Subcontractor Report

February 1999 • NREL/SR-520-26084

The Development of Standardized, Low-Cost AC PV Systems

Final Technical Report
8 September 1995 — 30 June 1998

S. Strong
Solar Design Associates, Inc.
Harvard, Massachusetts

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Contract No. DE-AC36-98-GO10337

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NREL Technical Monitor: H. Thomas

Prepared under Subcontract No. ZAF-5-14271-01

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Performance Period: **9/1/95 to 6/30/98**

EXECUTIVE SUMMARY

Solar Design Associates, Inc. (SDA), of Harvard, MA and Solarex Corporation, of Frederick, MD, teamed together with Advanced Energy Systems of Wilton, NH to pursue a multi-level program under PVMaT Phase 4-A1 targeted at design innovation, standardization and modularity with the goal to deliver low-cost AC PV systems to the utility-interactive market.

The team was supported by several other participants, the Sacramento Municipal Utility District (SMUD), the New York Power Authority (NYPA) and Arizona Public Service (APS), Baltimore Gas and Electric (BG&E), Oberösterreichische Kraftwerke AG (OKA, Austria), Kansai Electric Power Company (Japan) and Arizona State University (ASU). The role of these team members was to provide initial market and product development input and then to provide product testing and evaluation and, in the case of ASU, formal product testing and certification as well.

The work was divided into the following six key task areas:

1/ A System-level Review of PV Systems Components, Design & Installation
2/ Innovative Mounting Systems
3/ Enhanced Modular Inverters
4/ Pre-manufactured Wiring Systems
5/ Standardized, Pre-approved, Modular Designs
6/ US AC PV Products and Systems for Export

Each of these six major work tasks were split into two phases to match the two-year format of this PVMaT program effort.

At the core of this PVMaT effort was the development of a reliable and cost-effective DC-to-AC micro inverter which would make the concept of a large-area ‘AC PV module’ practical. This inverter was to be developed based upon the prototype 250 Wp analog-control modular inverter which had been developed with support from the US Department of Energy’s PV:Bonus (Building Opportunities in The US for Photovoltaics) program.

Midway into the work, it was recognized that the we were not able to meet the goals proposed for the commercialization of the AC module. The costs of the modular inverter were simply too high to justify a full-scale market introduction at the time. A request was made to redefine the work scope to incorporate what were considered more realizable goals. These goals were then achieved.

One significant result of this program is that Solarex has filed a US patent application on the new module frame and mounting system which was developed with support from PVMaT. The patent application is US Utility Patent # 09/123,724 for: “Photovoltaic Module Framing System with Integral Electrical Raceways”. Solarex has already started to manufacture this new combination framing and array mounting system and a number of residential scale installations are already in place in the field.

BACKGROUND

When this PVMaT effort was proposed to NREL in the fall of 1994, Robert Wills was an employee of Solar Design Associates. As Principal Electrical Engineer, he was to be responsible for the design and development of the enhanced digital inverter as well as supporting other work tasks in this PVMaT effort involving electrical engineering issues.

In September, 1995, Dr. Wills left Solar Design Associates to form a new company, called Advanced Energy Systems, Inc., to focus on the development and commercialization of power electronics for the renewable energy marketplace. This change was made with the support of Solar Design Associates.

Dr. Wills proposed to continue to be responsible for the development of the new modular inverter and those other tasks requiring electrical engineering support in the PVMaT Statement of Work with the assistance of AES staff. Therefore, Solar Design Associates proposed to NREL to carry out the PVMaT tasks with Advanced Energy Systems working as a subcontractor. This change was not expected to affect the scope of work, key personnel, budget, schedule or deliverables as presented in the original PVMaT proposal. NREL agreed to this change.

In the Spring of 1997, it was recognized that the work required to achieve the desired cost and reliability of the AES modular inverter would require time and resources beyond the scope of this PVMaT effort. This resulted in a reassessment of the program focus and a request to NREL for a change in Scope of Work. NREL agreed to this change in work scope and also granted an extension to the contract period. The original and the new work tasks are both included in the detail description of the work that follows.

OVERALL PROGRAM GOALS

The following section presents the overall program goals of the original PVMaT Statement of Work with a summary of the results followed by a description of the new tasks in the revised Statement of Work. The individual work tasks and their results are addressed in greater detail in the subsequent sections of the report.

The original PVMaT Statement of Work included the following six key tasks:

1/ A System-level Review of PV Systems Components, Design & Installation
2/ Innovative Mounting Systems
3/ Enhanced Modular Inverters
4/ Pre-manufactured Wiring Systems
5/ Standardized, Pre-approved, Modular Designs
6/ US PV Products and Systems for Export

The PVMaT program was divided into two one-year Phases. Accordingly, each of our six major work tasks were also divided into two phases to match the two-year format of the program. These key work tasks are summarized below in chronological order.

System-level Review: The first task was to perform a comprehensive review of past work and current practice in utility-interactive PV systems design and installation in the US as well as in Europe and Japan. The following three areas were the principal focus of this work: Flat-roof residential and commercial systems, sloped-roof residential and commercial systems and ground-mounted fixed arrays. Utilities, PV system integrators, PV dealers, distributors and manufacturers were questioned about current practice. Arizona State University assisted in gathering this research information and the findings were used to help define the standardized PV components and systems to be developed under this program.

Innovative Mounting Systems: The findings from the system-level review were used as a basis to help develop low-cost methods of array mounting for standard framed modules by creating standardized, pre-engineered components for flat-roof, sloped-roof and ground-mounted arrays. The use of adhesives was explored as a method of mounting arrays using unframed laminates as another method of potential cost reduction. Low-cost solutions were defined for each system type.

Enhanced Modular Inverters: A digitally controlled modular inverter was developed by Advanced Energy Systems using the 250 Wp analog-control modular inverter developed with support from the DOE's PV:Bonus program as a starting point. With digital control, AES believed that the volume manufacturing cost for the 250 Wp modular inverter could be reduced to below 20 cents per peak-watt (Wp) and even lower in very high volume.

The following table presents the inverter cost breakdown set as a goal:

Input Capacitor	$4
Power stage magnetics	$4
Power stage FET Switches	$5
Power supply components	$3
Bridge FETs	$3
Filter components	$2
Digital Control Chip	$8
Board & Assembly	$10
Misc. Components	$10
Total	$49

Pre-manufactured Wiring Systems: Array wiring was identified as a key 'balance-of-system' cost in PV system installation. Pre-manufactured interconnection cables were seen as a way to streamline PV system installation and reduce these costs. The development of pre-assembled wiring options for use with the new Solarex large-area modules which would eliminate the need for custom field wiring was undertaken.

To facilitate the easy installation and resultant cost savings and to receive UL listing, these wiring solutions needed to meet a series of requirements. The following goals were established for the wiring systems. They needed to snap in place, not requiring electrician's time and, replace the usual conduit and connectors. Further, they needed to be touch-safe and polarized to avoid the danger of shock and the risk of improper connections.

A quick-connect wiring harness was defined for connection of AC modules. When it was recognized that the modular inverter would not meet the required cost goals, program emphasis was shifted and a quick-connect electrical termination system was also developed and qualified for the Solarex 8 sq. ft. thin-film module and received UL listing.

Standardized, Pre-approved, Modular Systems: The innovations developed for array mounting and wiring together with the enhanced digital modular inverter were to be combined to develop standardized, modular AC PV systems.

These standardized systems were to be low-cost, pre-packaged systems - shipped complete with all BOS ready to install and be UL-listed as complete systems. With the near-infinite flexibility of the AC PV module, systems of virtually any size, from one module up to large-scale arrays could be installed using the same basic components.

When it was recognized that the modular inverter would not meet the required cost goals, program emphasis was shifted and a modular mounting and electrical interconnection system was developed and qualified for the Solarex large-area thin-film module and received UL listing.

US PV Products and Systems for Export: Two additional advanced digitally controlled modular inverters were to be developed, one for the Japanese and one for the European markets.

These market-specific inverters were to be offered together with the proposed innovations in low-cost mounting hardware and array wiring as an integrated, modular AC PV system package to these markets.

When difficulties were encountered with the modular inverter passing the necessary environmental and reliability testing, it was decided not to pursue the development of new versions for the foreign market but instead to concentrate first on the development of the basic design for the US market.

REVISED WORK PLAN

When it became clear that the digital-control modular inverter would not meet the established cost and reliability goals without a good deal more work and resources, the overall PVMaT statement of work was reviewed with the goal to redirect the focus of the work to define a new set of goals which would be achievable within the framework of the PVMaT program. The new tasks in the revised statement of work are listed in the following table and described below.

- Obtain UL Listing of the AC PV Module as an assembly
- Achieve Compliance with Codes and Standards
- Continue Work on Modular Inverter Cost Reduction
- Develop a Mounting System for Solarex Thin-film Modules
- Development of an Electrical Connector System for Solarex Thin-film Modules

Obtain UL Listing of the AC PV Module: It was recognized that an important milestone in the commercialization of AC modules would be to take the AES modular inverter though the steps necessary to achieve fully UL-listed AC PV modules. This was to be done in as generic a way as possible so the AES inverter could be used with several manufacturer's modules and, to help pave the way for the commercialization of AC modules in general.

