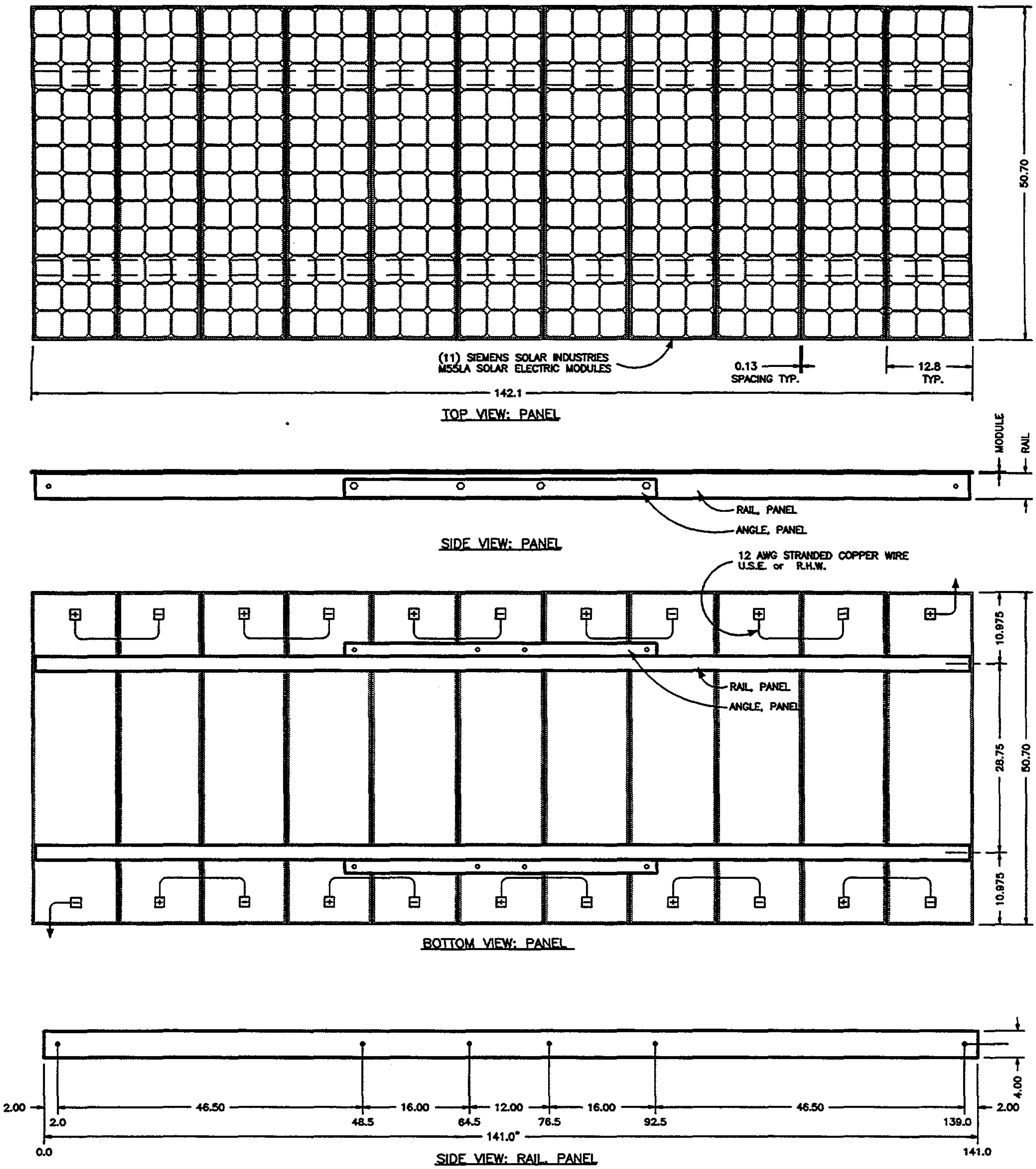

Figure 9. 11M55 Modular Panel.

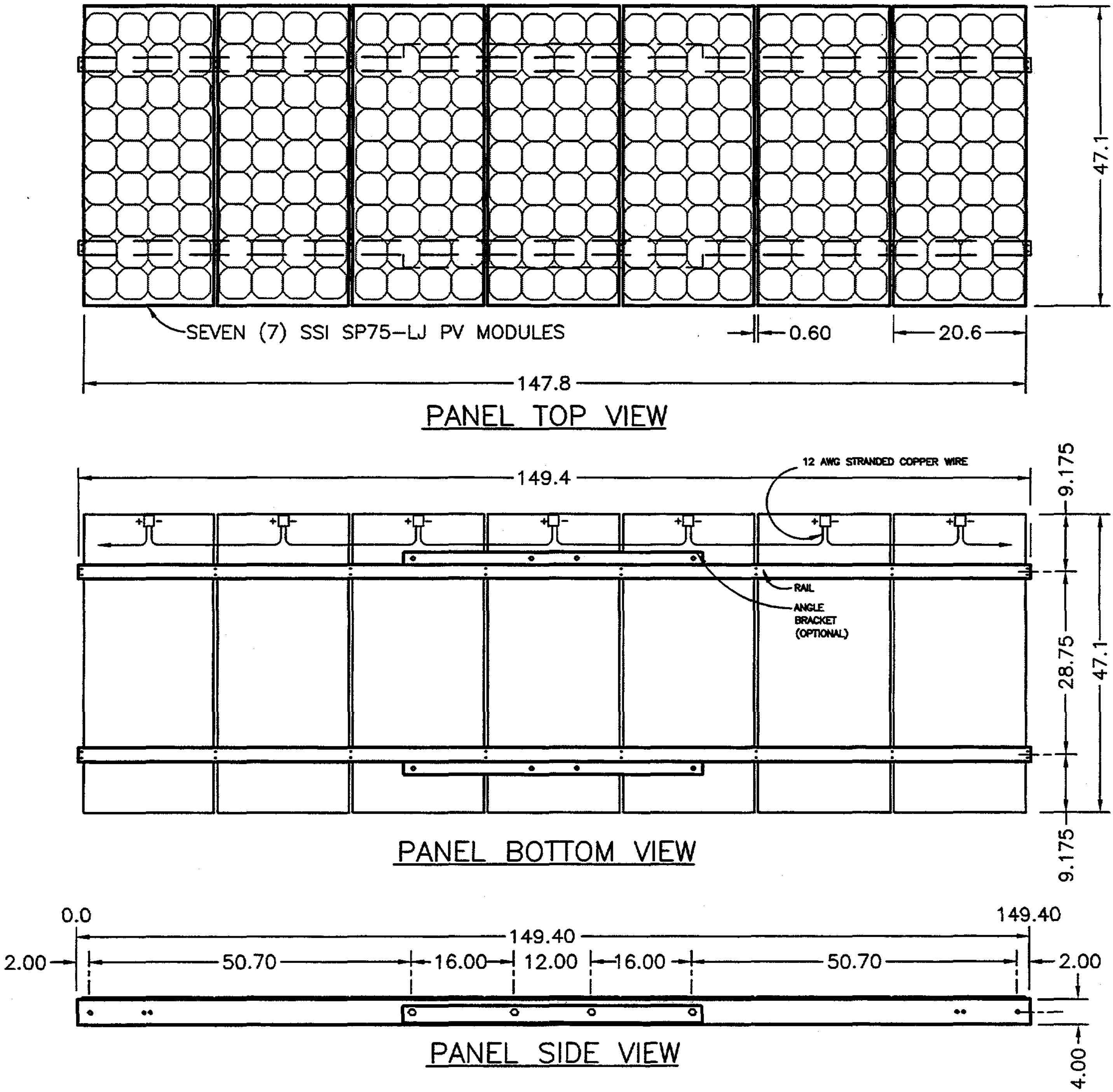

Figure 10. 7SP75 Modular Panel.

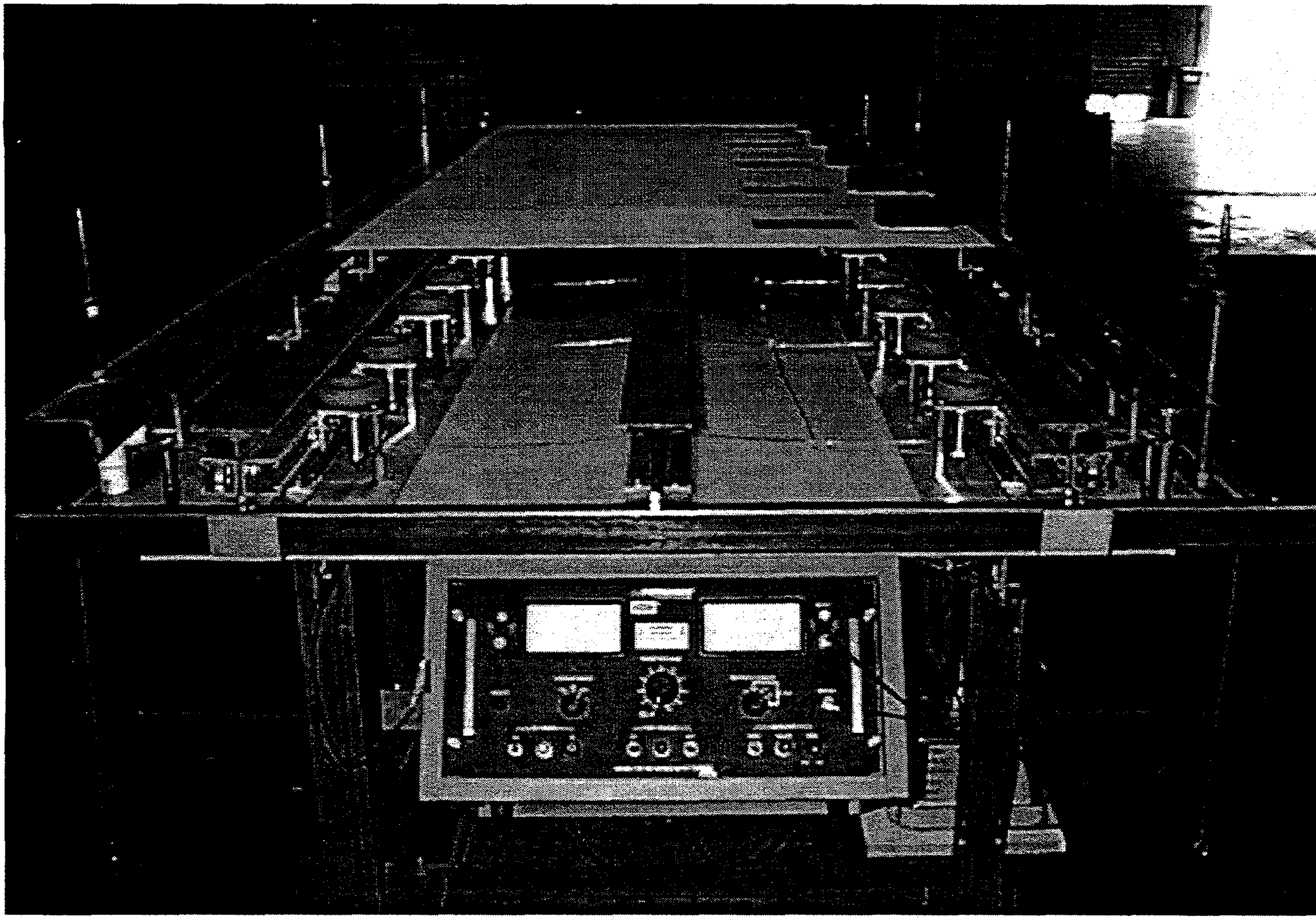

Figure 11. Modular Panel Manufacturing System.

An indirect module cost issue that was investigated by UPG and SSI is related to the packaging of modules for shipment. Given SSI's worldwide distribution network, a rugged four-pack and two-pack module shipping box is utilized for all shipments of the M55 and SP75 modules, respectively, but requires the disposal of almost two pounds of packaging materials per module. A 100-kW PV power system may use as many as 2400 PV modules which would result in the need to dispose of over two tons of packaging material per system. Implementation of a re-useable bulk pack container for unframed modules within the present SSI manufacturing and material handling environment was not cost effective during Phase I, so SSI developed a redesigned eight-pack shipping box for the M55 module which used the same amount of packaging materials as the four-pack box. This resulted in an immediate 50% reduction in the cost of shipping material, and in addition, UPG and SSI instituted a recycling/reuse program for the packaging materials.

In Phase II, SSI implemented a re-usable bulk pack for both M55 and SP75 modules which eliminated the disposal of any packaging materials. Although the cost savings associated with this development is less than five cents per watt, the use of disposable packaging materials is not compatible with the environmentally friendly philosophy behind the commercialization of photovoltaic technology.

One area in which costs increase due to the development of the Modular Panel is shipping. Prior to their development, UPG shipped modules directly to PV power system project sites and assembled the array panels in the field. Although factory assembly of MPs offers many advantages, it nonetheless requires a second freight operation to transport the completed MPs to the project site. Unfortunately, the packing efficiency or density of MPs is not as high as bulk packed PV modules and therefore more truckloads are required to transport MPs than modules.

Development of a suitable container or enclosure to transport the MPs proved to be more challenging than originally anticipated given the physical size and weight of the MP, and the sensitivity of unframed module edges to damage from impact. After consideration and testing of several designs and analysis of their fabrication costs, it became apparent that a typical cushioned container approach for MP shipments was not acceptable. UPG investigated several new concepts and focused on one which utilizes the MPs themselves as structural elements of a shipping "block". To eliminate glass-to-glass contact, a reusable steel fixture was designed to link a number of panels together in a transportable block. Building this block upon the wooden pallet on which the modules were shipped from SSI to UPG facilitates movement by forklift and pallet jack as well as serving to reuse the pallet.

Eight MP shipping fixtures were fabricated and tested by assembling eight prototype panels into a block as illustrated in Figure 12. Shipping the block via a common carrier for a distance of 700 miles between Chatsworth, California and Sacramento, California tested the concept. The block was unloaded and reloaded at each destination and the trip repeated four times. The MPs arrived without damage and additional fixtures were fabricated for use on subsequent UPG PV power system projects requiring the Modular Panels.