The AES modular inverter had already achieved UL listing. To obtain a UL listing for the AC PV module - defined as the assembly of the modular inverter and a large-area PV module - required the successful completion of several UL testing sequences. These included temperature cycling, humidity cycle, rain spray and an insulation breakdown test. In addition, a mounting adhesive strength test must be completed and passed.

Fortunately, NREL agreed to provide their environmental chamber for these tests which made this work possible as the high cost of renting a commercial test chamber were beyond our resources. The AES modular inverter attached to a PV module as an ‘AC PV module’ assembly did achieve UL listing as a result of this work.

Achieve Compliance with Codes and Standards: It was recognized that there were a number of issues in the existing codes and standards which govern the manufacture and installation of distributed PV systems which required revision to accommodate the differing characteristics of AC modules. AES was to review the current draft UL 1741 and IEEE 929 standards and work with the responsible committees to come up with practical solutions to the problems (without becoming too constrictive or product specific).

AES was then to modify the operation of their modular inverter as needed to achieve compliance with these revised codes. AES did become very involved in the assessment of existing codes and standards and their revision. This work resulted in streamlining the introduction and acceptance of AC modules.

Continue Work on Inverter Cost Reduction: The manufacturing costs for the MI-250 were so high that this model is not able to compete with larger (~2-5 kW) central inverter systems. To further reduce the manufactured cost of the MI-250, AES was to pursue design refinements to achieve cost savings in the following areas: A reduced-cost power-line carrier daughter card or other suitable data communications subsystem and, cost reductions from potting vs. conformal coat, mechanical design, and other general cost reduction possibilities.

AES did investigate alternate chip sets for the power-line carrier, including simpler and less capable schemes than the spread-spectrum system of Intellon. AES also worked with the New Hampshire Manufacturing Extension Program on potting vs. conformal coat, mechanical design, and general cost reduction possibilities. AES also explored other ways of reducing the cost of the MI-250 to the end user. This work resulted in a lower-cost modular inverter and also helped AES to develop their GC-1000 utility-interactive inverter.

Develop a Mounting System for Solarex Thin-film Modules: During the first 18 months of this PVMaT effort, the Solarex tandem-junction thin-film product was commercialized at their new facility in Toano, VA. In an effort to achieve the program goals for low-cost PV systems, Solarex was to develop a low cost mounting system for these new thin-film modules and obtain UL listing for the system.

Solarex did develop an integrated module / array mounting system for their thin-film product in sloped-roof applications. The system was tested and qualified to UL and ANSI Z97.1 to assure compliance with Building Codes and the NEC. It has received a UL listing.

Development of an Electrical Connector System for Thin-Film Modules: In conjunction with the effort to develop an integrated mounting system for their thin-film product, Solarex also was to define and qualify a low-cost, electrical connector system. Because of the larger number of modules required in a system, a quick-connect DC connector was preferred.

Solarex did develop/select a quick-connect DC connector for their thin-film modules to be used in conjunction with their new module / array mounting system. The connector was combined with a wiring system that satisfies NEC requirements and UL listing was obtained for this connector and wiring system.

Further detail discussion of the individual work tasks and their results is provided by each of the key subcontractors, Solarex and Advanced Energy Systems, and follows this section as separate reports dedicated to each subcontractor's work.

Final Report of Solarex's Work performed under NREL Subcontract # RAF-4-14271-01

PREFACE

This final report covers the work performed by Solarex as a subcontractor under Solar Design Associates' PVMaT Contract # ZAF-5-14271-01 entitled "Development of Standardized, Low-cost AC PV Systems".

The following personnel at Solarex contributed to the efforts covered in this report: Fiore Artigliere, Paul Garvison, George Kelly, Jean Posbic, Bill Rever, Jay Shaner, Don Warfield and John Wohlgemuth.

SOLAREX PROGRAM OVERVIEW

The original objectives of this program were to improve the reliability and safety and reduce the cost of installed PV systems by creating standardized, pre-engineered components and enhanced, low-cost modular inverters. The advances were to be combined with the new, large-area Solarex MSX-240 PV module to create standard, modular AC PV "building blocks" for the U.S., Japanese and European markets where identical units could be combined to create PV systems of virtually any capacity to suit virtually any application.

During the first year of the program, Solarex successfully developed mounting systems for sloped-roof, flat-roof and ground-mounted applications and built prototypes of each system at Solarex for testing and evaluation. The MSX-240 module received UL listing and qualification to IEC–1215 as configured in the mounting systems designed in this program. Solarex also worked with AES to identify and qualify a commercially available connector system for wiring of the AC modules.

During the first year Solarex also developed plans for the market introduction of the Solarex AC module which was to incorporate the AES modular inverter with the Solarex MSX 240 module. Solarex also participated in the effort to qualify the AES modular inverter for use with Solarex modules in a general outdoor climate. A preliminary modular inverter qualification procedure was developed to test the prototype inverters delivered by AES.

During the second year of the program, persistent problems with the reliability and cost of the AES modular inverter caused Solarex to make the difficult decision to postpone the AC module market introduction and led to a proposed change in the program objectives. The change expanded the work on creating standardized, pre-engineered BOS components to include developing mounting and electrical interconnection systems for the new 8-square-foot tandem-junction amorphous-silicon modules built in Solarex's new Toano, VA factory.

A new mounting system was developed and qualified for use in residential roof-top systems. A quick connect electrical termination was also developed and qualified. Both the mechanical mounting system and the electrical connector received UL listing. A prototype system was installed. Finally, these systems are now being sold through the PV-VALUE Program. A summary overview of the Solarex PV-VALUE Program is included at the end of this section as Figure 12.

SOLAREX INITIAL WORK PLAN

AC Module Mounting System: In this task Solarex was to work with SDA to develop innovative, low-cost methods of array mounting and structural support for residential and commercial buildings as well as ground-mounted arrays using pre-engineered, standardized components and large-area Solarex MSX-240 modules.

Initial discussions concentrated on methods for sloped roof installations. The following methods were selected for evaluation:

* Z-brackets with framed modules.
* Ready Mount frame.
* Aluminum beams with unframed laminates and low cost foot.
* B-Line channels with roof jacks and unframed laminates.

Our initial estimates indicated that one of the key drivers of total installed cost was the labor required for mounting the array. This was also the aspect of the different methods about which Solarex knew the least. Therefore, Solarex personnel demonstrated the use of each mounting method and videotaped the process for further analysis. The results are summarized below:

* Z-brackets with framed modules. This method required very little time on the roof. However, the brackets are definitely not as rigid as the other mounting methods.
* Ready Mount frame. The ready mount results in a very heavy system that is not easy to lift into place.
* B-Line channels with roof jacks and unframed laminates. The roof jacks require too much time on the roof for exact placement of the bracket.
* Aluminum beams with unframed laminates and low cost feet. This system was easy to install and projected to have the lowest cost - although aesthetics were not ideal.

A system with aluminum beams with unframed laminates and low-cost feet was selected for development. A drawing of this mounting concept is shown in Figure 1.

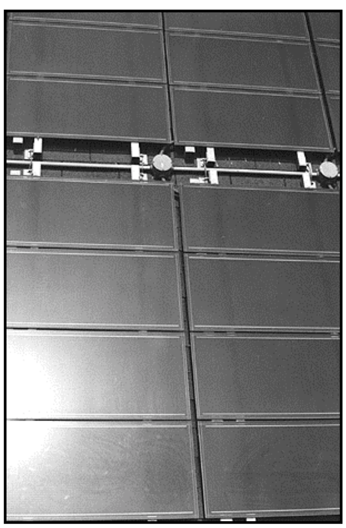

Figure 2:

Solarex assembled and installed a 1 kW prototype system on a simulated sloped roof structure at the Solarex facility in Frederick, MD. The array consisted of 12 panels, each made up of four MST-22ES modules, attached to aluminum beams with RTV. These were mounted to the roof using foot brackets and lag screws. A photograph of this system is shown in Figure 2.

The second application reviewed was for ground mounted support structures for AC PV modules. Solarex used unframed laminates with the same aluminum box beam as used for the sloped roof system. The major difference involves the method of support for this structure. Most ground mounted systems require too much site preparation, use too much material (poured concrete footers) or have high installation costs like buried telephone poles or screwed in anchors.

Rather than bury something in the ground, Solarex proposed to provide sufficient weight (like the roof pan systems) to keep the array from moving. Solarex selected a ground-mounted system that uses old tires filled with concrete at the site. Old tires are free (or sometimes you get paid to use them in an environmentally sound application) and the concrete would cost about $3.00 per tire. The module height is adjustable by sliding the laminate along the beam. The angle is adjustable by varying the length and angle of the support legs. A drawing of this system is shown in Figure 3. Each leg was connected to a copper strap to provide for array grounding.