Testing was performed on both the M-55 module and 11M55 Panel by UPG and SSI to obtain listing approval from Underwriters Laboratories under the requirements of Standard 1703. All samples submitted for testing met or exceeded all required levels of performance including those under IEEE Standard 1262-1995 for ground continuity, dry hi-pot, and wet resistance.

UPG received Underwriter's Laboratories listing for the Model 11M55 Panel in April 1996, and with a STC rating of over 600 watts, the 11M55 is believed to be world's highest power UL listed PV panel. Listing approval for the 525 watt Model 7SP75 Panel was received in August 1996.

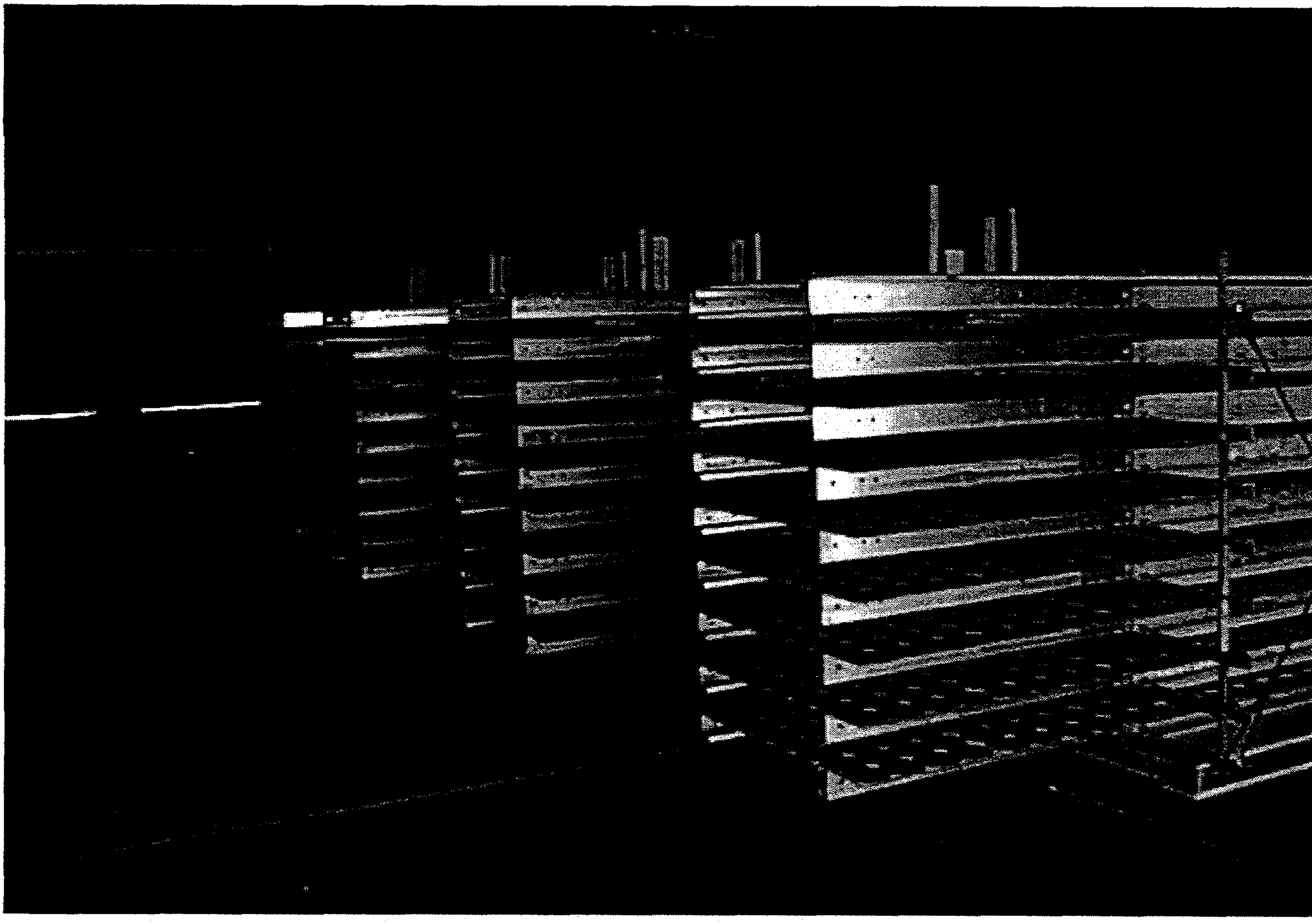

Figure 12. Modular Panel shipping block.

IPPU DEVELOPMENT

The Integrated Power Processing Unit ("IPPU") developed as a result of UPG's PVMaT Phase 4A1 work effort provides cost reductions to both the area related and power related cost elements of the BOS cost group as itemized previously in Figure 3. These cost reductions are primarily achieved through the consolidation, integration, and optimization of the following functions:

- Series sub-circuit protection
- DC bus disconnect
- Solar tracking control
- Tracker drive motor control
- DC to AC power conversion
- AC disconnect

The primary IPPU design criteria were as follows:

- Use of standard components
- Low power loss/high efficiency
- Compact geometry
- UL spacing requirements
- Ease of assembly
- Ease of troubleshooting
- Ease of enclosure mounting
- Low cost
- High reliability

Printed circuit board (PCB) technology was selected by UPG to serve as the foundation for the IPPU sub-assemblies to simplify fabrication, testing, assembly, and field maintenance. The alternative to this approach was to use PCBs in conjunction with a traditional panel mounting approach for specific discrete components. For example, switches, terminal strips, relays, and fuse blocks may be attached directly to a panel within the enclosure or to a wall of the enclosure itself. This approach requires the assembly and installation of a wire harness to facilitate the interconnection of these components, and complicates maintenance procedures.

UPG's total PCB approach simplifies manufacturing and maintenance operations by creating four (4) primary assemblies in which electrical components are mounted upon heavy duty printed circuit boards with integrated interconnects. All IPPU components are mounted upon PCBs except for the large and heavy contactor, disconnect, and inductors. The use of board edge connectors and ribbon cables allows each assembly to be easily factory or field tested both within the complete IPPU and as separate assemblies. In the unlikely event a field failure were to occur, repair procedures would consist of removing the assembly containing the failed component and replacing it with a new assembly. Ideally, this task could be performed by maintenance personnel without significant knowledge of electronics or electrical circuit design.

The existence of many outside contract manufacturing companies specializing in high throughput insertion and interconnection of printed circuit board components will permit UPG to focus on assembly level testing and final IPPU manufacturing tasks. In this manner, UPG's present facilities and staff will be able to produce over 200 IPPUs per year, representing over 3 MW of PV power systems.

Figure 13 itemizes the primary functions performed by each of the four assemblies. A fifth and optional assembly, called the DAS Assembly (Data Acquisition System) was developed to allow remote control and monitoring of each IPPU in an array field. Figure 14 lists the general specifications of the DAS Assembly.

DC INTERFACE ASSEMBLY	CONTROL ASSEMBLY

PV sub-circuit conductor termination
PV sub-circuit overcurrent protection
Visible dc disconnect
Blocking (paralleling) diodes
Crowbar function
DC contactor
DC current sense
DC ground-fault current sense
DC bus precharge and discharge
 	
AC INTERFACE ASSEMBLY
3-phase utility conductor interface
Fused power distribution
AC contactor (bridge isolation)
Regulated control power supply
Tracker drive motor relays and interface
Utility voltage sense
Output inductor interface
Output EMI filter
DAS interface point
 	
DAS ASSEMBLY OPTION
Machine state information
Fault delineation
3-phase ac power calculator
AC line voltage
AC line current
AC kilowatts
DC bus voltage
DC bus current
Remote enable / disable interface
Isolated digital link to modem
	Start, wake-up, disable and stop logic
	Machine state logic
	Digitally synthesized sinewave reference
	Line synchronization circuit
	Output sinewave current regulation
	Bus voltage regulation
	Diagnostics and fault detection
	    Lowpower (nightly shutdown)
	    Overpower, overvoltage bus
	    Line synchronization error
	    Frequency out of tolerance
	    Utility voltage imbalance, blown fuse
	    Utility undervoltage
	    Utility overvoltage
	    System fault
	    Control logic fault, undervoltage
	    Overtemperature
	    DC ground fault
	    Tracker drive fault
	    Disable, local or remote
	Electrical max.-power-point tracking
	AC power calculator
	LCD display driver
	Tracker drive logic and user interface
	
	BRIDGE ASSEMBLY
	15-kHz 3-phase ultra fast IGBT bridge
	Opto isolated IGBT drivers
	DC voltage sense
	Fast line-overcurrent detection

Figure 13. IPPU Assembly Functions.

Specifications were derived for each functional group based upon the following general IPPU specifications and were analyzed to ensure performance and interface compatibility. UPG successfully realized its goal to not only integrate all sub-array functions into a single unit, but also to develop the industry's highest switching frequency, highest conversion efficiency, and lowest cost inverter section. Figure 14 lists the general specifications of the IPPU.

Utility Interface, 3-phase	100/173*
Nominal Power Rating	14.5 kW
Maximum Output Power	17 kW
Power Factor, 25%-100% Output	>.99
Frequency, Nominal	60 Hz
Current Distortion, 25%-100% Output	<3% THD
3-Phase Current Imbalance	<2%
Photovoltaic Interface	
Operating Voltage, Nominal, 20°C Ambient	335
Max Power Tracking Range	300-380
Max Open Circuit Voltage	600
Ripple Voltage, RMS	<1%
Performance	
Conversion Efficiency, 100% Output	>97%
25% -100% Output	>96%
Switching Frequency	20kHz
Standby Losses	<15W
Max Power Track Accuracy	+/- 1%
Auto Start Sense	Array Current
Auto Shutdown Sense	Pout<300W
Diagnostics/Fault Detect	Auto
Packaging/Environmental	
Dimensions	48" x 20" x 8"
Weight	285 lb.
Operating Temp, Ambient	-25°C to +45°C
Humidity	0-100%
Integrity, DC Interface	Weatherproof
Bridge/Control	Weather/Dust proof
AC Interface	Weatherproof
Cooling	External Forced Convection
Finish	Powder Coat, White
Noise	<50 dBA (Fans on)

Figure 14. General IPPU Specifications

Disconnects	
Contactors	DC, AC Load Break
DC Disconnect	Pull Switch
AC Disconnect	3-Pole Pull Switch, Fused
Protection/Fault Detection	
Overtemperature - IGBT Junction Temp>100 deg C	
System Fault - Undervoltage Control Power	
DC Ground Fault - Ground Current >2 Amps dc	
Synchronization Error - Loss of Line Synchronization	
Overpower - Over Voltage DC Bus>425Vdc	
Overcurrent - Line Current>90 Amps Peak	
Frequency Fault** - Line Frequency>61.0 Hz or <59.0 Hz	
Utility Voltage Fault** - Vac>106% or < 86%	
Design Standards & Code Guidelines	
1996 NEC, UL 508, UL 1741	
Front Panel Control (Local Disable Overrides Optional Remote Reset)	
Run	
Stop/Emergency Off/Disable	
Reset	
Status Indicator, Front Panel	
Power Transfer (AC, DC Present)	
Standby (AC Present, Low DC Power)	
Shutdown (Reset Required)	
LCD Front Panel Display Status/Instrumentation	
Standby: "STANDBY"	
Run: "PCU xx.x kWAC ...SCROLL...xx.x Vdc"	
Shutdown: "SHUTDOWN" (Fault display on control board)	
Remote Control	
Disable - Remote Contact Closure (+5 vdc to +15 vdc)	
Reset - By Momentary Closure/Toggle of Disable Contact/Switch	

* Maximum allowed line voltage to meet requirements of UL 1703 and provide maximum power tracking over the specified ambient temperature range.

** Field Testable by Signal Injection

Figure 14. General IPPU Specifications (Continued)

Upon completion of the initial functional, electrical, and mechanical design of the IPPU assemblies, an all weather enclosure was designed to integrate the inverter with UPG's single axis solar tracker drive assembly for direct mounting to the sub-array support structure. To obtain the maximum cost and performance benefit from design integration, the enclosure was required to provide varying levels of environmental protection based upon the particular functions performed by each PCB sub-assembly. In addition, given the power density of the inverter bridge section, heat management was a critical criteria in the design of the enclosure. The reliability and performance of power electronics systems are dependent upon satisfactory removal of heat. That includes internally generated and externally absorbed heat.

As illustrated in Figure 15, the enclosure is a single unit with three distinct compartments, each designed to provide a specific level of environmental protection. The IPPU is designed to be mounted in the center of each sub-array to provide a balanced load for the tracker drive mechanism and to minimize conduction losses of the dc wiring. The uppermost compartment houses the DC Interface Assembly that parallels all of the sub-array's source circuits. The source circuit wires are housed within the galvanized steel torque tube which runs the entire length of the sub-array serving both as a structural member and as a wire conduit. The torque tube is one continuous length except for a short center separation where it passes through a rotary seal and into the top compartment of the IPPU. This separation allows the PV source circuit wires to enter the compartment and connect to the DC Interface Assembly. This compartment contains filtered vents since it is open to the ventilated torque tube. Torque tube rotation limit sensors are installed in this compartment and are electrically interfaced with the solar tracking motor control that is located on the AC Interface Assembly in the lower compartment.

The center compartment houses the door-mounted Control Assembly and the Bridge Assembly which is mounted to the rear surface of the enclosure. Given the complexity of these assemblies, the center section is environmentally isolated from the upper and lower compartments. The rear surface of the enclosure contains an integral heat sink which is augmented via forced convection along its exterior surface. Electrical interconnection between the compartments is performed through standard ribbon cables. The optional DAS Assembly is located in this compartment and plugs directly into a connector located on the Control Assembly.