Figure 1

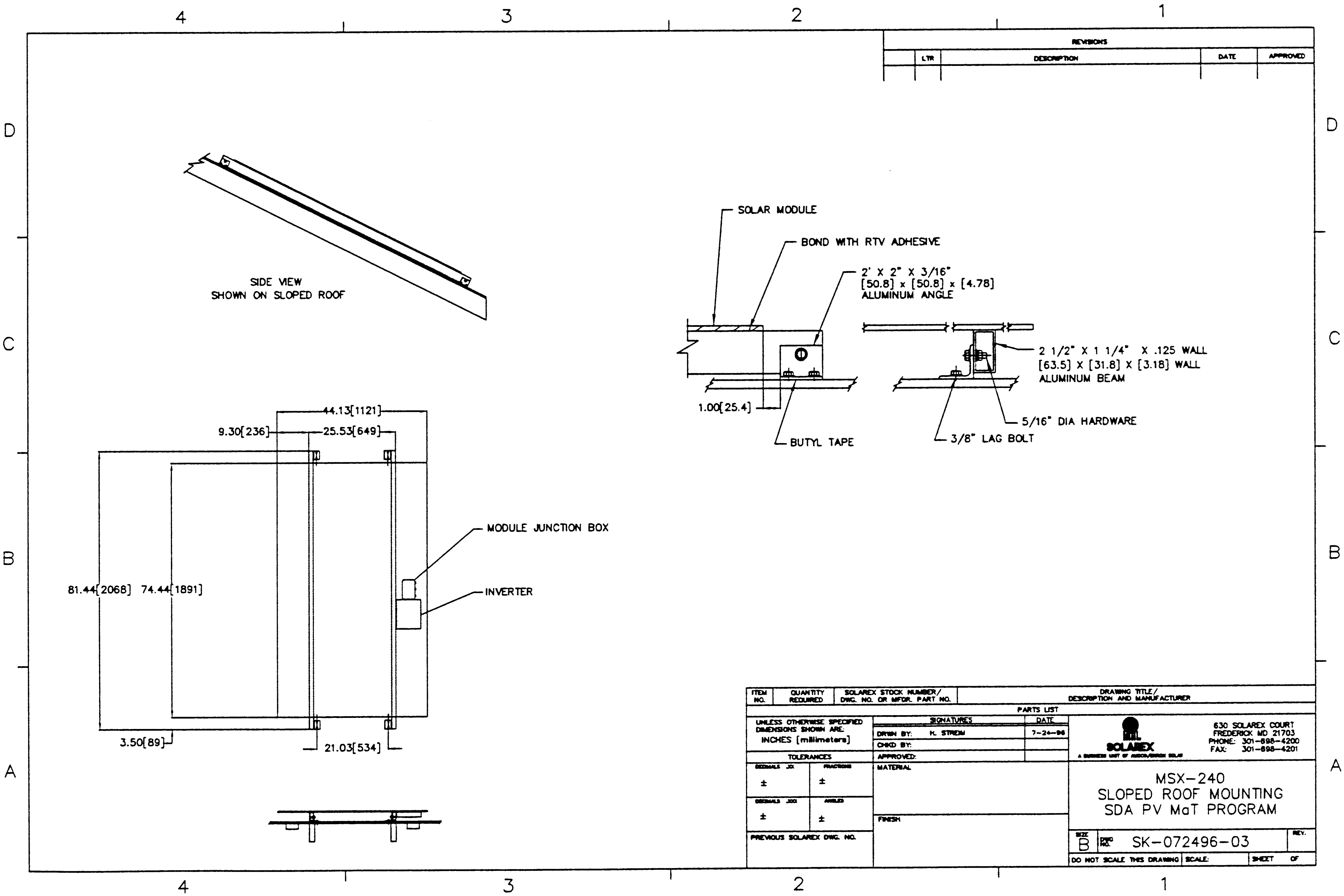
SIDE VIEW
SHOWN ON SLOPED ROOF
SOLAR MODULE
BOND WITH RTV ADHESIVE
2' X 2" X 3/16"
[50.8] x [50.8] x [4.78]
ALUMINUM ANGLE
2 1/2" X 1 1/4" X .125 WALL
[63.5] X [31.8] X [3.18] WALL
ALUMINUM BEAM
1.00[25.4]
BUTYL TAPE
5/16" DIA HARDWARE
3/8" LAG BOLT
44.13[1121]
9.30[236]
25.53[649]
MODULE JUNCTION BOX
INVERTER
81.44[2068]
74.44[1891]
3.50[89]
21.03[534]
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
PARTS LIST
INCHES [millimeters]
TOLERANCES
SIGNATURES
DATE
APPROVED:
MATERIAL
FINISH
PREVIOUS SOLAREX DWG. NO.
SOLAREX
630 SOLAREX COURT
FREDERICK MD 21703
PHONE: 301-698-4200
FAX: 301-698-4201
MSX-240
SLOPED ROOF MOUNTING
SDA PV MaT PROGRAM
B
SK-072496-03
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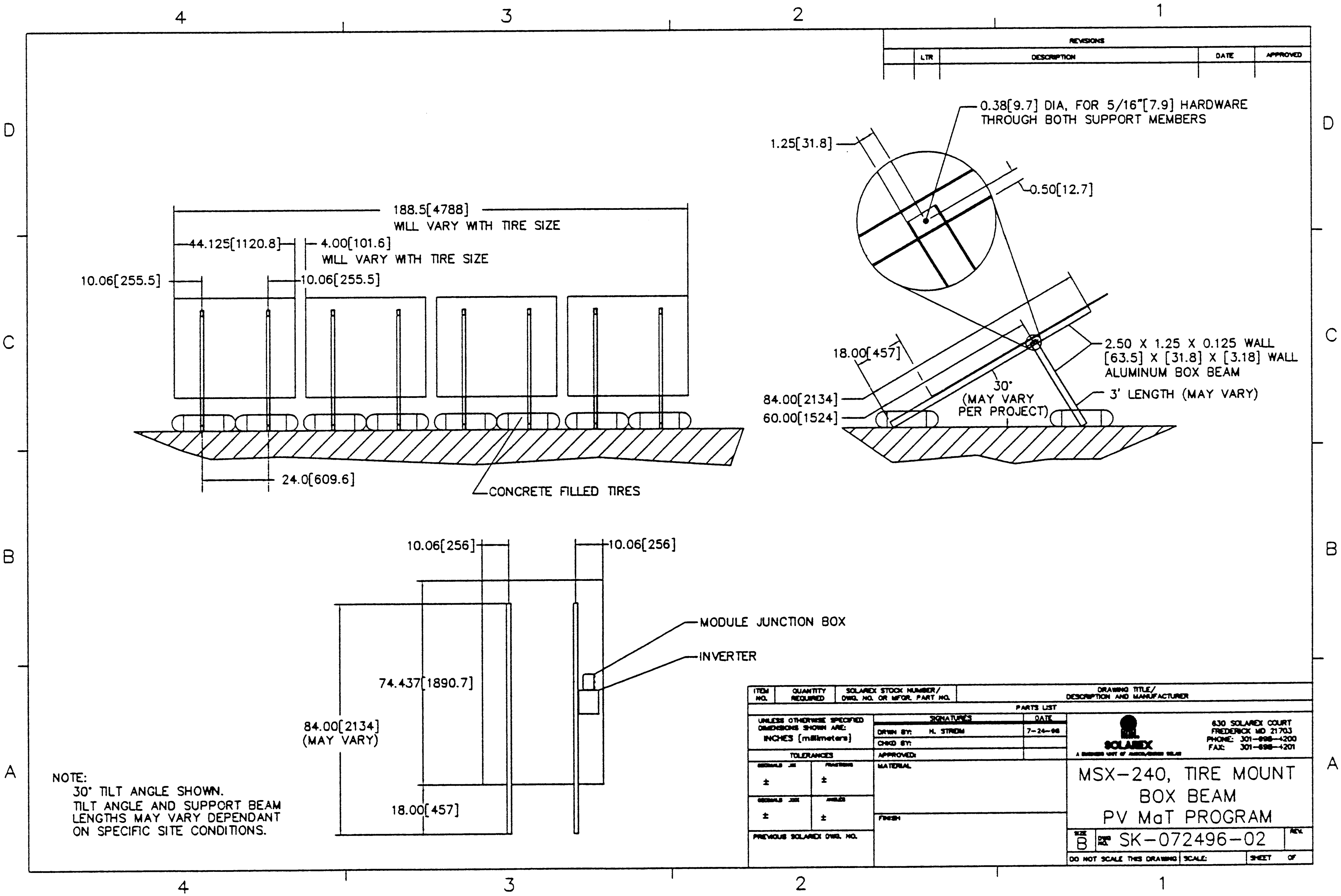
Figure 3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44.125[1120.8]
4.00[101.6] WILL VARY WITH TIRE SIZE
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10.06[255.5]
2.50 X 1.25 X 0.125 WALL [63.5] X [31.8] X [3.18] WALL ALUMINUM BOX BEAM
18.00[457]
30° (MAY VARY PER PROJECT)
3' LENGTH (MAY VARY)
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MODULE JUNCTION BOX
INVERTER
74.437[1890.7]
84.00[2134] (MAY VARY)
18.00[457]
NOTE:
30° TILT ANGLE SHOWN.
TILT ANGLE AND SUPPORT BEAM LENGTHS MAY VARY DEPENDANT ON SPECIFIC SITE CONDITIONS.
ITEM NO.
QUANTITY REQUIRED
SOLAREX STOCK NUMBER/ DWG. NO. OR MFGR. PART NO.
DRAWING TITLE/ DESCRIPTION AND MANUFACTURER
PARTS LIST
UNLESS OTHERWISE SPECIFIED DIMENSIONS SHOWN ARE: INCHES [millimeters]
SIGNATURES
DATE
DRWN BY: H. STREM
7-24-96
CHKD BY:
APPROVED:
TOLERANCES
MATERIAL
FINISH
PREVIOUS SOLAREX DWG. NO.
SOLAREX
630 SOLAREX COURT FREDERICK MD 21703 PHONE: 301-698-4200 FAX: 301-698-4201
MSX-240, TIRE MOUNT BOX BEAM PV MaT PROGRAM
B
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Solarex installed four MSX-240 frameless modules in a cement-filled tire ground-mount configuration. A photograph of this system is shown in Figure 4. Installation went quickly with each array requiring less than 10 minutes to align and level. The most time consuming part of the installation was the mixing and pouring of cement. Of course, for a large system, a cement truck would be used to pour concrete into each tire. This particular array used simple aluminum channel, which was buried into the cement at four points. Average hold-down weight per large-area module was approximately 880 pounds or 220 pounds per tire, which is adequate to meet wind loading requirements from IEEE 1262.