The lower compartment houses the AC Interface Assembly and serves as the termination point for underground conduit leading from the array transformer and utility-grid interconnection point. This compartment is vented to the exterior environment as is the top compartment since the conduits are open-ended and condensation is an undesirable occurrence.

Although the enclosure appears to be just a simple box, it nonetheless performs a number of critical functions and is a key component of the IPPU.

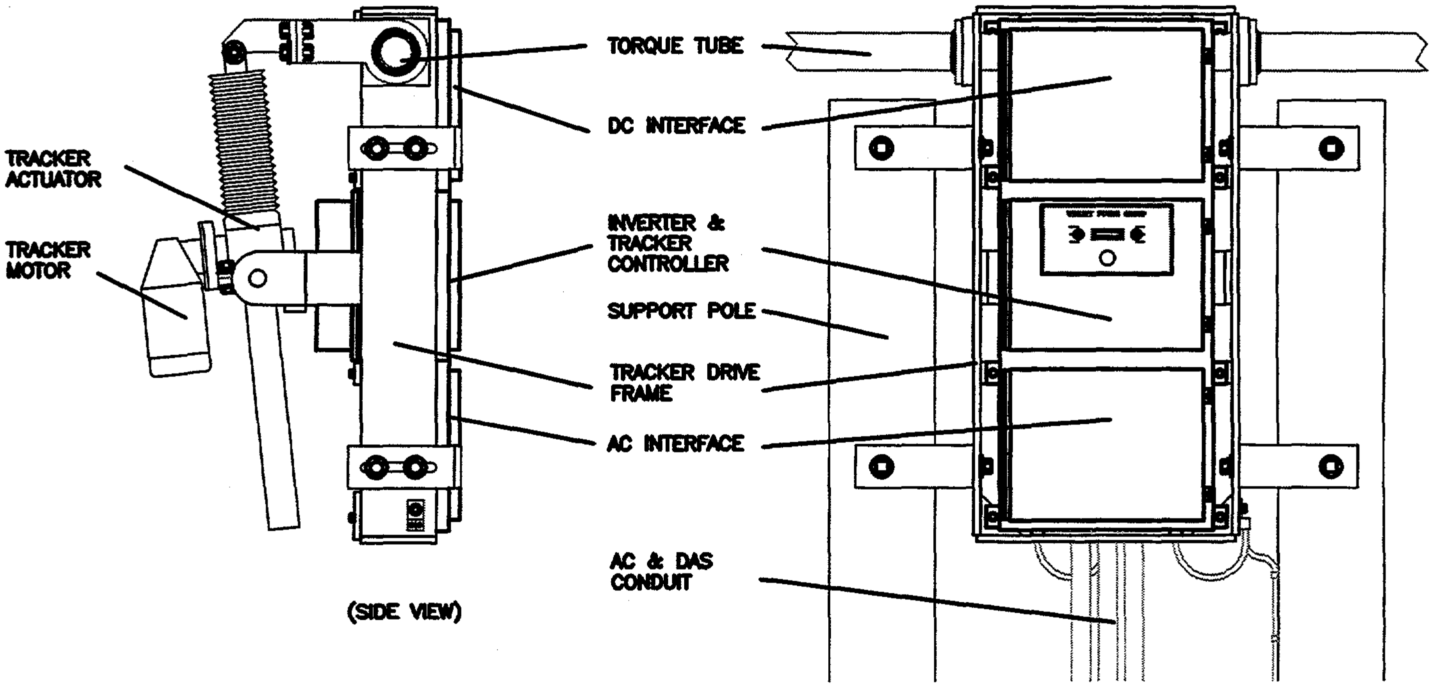

Figure 15. IPPU Enclosure

The output power rating of the IPPU was based upon the number of PV modules supported by UPG's existing single-axis solar tracking array support structure. Although a larger sub-array size may offer greater economies of scale, for multi-megawatt PV power systems, the IPPU and modular sub-array was initially designed for a nominal rating of 20 kW AC as indicated by the title of this report. To meet the voltage requirements of UL Standard 1703 and the 1996 National Electrical Code, however, the nominal rating of the IPPU/Sub-Array as manufactured was derated to 15 kW ac.

Due to the complexity of the IPPU, UPG's development effort proceeded in three stages. First, an engineering prototype was designed and fabricated to allow preliminary factory and field testing and evaluation. Second, building upon the results of the engineering prototype, a pre-production version was developed, fabricated, and subjected to comprehensive factory and field testing. Third, a production version was developed for commercial manufacture incorporating all of the improvements learned from the production prototype version in addition to a number of other modifications related to higher production quantities.

UPG fabricated one engineering prototype IPPU at the end of Phase I and subjected it to a series of factory stress tests. The following problems were observed and solutions implemented:

IGBT SWITCHING NOISE EFFECTING OUTPUT REGULATION

Upon completion of preliminary sub-assembly testing, the first engineering prototype IPPU was assembled and quickly became operational in the grid-tied configuration. The sine wave current output, however, was not stable at over 30% of full power. At higher power levels Insulated Gate Bipolar Transistor (IGBT) failures occurred. UPG's analysis of possible problems indicated current feedback loop instability, common mode noise injection, radiated noise pickup, opto-isolator dV/dT failure, and/or induced noise on the ribbon cables. A number of remedies were attempted and a solution was obtained.

OVERSHOOT ON THE DC BUS

The inverter power section utilizes ultra fast IGBTs in the bridge design with current fall times on the same order (160nS) as Field Effect Transistors (FET). The parasitic dc bus inductance and bus capacitance equivalent series reactance as seen by the IGBT must be very low or the IGBT maximum voltage rating will be exceeded by the voltage overshoot. Initial measurements of the bus overshoot were performed with a Tektronix 2220 60MHz digital oscilloscope and the overshoot, as measured, was within design limits. Unfortunately, IGBTs continued to fail at high power levels. It was decided to put resistor-capacitor-diode (RCD) snubbers across each switching device with the intent to limit turn-off dI/dT. To optimize the snubber design, a Fluke PM3394A, 200Mhz digital scope was obtained, and it revealed that the voltage overshoot was three times the amplitude as measured with the slower Tektronix equipment. The overshoot, and not excessive dI/dT, was determined to be responsible for the failing devices. Installation of optimized resistor-capacitor (RC) snubbers to damp the overshoot solved the problem and allowed the inverter to operate at full power. Unfortunately, the addition of the snubbers reduced the conversion efficiency by one full percentage point.

CONTROL BOARD NUISANCE FAULTS

Factory testing revealed a problem with nuisance faults upon system start-up which caused the system to randomly trip off. Numerous attempts to solve this problem were made including slowing down faults which had non-critical response times, suppressing ac and dc contactor transients, and reworking the input impedance's into the fault multiplexer, yet were met with little success. The problem was eventually solved by holding off all faults (except the critical line overcurrent and overvoltage bus faults) for 50mS following the run command, allowing the contactors to settle mechanically before the faults were enabled.

THERMAL EFFECTS

Testing revealed that the thermal resistance in the critical path from IGBT junction to ambient was greater than the original design calculations had shown. Compounding the problem was the addition of heat associated with the previously described snubber losses. The solution to this problem was the addition of an external fan shroud and two small DC fans (6W each). Although such active cooling components slightly compromise long term performance, this modification allowed IPPU operation at full power in 113° F ambient temperatures with an addition margin of safety. Secondary improvements included perfecting a method of soldering the TO-247 IGBT cases to the heat spreader block, reducing snubber losses with a new bridge board layout, and installing a sun shield to prevent additional external heatsink temperature rise.

TRACKER CONTROL MICROCONTROLLER

The "Solartrak" array tracker controller circuitry utilized by UPG was originally designed by Alex Maish at Sandia National Laboratories, Albuquerque for use in single and two-axis solar tracking systems without real time rotational feedback. UPG integrated the "Solartrak" into the IPPU with the use of a potentiometer and integral pendulum to provide a positive feedback signal. The software/firmware changes required for this implementation were more complex than initially expected. Alex Maish and Sandia assisted in the technology transfer and debugging of these modifications until completion and consistent operation of the tracking function was achieved.

Based upon implementation of these results derived from testing the engineering Prototype, UPG fabricated eight (8) pre-production IPPUs for delivery under a PV power systems contract from the Sacramento Municipal Utility District. These IPPUs were installed during July, 1996 and testing and evaluation of these continued over a period of several months.

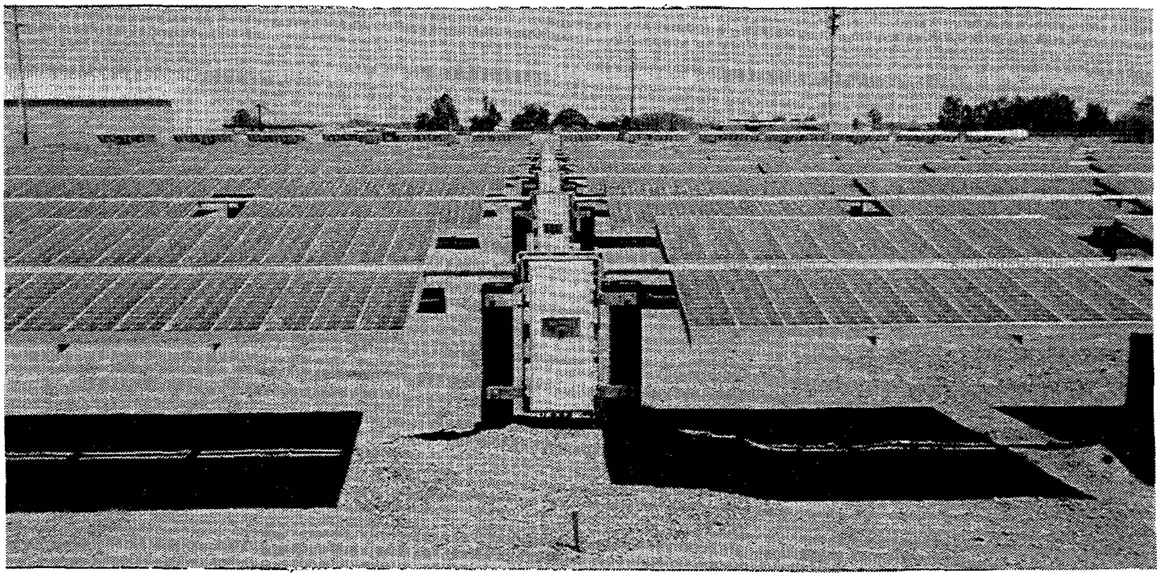

Figure 16. Prototype sub-arrays in Sacramento, California.

After completion of the field testing of the 8 pre-production units, early in Phase II, UPG entered the third stage of IPPU development and prepared to fabricate the production version. The design was updated to seamlessly implement all changes, retro-fits, and modifications to enhance performance and reliability that were learned from the manufacturing, factory testing and field evaluation of the pre-production units. There is no substitute for field testing of PV systems and components in terms of identifying areas of design requiring improvement. Parallel operation of grid connected inverters in a field array yielded particularly important data. The design and/or operational modifications of each assembly which were determined to be required for the production version are summarized as follows:

The DC Interface Assembly: Individual fuses for each PV source circuit were added. The mechanical layout was modified to allow more room for the source circuit wiring, and to include an integral strain relief for the source wires. The rotational feedback circuit was simplified with the addition of east and west directional limit sensors.

The AC Interface Assembly was modified to include a fused disconnect.

The Bridge Assembly was modified to provide a very low inductance power path. The switching waveforms were optimized for low dissipation and high efficiency. The heat spreader blocks were re-designed with a lower profile which resulted in a lighter weight and more easily installed assembly.

The Control Assembly and the Regulator Assembly were combined into a single updated PCB. Removing the regulator functions from the Bridge/Regulator Assembly and placing them on the Control Assembly had several advantages: 1) The overall complexity of the Control Assembly is about the same, while reducing the complexity of the Bridge Assembly; 2) The noise problems were controlled; 3) Testing was simplified by having all of the control functions on a single assembly; and 4) There are fewer interconnections.

The Data Acquisition System (DAS) Option incorporates a Campbell Scientific datalogger for all of the memory storage and remote access functions. There is no longer a requirement for an on-board computer in each IPPU. The DAS circuitry in the IPPU consists only of signal conditioning and a digital interface.

Fabrication of the production version required the establishment of a product structure, parts lists data base, test procedures, and manufacturing quality control procedures. Upon completion of the production version of the IPPU design, engineering drawings were generated and used to create production level documentation. Figure 17 provides an example of one of the factory test procedures developed.

DC Assembly A03500
Test Report

A03502 Serial #: ________________ **Rev.:** __________ **Test By:** ________________

A03501 Serial #: ________________ **Rev.:** __________ **Date:** ________________

Oscilloscope Setup:	Connect To:	
Channel 1: 100 Volts/div.	Cathode of a crowbar Diode	
Channel 2: 100 Volts/div.	Cathode of a Paralleling Diode	
Pre-charge Test:		
Release Mushroom Switch		
Set Input Voltage:	430 VDC through a 7 ohm resistor.	
	Verify that pre-charge does not begin	(✓)
Push in and release Mushroom Switch	Verify 600OS to 1000OS crowbar	OS
	Verify that pre-charge begins	(✓)
Push in Mushroom Switch	Verify that discharge begins.	(✓)
Release Mushroom Switch	Verify that pre-charge takes between 1 minute and 2 minutes.	Min Sec
Crowbar Waveforms:	Operate unit at bus voltage of 350 to 360 V	
At start-up:	Verify that crowbar is fully on for 50⊕5 mS.	mS
At shutdown:	Verify that crowbar is fully on for 25⊕5 mS.	mS
	Verify that overshoot on both probes is <650 Volts.	Volts
Contactor Driver Waveform:		
Oscilloscope Setup: 20 Volts/div.	Right "Coil" Terminal	
At start-up:	Verify that coil voltage is 0.	(✓)
At shut-down:	Verify that coil voltage overshoot is 51⊕5 Volts for 7⊕2 mS.	Volts mS
DC Ground Fault Detector:		
Oscilloscope Setup: 100 mV/div.	DCGF Test Point	
Adjust DCGF Null for 0 Volts with unit off.	Verify that it is O100 mV with unit operating.	mV
Low Power Detection:		
Oscilloscope Setup: 5 Volts/div.	D5 Cathode	
Reduce input current until D5 Cathode toggles from 15 to 0 V.	Verify that D5 Cathode toggles low when the input current is 1⊕0.5 Amp.	Amp
Fan Driver/Thermal Switch:		
Use heat gun on rear DC board with unit operating:	Verify that fan comes on in about 1 minute.	(✓)
Turn off heat gun.	Verify that fan goes off in about 1 minute.	(✓)
Repeat.		(✓)
Limit Switches		
East Limit	Verify that left limit switch limits travel East	(✓)
West Limit	Verify that right limit switch limits travel West	(✓)