Figure 4:

For the flat-roof system, Solarex selected a roof-pan system filled with stones. This works well, but is considerably more expensive than the other two types. The pans themselves can cost up to \$0.25/watt. A drawing of the roof-pan system is shown in Figure 5.

A flat-roof demonstration system of four MSX-240 modules was installed on the west wing roof of the Frederick Technology Center. That system was grounded through the metal support structure per the NEC code. AC wiring has been provided to the array. A picture is shown in Figure 6.

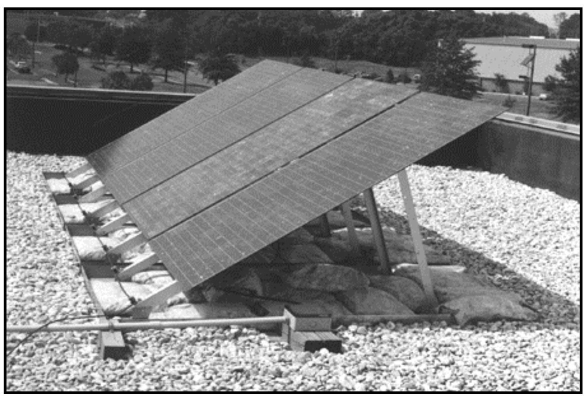


Figure 6:

A mechanical load test fixture was prepared for the MSX-240 using water as the weight. Solarex performed mechanical load tests on a MSX-240 in this fixture. The module was mounted using the same beam configuration as used on the ground-mounted tire array. It successfully passed the IEEE 1262 mechanical load test at 50 psf and the IEC 1215 snow load of 113 psf.

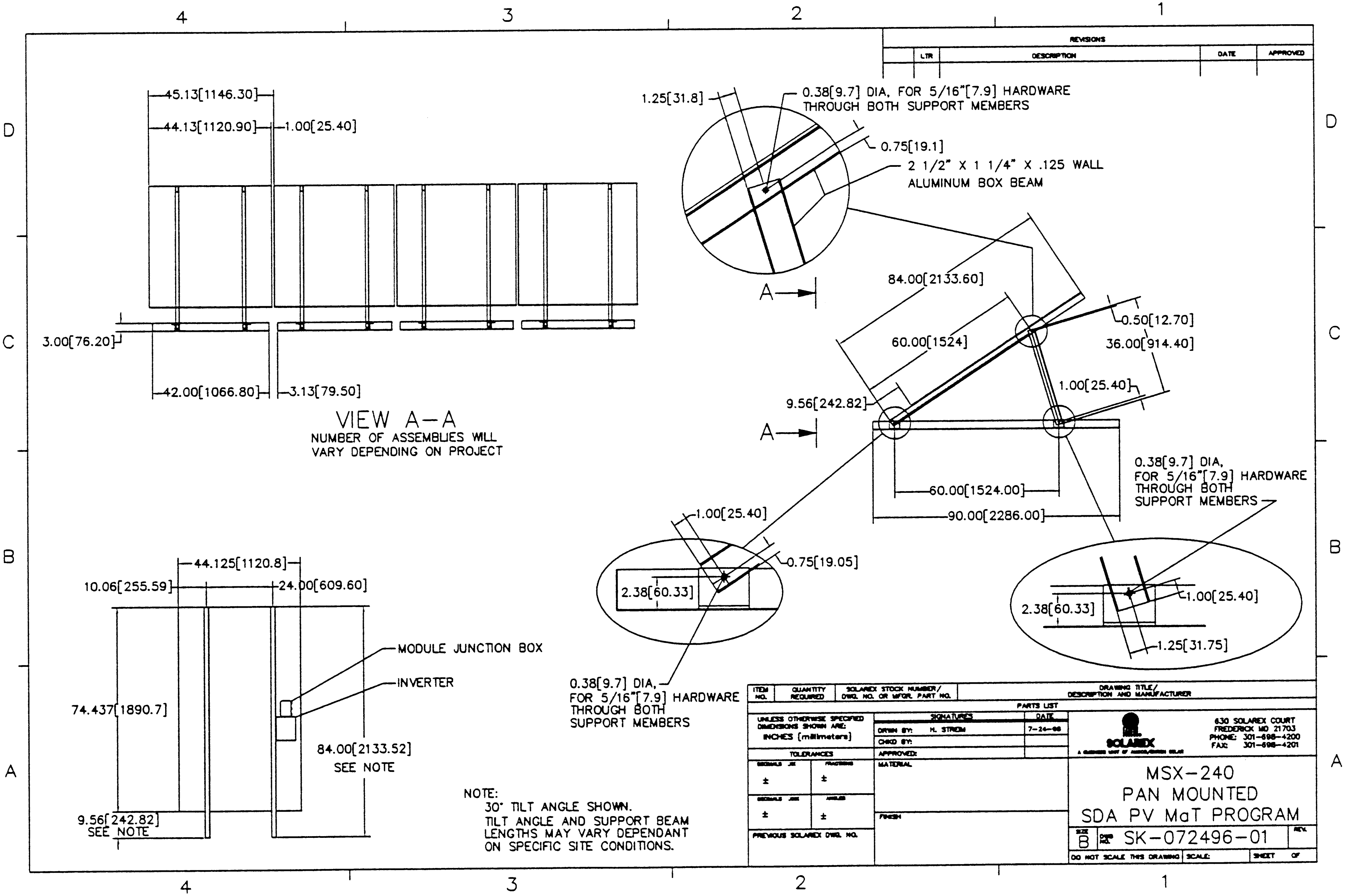
The three prototype systems have now been deployed for more than 2 years. No problems have been encountered with these systems.

AC Module Electrical Connector: In this task, Solarex and SDA were to define and develop innovative, low-cost methods of module-to-module electrical interconnection, array wiring, string interconnection, lightning protection and array grounding for systems on residential and commercial buildings as well as ground-mounted arrays through the use of pre-engineered, standardized components.

A conceptual design was developed for a wiring harness capable of connecting up to four modules in parallel, and a circuit combiner box capable of connecting two groups of four modules. The output of the combiner box had to be compatible with connection to a standard 20 amp AC circuit breaker. The goal was to identify UL-listed connectors suitable for use in such a wiring harness and combiner box.

The original wiring plan called for the AC wiring of the inverter to come back into the Solarex module junction box through the same hole that the DC wiring goes through. For this case Solarex proposed the use of a Turck connector system that attached through one of the knock-outs in the J-box. However, during the UL review of the inverter, UL determined that there was not enough

Figure 5



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VARY DEPENDING ON PROJECT
1.25[31.8]
0.38[9.7] DIA. FOR 5/16"[7.9] HARDWARE
THROUGH BOTH SUPPORT MEMBERS
0.75[19.1]
2 1/2" X 1 1/4" X .125 WALL
ALUMINUM BOX BEAM
A
84.00[2133.60]
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MODULE JUNCTION BOX
INVERTER
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84.00[2133.52]
SEE NOTE
9.56[242.82]
SEE NOTE
0.38[9.7] DIA.
FOR 5/16"[7.9] HARDWARE
THROUGH BOTH
SUPPORT MEMBERS
NOTE:
30° TILT ANGLE SHOWN.
TILT ANGLE AND SUPPORT BEAM
LENGTHS MAY VARY DEPENDANT
ON SPECIFIC SITE CONDITIONS.
ITEM NO.
QUANTITY REQUIRED
SOLAREX STOCK NUMBER/ DWG. NO. OR MFGR. PART NO.
DRAWING TITLE/ DESCRIPTION AND MANUFACTURER
PARTS LIST
UNLESS OTHERWISE SPECIFIED DIMENSIONS SHOWN ARE:
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TOLERANCES
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630 SOLAREX COURT
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volume in the junction box for both DC and AC wiring. Therefore, the system had to be redesigned with an AC connector on the far end of the inverter. A Lumberg connector was chosen as a cost-effective connector for this application. This information was provided to AES for incorporation into the modular inverter.

Modular Inverter Testing: In this task, Solarex was to assist AES and SDA to develop tests to verify inverter performance and ability to withstand environmental stresses. Ultimately a standardized modular inverter qualification test sequence must be developed.

The modular inverter was designed to be mounted on the back of the module. The inverter will likely experience same stresses that the module does. Therefore, Solarex used the module qualification sequences (IEC-1215 and IEEE-1262) as guides to develop a modular inverter test sequence. As a start, Solarex decided to expose the inverter to thermal cycling and damp heat tests.

The first environmental test Solarex defined was the thermal cycle test. In IEEE 1262 modules are exposed to 200 temperature cycles from -40° C to + 90° C. To simulate inverter operations, Solarex designed the test to have AC input at all times, but no DC input during the low temperature excursion. As the chamber heats up to room temperature, the DC voltage is switched on. It remains on until the temperature drops below room temperature (20°C). The output of the inverter was monitored throughout the test.

The two prototype AES inverters completed 200 thermal cycles and were still performing well. Solarex decided to continue the thermal cycling tests beyond the normal 200 cycles. Soon after 200 cycles, the inverters began to buzz when energized. After 300 cycles, both units failed to ramp up in output power as the DC increased and randomly shut down in apparent attempts to re-start. The modems could still communicate with both units. These units were returned to AES for failure analysis.

Two prototype AES inverters were subjected to the damp heat test (1000 hours at 85° C, 85% RH). Both units failed during the test. Neither had any output nor could either communicate with the modem. These units were also sent back to AES.

Throughout the spring of 1997, the AES modular inverters continued to fail environmental qualification testing at Solarex. Solarex management made the decision to discontinue what had become a continued series of engineering development tests until AES could deliver a fully complete and finalized modular inverter ready for qualification testing.

AES continued to modify their inverter design and potted the contents. After these modifications, Solarex did test two inverters through 400 thermal cycles and 1000 hours of damp heat exposure.

REVISED SOLAREX WORK PLAN

AES efforts to develop a modular inverter that could withstand the necessary qualification tests were proceeding at a pace much slower than projected and, in June 1997, Solarex determined that modular inverter progress was not meeting their market schedule. A formal request for quotation for modular inverters with detailed specifications and performance, warranty and delivery requirements was issued.

AES's response to the request for quotation was too high for Solarex's requirements. The projected cost to Solarex had increased from the $1/watt goal at the beginning of the program to approximately $2/watt in the quote. Solarex believes that there is little commercial market for a modular inverter at this price.

With the AES response to the Solarex RFQ and knowledge of the AES modular inverter unit cost and reliability history, Solarex concluded that the present inverter design was simply too far from commercial readiness in terms of cost and reliability and decided reluctantly to discontinue their development effort on an AC module product based on the AES modular inverter.

Solarex proposed that AES continue development of the modular inverter, particularly in terms of reducing the cost and increasing reliability. Since Solarex felt that the modular inverter was priced too high with no foreseeable near-term reduction in cost or improvements in reliability from AES, it did not make sense to pursue BOS development exclusively for use with this inverter. Therefore, Solarex proposed a change in the statement of work for the program to extend the mounting systems for use with the new large-area thin-film modules being produced in the Solarex facility in Toano, VA.

Change in Work Scope: In the first year of this PVMaT program, Solarex developed mounting systems for the crystalline silicon AC modules. The three mounting systems (ground-mount, sloped-roof mount and flat-roof mount) were all based on the use of a frameless module design. Glass laminates were bonded to aluminum beams that formed the support structure. When this approach was applied to the thin-film modules a number of problems were identified:

1. High breakage during shipping of the pre-fabricated panels.
2. High breakage during installation, due to torsion.
3. High packaging and shipping costs.
4. Difficulties encountered with field replacement of modules.
5. The heavy weight of the panels, requiring careful rigging and extensive training of the installers.
6. The use of untempered glass without perimeter framing is questionable in terms of meeting US building codes.

The lack of tempered glass, the extra weight of the double-glass construction, and the smaller module size, make the frameless mounting system incompatible with the thin-film technology. Also, because of the larger number of modules needed for an array, a quick-connect DC connector is preferred. While several quick connects had been identified (and used in PV systems), none were UL approved and could not be utilized under the NEC rules. Therefore, Solarex proposed to:

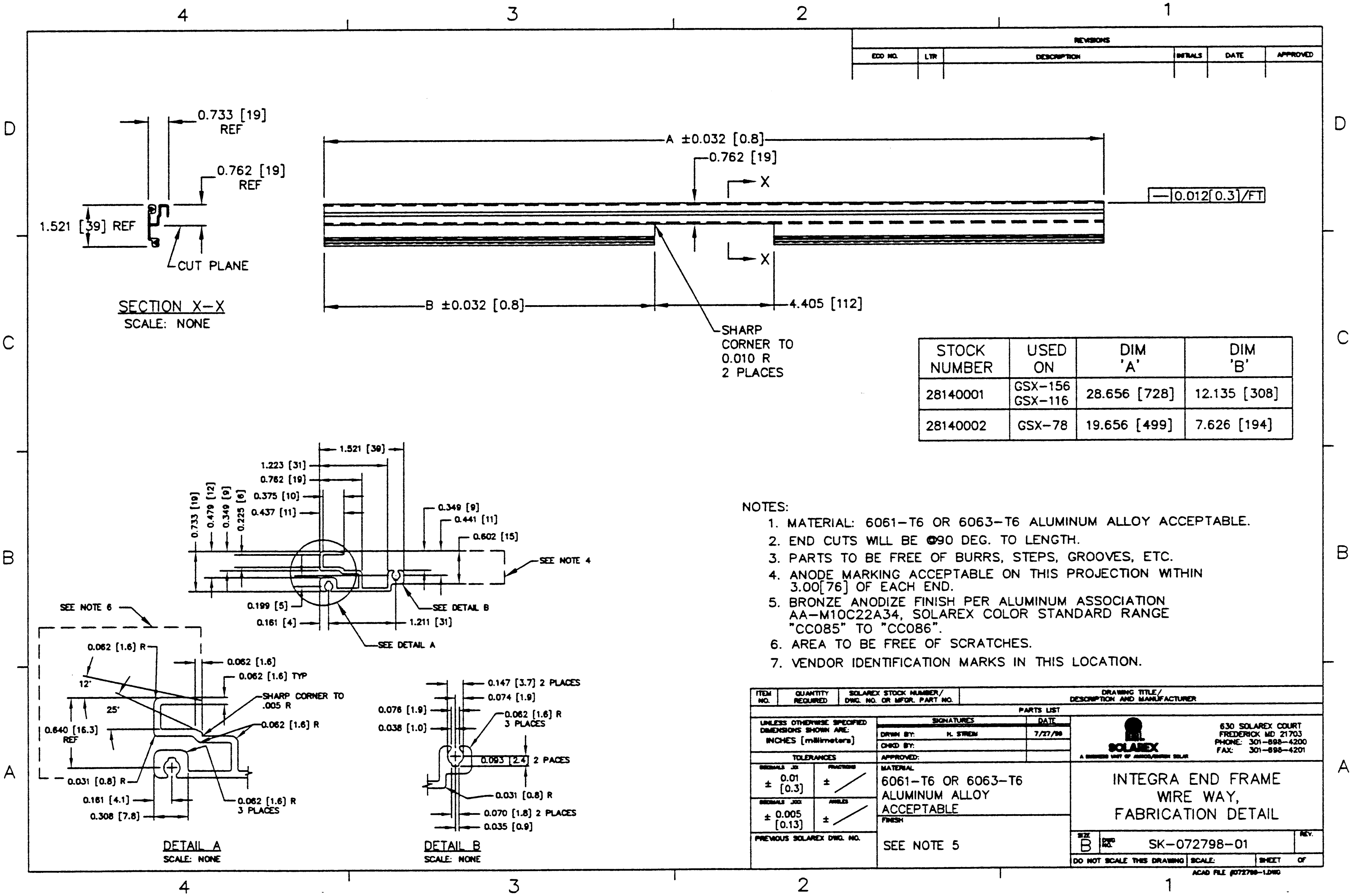
- Develop a low-cost, sloped-roof mounting system for Solarex's tandem-junction thin-film modules. The system would then be tested and qualified to UL 1703 and ANSI Z97.1 to assure compliance with building codes and the NEC.
- Obtain UL qualification for a Solarex tandem-junction thin-film module using quick connectors and, to combine this with a wiring system that meets NEC requirements.

Mounting System for Thin-film Modules: After reviewing a number of candidate mounting systems, Solarex selected a frame that also serves as the roof mounting system. The frame design of the flush-mounted module meets our requirements for strength, ease of installation, appearance, and accommodation of the interconnection wiring and connectors. This approach appeared to offer the overall lowest installed cost, as module assembly into the frame can be performed in the factory. The time spent on the roof installing the array was also minimized. Other features of the design include:

- Requirement to handle only a single module at a time during installation.
- Minimization of the number of attachment bolts, since the frame of one module connects to the next.
- Use of the frame as the wire raceway.
- Use of a clip to provide grounding to all of the modules in a row.
- Excellent cosmetic appearance.

Figures 7, 8 and 9 show drawings of the frame cross-section.

Figure 7



STOCK NUMBER	USED ON	DIM 'A'	DIM 'B'
28140001	GSX-156 GSX-116	28.656 [728]	12.135 [308]
28140002	GSX-78	19.656 [499]	7.626 [194]

NOTES:
1. MATERIAL: 6061-T6 OR 6063-T6 ALUMINUM ALLOY ACCEPTABLE.
2. END CUTS WILL BE @90 DEG. TO LENGTH.
3. PARTS TO BE FREE OF BURRS, STEPS, GROOVES, ETC.
4. ANODE MARKING ACCEPTABLE ON THIS PROJECTION WITHIN 3.00[76] OF EACH END.
5. BRONZE ANODIZE FINISH PER ALUMINUM ASSOCIATION AA-M10C22A34, SOLAREX COLOR STANDARD RANGE "CC085" TO "CC086".
6. AREA TO BE FREE OF SCRATCHES.
7. VENDOR IDENTIFICATION MARKS IN THIS LOCATION.