Figure 17. DC Assembly Factory Test Procedure

The production version of the IPPU was taken to Sandia National Laboratories for testing which confirmed UPG's expectation that the DC to AC conversion efficiency of the inverter section was higher than any other commercially available inverter of similar size. (Figure 18)

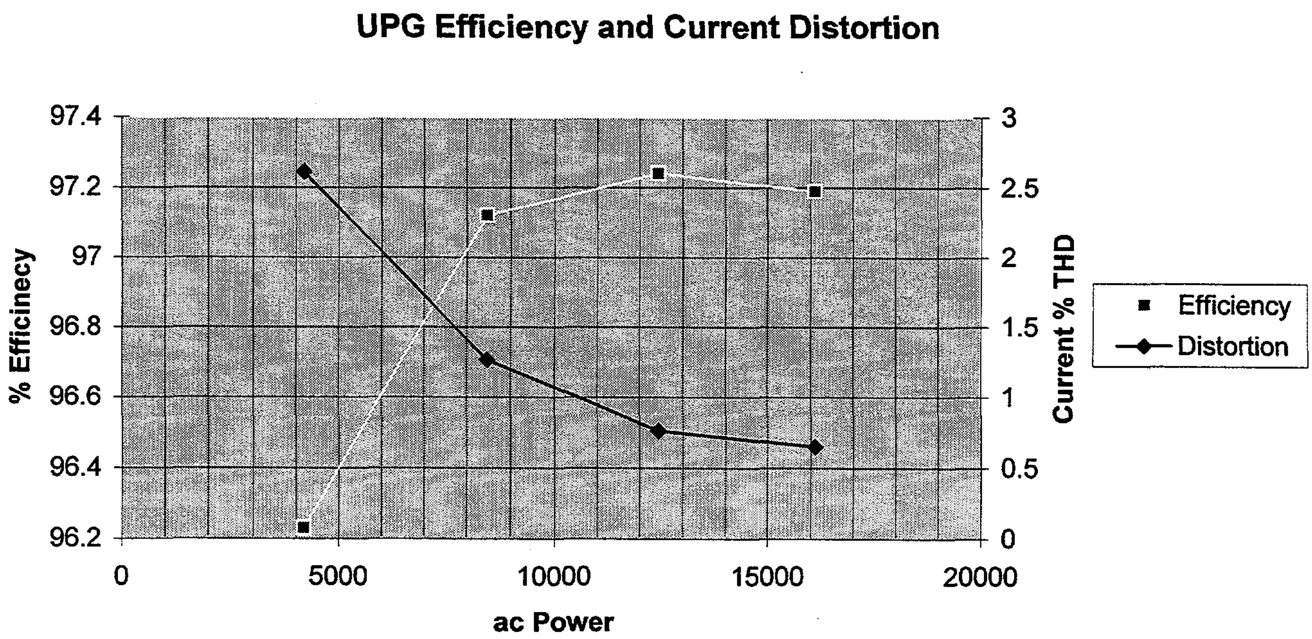

Figure 18. IPPU Efficiency and THD results of SNL testing.

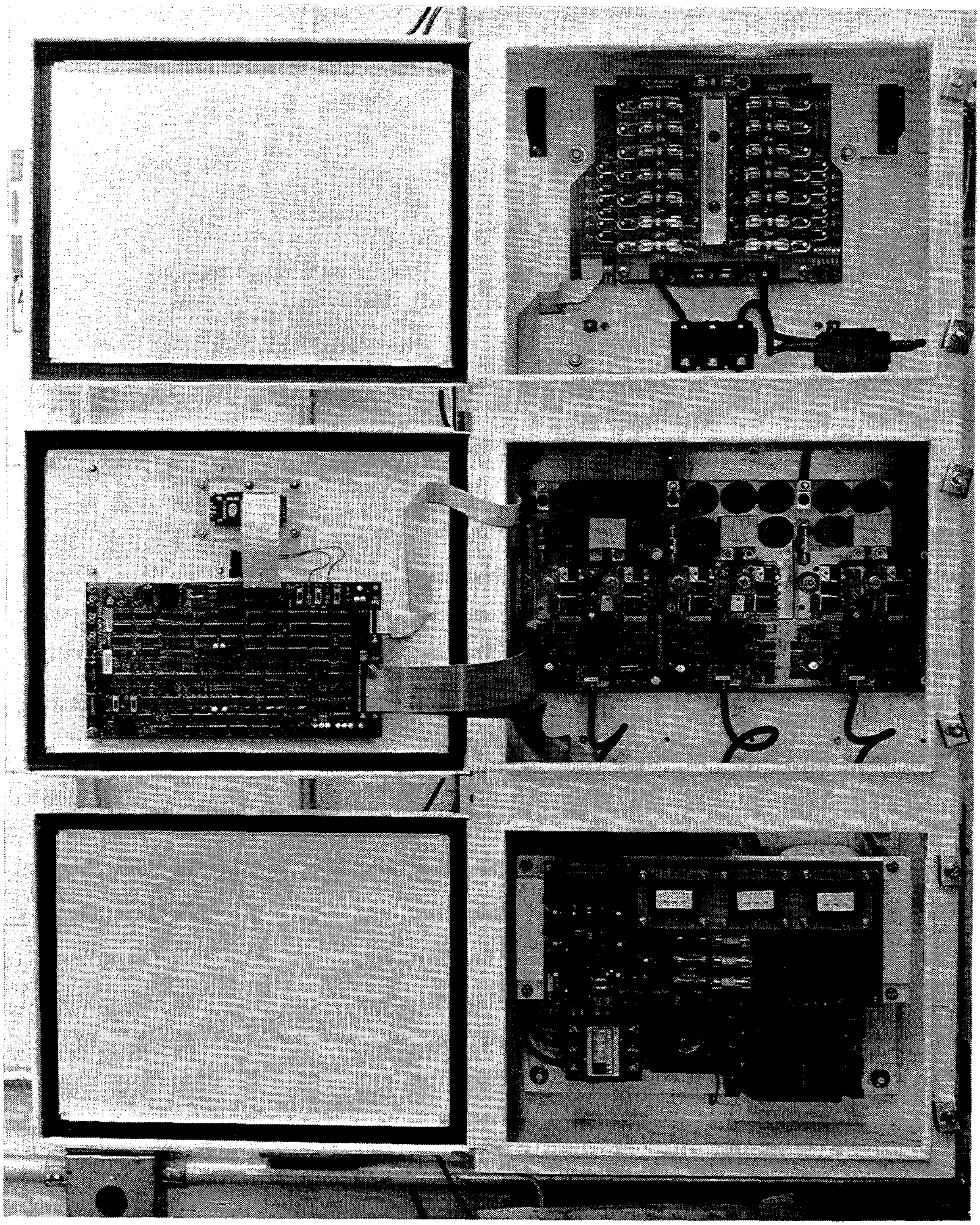

Figure 19. Photograph of production version IPPU.