Figure 8

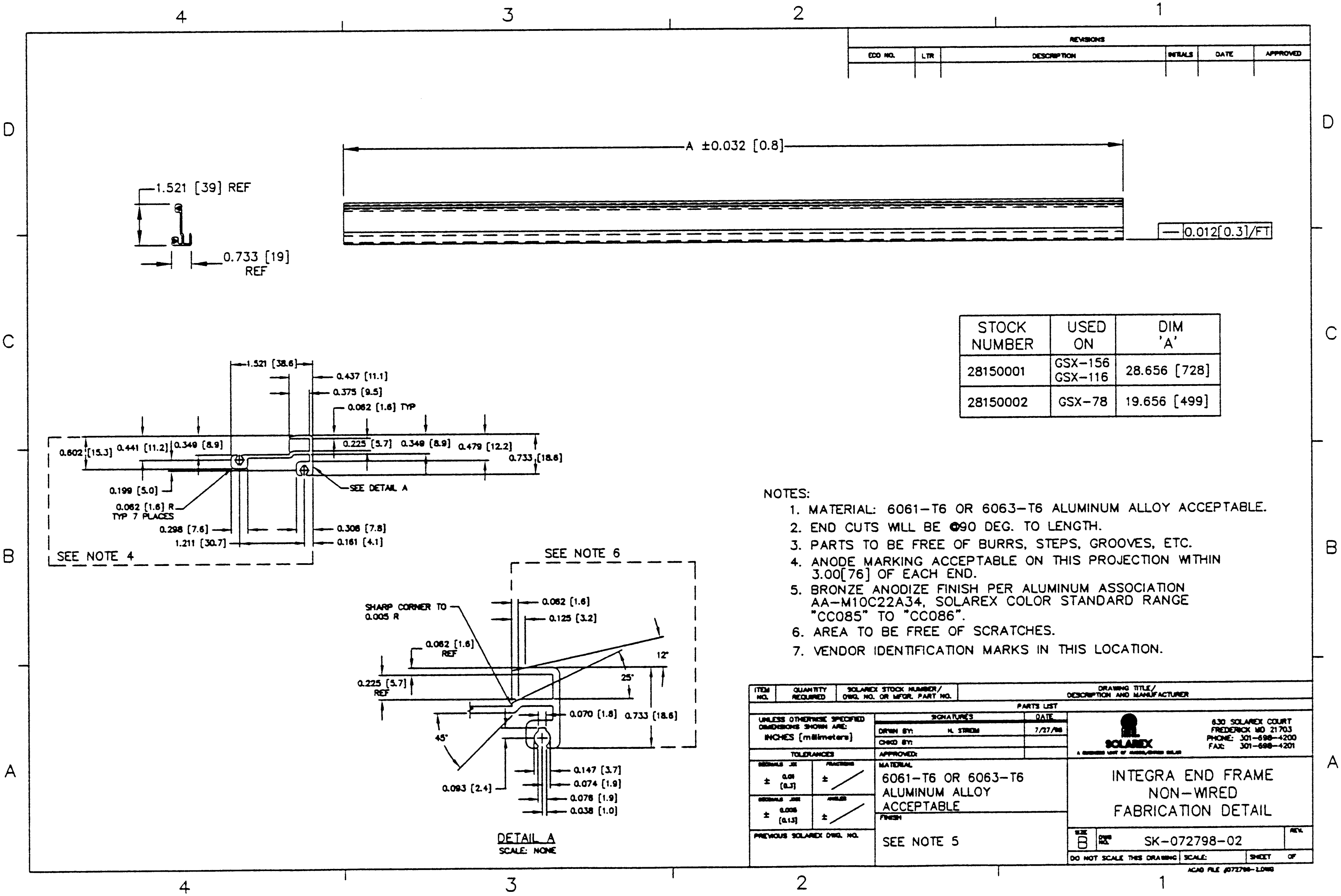
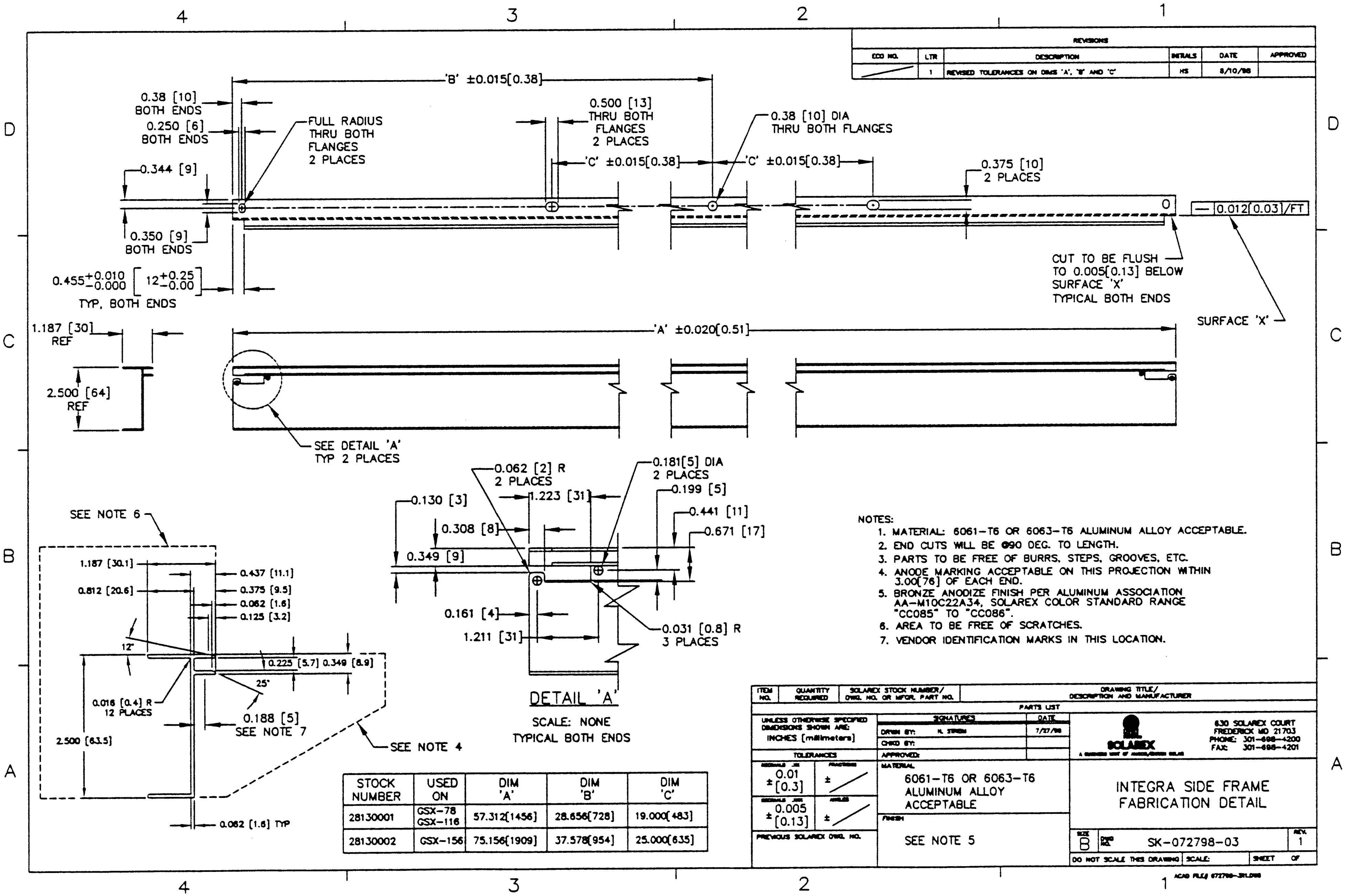

A ±0.032 [0.8]
1.521 [39] REF
0.733 [19] REF
0.012[0.3]/FT
STOCK NUMBER | USED ON | DIM 'A'
28150001 | GSX-156 GSX-116 | 28.656 [728]
28150002 | GSX-78 | 19.656 [499]
SEE NOTE 4
SEE NOTE 6
SEE DETAIL A
DETAIL A
SCALE: NONE
NOTES:
1. MATERIAL: 6061-T6 OR 6063-T6 ALUMINUM ALLOY ACCEPTABLE.
2. END CUTS WILL BE ⊕90 DEG. TO LENGTH.
3. PARTS TO BE FREE OF BURRS, STEPS, GROOVES, ETC.
4. ANODE MARKING ACCEPTABLE ON THIS PROJECTION WITHIN 3.00[76] OF EACH END.
5. BRONZE ANODIZE FINISH PER ALUMINUM ASSOCIATION AA-M10C22A34, SOLAREX COLOR STANDARD RANGE "CC085" TO "CC086".
6. AREA TO BE FREE OF SCRATCHES.
7. VENDOR IDENTIFICATION MARKS IN THIS LOCATION.
6061-T6 OR 6063-T6 ALUMINUM ALLOY ACCEPTABLE
SEE NOTE 5
INTEGRA END FRAME NON-WIRED FABRICATION DETAIL
SOLAREX
SK-072798-02

Figure 9



STOCK NUMBER	USED ON	DIM 'A'	DIM 'B'	DIM 'C'
28130001	GSX-78 GSX-116	57.312[1456]	28.656[728]	19.000[483]
28130002	GSX-156	75.156[1909]	37.578[954]	25.000[635]

Figure 10 is a photograph of one of the prototype framed modules. The prototypes were tested and successfully passed the mechanical loading requirements of IEEE-1262. The tandem-junction thin-film module was qualified under UL 1703 as mounted in this frame.

Figure 10:

Solarex completed a prototype installation on a home in Maryland near the Frederick facility. A 16-module rooftop array was installed in less than 10 man-minutes per module using a crew of two. This included staging, mechanical, and electrical installation, and array output termination. A tooling modification was made to the module ground clip hole based on the observations made during this installation. The completed installation is attractive and clean with no exposed wiring. See the photograph in Figure 11.

Based on the success of this prototype system, Solarex ordered production tooling for the frame. This mounting system is now commercially available in grid connected PV systems under the PV-VALUE Program.

Figure 11:

An Electrical Connector System for Thin-film Modules: The goal was to identify and qualify a low-cost electrical connector system for use with thin-film modules. Solarex investigated quick-connect plugs and sockets that could be attached to the back of the thin-film module as part of a four-pigtail assembly, allowing either series or parallel connections.

Our initial leading candidate was the Amp EconoSeal connector, because it had the lowest quoted price, about $1.54 per pair (not including wire). The manufacturer, Amp, Inc. was not able to provide information on current rating for this connector, but did specify that the rated current should not increase the operating temperature of the connector by more than 30° C. Solarex determined that the connector could carry 15 amps without exceeding this temperature rise. Amp repeated the tests and confirmed our results. The 250-volt rating on the connector is between pins in the same connector. Since our design uses a single-pole connector, the appropriate rating is the 1200 volt dielectric withstand rating. Modules using this connector have been qualified for use up to 600 volts by UL.

Solarex discussed connector qualification with UL. Solarex and UL both agreed that the most appropriate testing would be to run modules with the connectors through the IEEE 1262 and UL 1703 sequences. They suggested Solarex run a couple of quick "screening" tests for pull strength and wet hi-pot. When running these tests on the EconoSeal connector, Solarex observed significant differences between "good" and "bad" crimping of the contact to the wire, so crimp quality will be an important parameter in further work.

The "good" crimp failed at 29 lb., well above the UL requirement of 20 lb. However, the "bad" crimp failed at only 9 lb. Likewise, the "bad" crimp failed an immersion wet hi-pot test, probably indicating that the connector's rubber seal was not fitting properly when the contact was not positioned on the wire correctly. The "good" crimp did provide an adequate seal, and the connector passed a 3-minute immersion at 2200V with less than 1 microamp leakage current.

Solarex also found a test report from the International Energy Agency, indicating that improperly crimped EconoSeal connectors exhibited corrosion after 10 years exposure in the field. This is another indication that crimp quality is a potential source of problems with these connectors, and must be carefully controlled.

Solarex assembled sample connector pairs and placed them in the chambers for environmental exposure. Two samples each were exposed to thermal cycling, damp heat, and humidity/freeze. All samples were connected to power supplies, and 13 amps of current (expected peak power current) were run through the connectors for the duration of the environmental exposures.

Solarex measured the voltage drop across each connector pair at the beginning of each exposure, and every few days thereafter. All the connectors had a baseline voltage drop of approximately 0.03 volts. The two connectors in humidity/freeze cycling completed the 10-cycle test without a significant change in voltage drop. The two in damp heat completed the 1000-hour test, also without significant change. The two connectors in thermal cycling each increased by about 0.05 volts after 200 cycles. Solarex started another thermal cycling test, this time with the current being switched on and off every half hour. This caused a secondary thermal cycle of about 6 degrees in addition to the normal +90 and -40. The results of this test were the same, which was judged to be acceptable.

Solarex assembled a number of connectors as samples for UL to test. In the process, Solarex identified a significant difficulty in assembly, which may be damaging the connector's seals. The process Solarex used was to crimp the metal contact onto the wire, then insert the contact through the rubber seal at the back of the connector, until it locked in the proper position. Since there are several sharp points and edges on the contact and it is a tight fit to the seal, Solarex suspected that the seal was being damaged. Evidence of this damage was provided by an immersion wet hi-pot of the connectors. Only 6 of the 19 pairs passed a 3-minute test at 2200V, with a typical leakage of 20-30 microamps.

Ten of the pairs failed immediately, with leakage greater than 100 microamps. The remaining 3 pairs withstood the voltage initially, but failed between 1 and 2 minutes of immersion. The test was repeated at 500V, and the results were the same, with one exception. One of the pairs that had failed between 1 and 2 minutes was able to withstand the 500V for the full 3 minutes. (It should be noted that the wet high-pot immersion test is an extreme test that is not required for UL 1703 qualification nor is it typical of field conditions. It was performed as part of our internal evaluation and testing procedure. Solarex is utilizing it to assist in developing better assembly procedures for the connectors.)

Solarex revised the design of the cable assemblies to make assembly much simpler. A key part of this redesign was the decision to eliminate the diodes from each module.

Crystalline modules typically require the use of bypass diodes every 10 to 20 cells to prevent hot spot damage in the event that a cell is reverse biased due to shadowing or cracking. Solarex has determined experimentally that tandem-junction amorphous silicon thin-film modules do not require bypass diode protection because of the soft knee in the I-V curve and uniform reverse current leakage.

The blocking diode requirement was also evaluated and determined to be unnecessary. In crystalline systems blocking diodes are used to protect parallel strings from having reverse current flow from the rest of the system and to prevent one “bad” string from reducing the power output of all the other strings in parallel with it. Once again it was experimentally determined that Solarex thin-film modules do not produce enough voltage to cause significant reverse current to flow through a shadowed module connected in parallel. Finally, there is no known module short circuit failure mode that would reduce the output power of the remaining paralleled strings. In addition to assembly improvement, elimination of blocking diodes improves output of the PV-Value 1.2 Kilowatt system by more than 1%.

Based on this testing and analysis, blocking diodes have been eliminated from the design and a "parallel first" electrical interconnection scheme has been adopted. By paralleling first and then connecting parallel groups of modules in series, a very simple electrical installation can be performed, resulting in fewer field-wiring errors.

After making the noted changes in assembly procedure, the connector successfully passed all the testing requirements for UL listing.

Solarex purchased 30 pairs of cables from the assembly subcontractor for use on the first prototype system. Solarex performed the 2200 V immersion hi-pot test, and found a 10% failure rate. This was better than our initial attempts, but still a cause for some concern. Even though this test is not required to meet any particular specification, it is a good indicator of potential corrosion problems after long-term field exposure.

Solarex identified a new technique for assembling the connectors, which allows 100% to pass the 2200 V immersion test. The rubber seal is removed from the connector shell and placed over the wire before it is stripped. The contact is then crimped onto the wire and inserted in the shell; then the rubber seal is pushed back into the shell. This method is more labor-intensive and so more expensive, but results in a much more reliable product.

Solarex has purchased production quantities of the EconoSeal connector and has begun shipping this product.

CONCLUSION

Solarex has incorporated the mounting system and quick connector into their PV-VALUE system. These systems are now commercially available. System specifications and a system installation manual have been published. Solarex has already received orders, fabricated and shipped a number of these PV-VALUE systems.

Solarex is still interested in development of an AC PV module. If and when a qualified modular inverter is available at the right price, Solarex will begin marketing it. In the meantime, the three mounting systems, developed for the AC PV module in Phase 1 of this program, are being utilized for systems with two MSX-120 modules replacing one of the MSX-240 AC module.

An Overview of the Solarex PV-Value Program

Introduction The Solarex Photovoltaic-Vendor Assisted Low-cost Utility Enterprise (PV-VALUE^{TM}) targets the residential market for solar power. In May 1996, PV-VALUE was awarded a Department of Energy TEAM-UP program grant through the Utility Photovoltaic Group (UPVG), and we are using this money to buy down the homeowner's purchase price of solar electric systems.

Program Description The key to the program's success is our Marketing Partners, a nation-wide network of utilities, builders, and solar electricity system retailers working closely with Solarex to sell packaged solar electric systems. Marketing Partners arrange for the sale of the systems, plan (and in some cases execute) the installation, and provide after-sale service.

Product PV-VALUE offers three standard grid-tied solar electric systems packaged for both retrofit and new home construction; the systems are currently rated at 1.2kWac, 1.6kWac and 2.0kWac. System packages include PV modules, interconnects, installation hardware, and an indoor/outdoor inverter; the installation contractor provides the wiring from the rooftop array to the inverter.

Price Solarex designed the program to reduce the cost of photovoltaics by 1) offering standardized systems and 2) selling systems to our Marketing Partners in blocks of ten or more systems. Solarex has priced the packaged systems aggressively and offers a utility cost-share option which would drop the price even lower. Shipping with in the continental US is included in prices for systems cost shared by UPVG during the buydown period.

Thin-film Technology We have targeted the grid-tied market with the latest generation of Solarex technology, tandem amorphous silicon thin-film. Solarex manufactures thin-film at TF1, our new 10MW/year factory near Williamsburg, Virginia. With PV-VALUE, Solarex takes the first step in deploying thin-film modules in the domestic grid-tied market. Systems offered through PV-VALUE are specially engineered for easy, low cost installation and attractive aesthetics. The program, then, has become our primary vehicle to achieve the price threshold that UPVG believes will open major grid-tied markets.