SUMMARY

UPG successfully completed the planned two-year PVMaT Phase 4A1 work effort by demonstrating the design, fabrication, and installation of a modular and integrated 15 kW ac solar tracking PV power system sub-array. Each sub-array utilizes one (1) center mounted production IPPU in combination with either twenty-eight (28) 11M55 Modular Panels or thirty (30) 7SP75 Modular Panels.

UPG exceeded its goal of providing a 40% reduction in area-related balance-of-system costs and a 50% reduction in power related balance-of-system costs by achieving cost reductions of 53% and 52% respectively. The net reduction in the total cost of single-axis solar tracking grid connected PV power systems achieved by UPG was 23.3%. Through 1997, UPG installed a total of 50 integrated and modular sub-arrays in the United States representing over 700 kW of new PV power systems. When applied to these new systems, UPG's cost reduction achievement resulted in over $1.4 million in savings to UPG's electric utility customers which include the Sacramento Municipal Utility District, Arizona Public Service, and Detroit Edison.

The following key developments were responsible for most of the final cost reductions itemized in Figure 20:

- Integration of seven discrete electrical enclosures into a single multi-functional power processing unit.
- Elimination of extruded aluminum frames on each PV module.
- Simplification of the panel support structure.
- Replacement of 4-pack module shipping boxes with reusable bulk pack crates.
- Substitution of factory labor for field labor in the assembly of Modular Panels.
- UL listing of UPG's 11M55 and 7SP75 Modular Panels.
- Increase in Modular Panel manufacturing capacity from 1MW to 6 MW per year.
- Increase in IPPU manufacturing capacity from 200kW to 3 MW per year.
- Reduction of the number of sub-array field installation tasks from 36 to 19.

MAJOR PV SYSTEM COST GROUP	% OF TOTAL PV SYSTEM COST PRE-PVMaT	PVMaT PHASE 4A1 COST REDUCTION	NET PVMaT PHASE 4A1 COST REDUCTION
PV MODULES	60%	5%	3.0%
AREA RELATED BOS	25%	50%	12.5%
POWER RELATED BOS	15%	52%	7.8%
TOTAL NET PV SYSTEM COST REDUCTION			**21.3%**

Figure 20. Final system cost reduction results.

Figure 21 compares the major field tasks required to design and install a nominal 100 kW grid connected PV power system before and after the development of UPG's integrated sub-array concept. The reduction in the number of discrete installation tasks of almost 50% indicates the extent of BOS cost reduction. In addition, reduced field labor typically translates into higher installed PV system quality, and a reduced component count typically results in greater PV system reliability.

	MAJOR FIELD TASKS: Before PVMaT Phase 4A1 Development		**MAJOR FIELD TASKS: After PVMaT Phase 4A1 Development**
1	Electrical Design	1	Modular Design Package
2	Mechanical and Structural Design	2	Site Mobilization
3	Site Mobilization	3	Site Preparation
4	Site Preparation	4	Support Pole Hole Augering
5	Support Pole Hole Augering	5	Support Pole Installation
6	Support Pole Installation	6	Drill Tracker Drive Assembly Mounting Holes
7	Install Conduit Junction Boxes	7	Drill Torque Tube Bearing Plate Mounting Holes
8	Install AC Tracker Motor Junction Boxes	8	Install Torque Tube Bearing Plates
9	Conduit Trenching	9	Install IPPU Assemblies
10	Electrical Equipment Concrete Pad Excavation	10	Conduit Trenching
11	Electrical Equipment Concrete Pad Form	11	Lay Conduit
12	Lay Conduit	12	Set Pre-Cast Transformer Pad and Transformer
13	Backfill and Compact Conduit Trenches	13	Pull Conduit and Torque Tube Wires
14	Pour Concrete Electrical Equipment Pad	14	Backfill and Compact Conduit Trenches
15	Drill Torque Tube Bearing Plate Mounting Holes	15	Install Torque Tubes
16	Drill Tracker Drive Assembly Mounting Holes	16	Install PV Panels
17	Install Torque Tube Bearing Plates	17	Connect All Wires
18	Install Tracker Drive Assemblies	18	Test IPPU's
19	Install Torque Tubes	19	Array Start-Up
20	Install Struts	20	
21	Install PV Module Rails	21	
22	Install PV Modules	22	
23	Install Row Junction Boxes	23	
24	Install Tracker Limit Switch Junction Boxes	24	
25	Install Inverter	25	
26	Install Transformer	26	
27	Install DC Interface Enclosures	27	
28	Install Tracker Drive Control Enclosure	28	
29	Wire PV Modules	29	
30	Pull Conduit and Torque Tube Wires	30	
31	Connect All Wires	31	
32	Test Source Circuits	32	
33	Test Sub-Arrays	33	
34	Test Inverter	34	
35	Test Tracker Controller and Tracker Motors	35	
36	System Start-Up	36	

Figure 21. PV power system field installation tasks.

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13. ABSTRACT *(Maximum 200 words)*
Utility Power Group (UPG) completed manufacturing modifications and power-processing improvements for larger utility-interactive systems using PV subarray unit building blocks of 7- to 15- kW. These can be interconnected to construct multi-megawatt PV fields. UPG determined that the most important factor to reduce costs and improve reliability was to bring as much of the field installation work as possible onto the factory floor; they implemented this approach to develop a modular panel of frameless PV laminates and an integrated power control system. UPG established a manufacturing process for integrating PV laminates into pre-assembled, field-deployable modular panels. Individual frameless PV laminates are factory-mounted and interconnected into Modular Panels (MP), then mounted into recyclable shipping fixtures and delivered to the field, ready for placement on the ground-support structure. For power conversion, UPG enhanced the performance of power-related balance-of-system (BOS) components by integrating power conversion/control electronics, array-tracking control electronics, source circuit protection hardware, and DC and AC switchgear into a single, pre-assembled unit termed an Integrated Power Processing Unit (IPPU). The IPPU is a 3-compartment enclosure designed to be mounted in the center of each sub-array, with the tracking mechanism attached to the back. The IPPU inverter is 3-phase, 96% efficient with less than 3% total harmonic distortion over a 25% to 100% output range. UPG also refined area-related BOS costs associated with the field installation of single-axis tracking PV power systems. The company accomplished their objectives, achieving a 40% reduction in area-related BOS costs and reducing net total costs of their systems by 23%. Systems were deployed for beta-testing, and 700 kW of new PV power systems were deployed during 1996 and 1997.

14. SUBJECT TERMS

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