Joining the PV-VALUE team For more information about becoming a PV-VALUE Marketing Partner, please contact a Solarex regional sales office in your area or Gerry Braun at: :

Solarex -- PV-VALUE Program Office
630 Solarex Court
Frederick, MD 21703
phone: 301-698-4453
fax: 301-698-4201
gbraun@solarex.com

Figure 12. Overview of the Solarex PV-Value Program

Final Report of Advanced Energy Systems, Inc. Work performed under NREL Subcontract # RAF-4-14271-01

AES PROGRAM OVERVIEW

The objectives of this two-year program were "to improve the reliability and safety and to reduce the cost of installed, grid-connected PV systems by creating standardized, pre-engineered components and an enhanced, low-cost 250-Watt micro inverter. These advances were to be combined with the new, large-area Solarex PV module (the MSX-240) resulting in standard, modular AC PV building blocks.

Unfortunately, modest market demand and the cost of inverter manufacture at low volume resulted in a significant shift in direction for the program in year two. Because of this, Solarex refocused their work towards low-cost mounting systems for thin-film PV modules, and Advanced Energy Systems, Inc. (AES). changed from a market development focus to one of cost reduction and a continuation of codes and standards work to remove barriers to future market growth.

AES TASK OVERVIEW

The following is a description of the tasks that were completed by AES under PVMaT:

Development of a Digitally Controlled 250W Inverter: This task was very successful. AES managed to integrate for the first time the inverter control & supervisory functions on one chip, and to implement a fully digital control scheme. AES used a Dallas high-speed 80C51 part (with about 6 MIPS (Million Instructions per Second) of processing power) and a Lattice programmable logic device to perform some of the tasks in hardware. Various pre-production units were built, but AES was far from our target of 20-25 cents/Watt at quantity 10,000.

Wiring Systems: The main work in this Task was the adoption of a Lumberg three-conductor connector for the AC module output (AC) connection. A second source was available from the Brad Harrison company. The cost of the bulkhead mounted male and the cord end female was about $15 in quantity 100. This has proven to be a good choice - the connector even works underwater. AES addressed the DC interface by designing the inverter to mate with the standard Solarex junction box. This meant that standard DC PV modules could be used (and inventoried by distributors). A photograph of the AES digital modular inverter with the Lumberg three-conductor connector is shown as Figure 13.

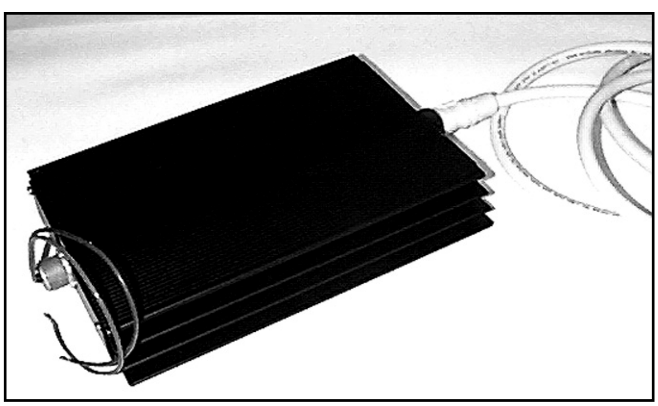


Figure 13:

The AC connector choice also solved another problem as Underwriter's Laboratories had voiced concerns regarding AC & DC wiring in the same (module) junction box, although the final resolution of the issue was that combining AC and DC in one box is not a problem (the NEC disallows branch circuits of other systems in the same box as the PV DC, but does allow inverter AC and DC wiring to coexist. The actual limitation was that the Solarex junction box volume was insufficient for the number of conductors.

Export Versions: In this task, AES developed, prototyped and tested two inverters that were configured for 220V/50 Hz and 120V/50 Hz (destined for the European and Japanese markets). Further work on export versions was halted when it became clear that production costs would severely limit even US sales volumes.

Production Planning & Customer Survey / Feedback: A survey of potential customers showed continued interest in the product, but also indicated that concerns over reliability, roof access and cost could inhibit market growth. This survey led in part to AESI planning a 1-kW string inverter product line (the now commercial GC-1000 unit).

UL Listing of the AC PV Module: In this task, AES subjected an MI-250 inverter to the same temperature and humidity cycling tests that PV modules undergo. Mechanical fastening to module backskins was also tested. The MI-250 inverter is now UL listed for both standard PV grid connected applications and for use in AC module systems.

Compliance with Codes and Standards: It became apparent several years ago that the need to negotiate interconnection of every PV system (even at the 250-Watt level) with local utilities was a burden that the industry could not bear. AESI has been working with industry groups for five years to develop simpler solutions for the interconnection process. The result of this work is new, revised versions of Article 690 (Photovoltaic Systems) of the National Electrical Code, IEEE 929 and UL 1741, which together should make the task of technical interconnection simple and straight forward. Full details of this work are included in the Deliverable 2.6 (Codes and Standards) final report which is attached as Appendix A.

Inverter Cost Reduction: AES brought the MI--250 Modular inverter into production after it achieved UL listing on May 27, 1997. Our production cost (at volume 100, the first production quantity) was significantly over our cost goals (over $300 each vs. a target cost of under $200). This led to a major revision of the company's business plan, and that of our development partner, Solarex. Plans for building 1000 units in the first year were shelved.

Our conclusion was that AES had a major chicken and egg problem - cost reduction for module integrated inverters required market volume, and market volume required cost reduction. To cap it off, the total grid-connected PV market is still small and immature. It looked like AES had a product that was ahead of its time.

In early 1998, AES revisited the cost issues of the MI-250 inverter as part of our PVMaT work on integrated PV systems. AES defined three sub-tasks that would produce guaranteed immediate and future cost reductions:

- To construct a prototype GC-250, a low-frequency transformer-based inverter (vs. the high frequency MI-250 approach.
- To estimate the manufacturing cost of the GC-250 alternative
- To revisit the MI-250 design and to estimate the cost reduction possible by:
  - Changing the power line carrier to a 3 wire isolated scheme
  - Using a PIC rather than a Dallas microcontroller
  - Eliminating the Lattice logic chip.

- Adopting design suggestions as proposed by our manufacturers and the New Hampshire Manufacturing Extension Partnership.

Our conclusions at the end of this task were:

1. There is little cost difference at this point between the low and high frequency inverter approaches. As the MI-250 design is smaller, lighter and more efficient, AES plans to continue with the high-frequency approach.

2. Even with cost reduction efforts (about $100 at low quantity), the MI-250 will cost over $1/Watt at quantity 1000. AES will have to wait for the market to develop in the USA before locally made inverters for AC modules break the $1/Watt retail price barrier.

CONCLUSIONS

Together with our partners in this work, Solar Design Associates and Solarex, AES achieved a considerable amount. In particular, the contributions of Steven Strong in aspects of systems integration, and the design team at Solarex (especially Jean Posbic, John Wohlgemuth and Don Warfield) should be noted. AES learned a lot by sharing ideas at the early design meetings at Frederick. Concepts generated there and, in part, brought to practice under this PVMaT program will change the PV industry.

Although all our goals were not fully met, much was achieved. The major AES accomplishments may be summarized as follows: A reliable, fully UL listed and FCC compliant AC module inverter was developed under this program. It passed various environmental tests including those required by UL (the same temperature and humidity cycling tests that PV modules require). It is now in commercial production.

We believe that AC photovoltaic modules potentially offer the least-cost way of installing PV systems. This is clearly, conceptually, the simplest form of installation and, this is being proven in the marketplace as Evergreen Solar begins selling their AC module systems (which use our inverters) - for small installations, there is no simpler or less expensive way to go.

While AES achieved our technical goals of designing and bringing to contract manufacturing a reliable, UL-listed, FCC and code compliant AC module inverter, there is a technical problem that still remains. A UL-listed AC ground-fault disconnecting device, as required by the 1999 NEC, is not yet available. Technically, this means that AC modules cannot be installed on residential roofs - their largest potential application. There is also the non-trivial criticism of this approach that the electronics is in a harsh environment, and is difficult to access for repair or replacement. Only time will prove the reliability of the inverters, and this in turn will allow the market to develop.

Our reliability record looks good - the 77 units running at SUNY Albany have operated with only one failure over the past 18 months. Our main problem is simply is that the grid-connect PV market is still emerging, and production runs of over 100 pieces are hard to justify (1988 sales were under 200 units). AC module inverters rely on volume production to reduce cost. AES must either wait for the market before AC modules become economically viable, or seek subsidies, as our competitors in Holland have done.

There is hope that this market will evolve and grow quickly. Both AES and Ascension Technologies AC module inverters were chosen as "100 best products of the Year" by Popular Science magazine, and the "Million Roofs" program also points to the potential for rapid growth for grid-connected photovoltaics. AES is therefore confident that this work with AC PV modules will lead, in time, to be a significant power conversion option for grid-connected PV systems, and we will continue with our efforts to reduce cost, increase ease of use, and to improve reliability.

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13. ABSTRACT *(Maximum 200 words)*
Solar Design Associates, Inc. (SDA), of Harvard, Massachusetts, and Solarex Corporation, of Frederick, Maryland, teamed with Advanced Energy Systems (AES) of Wilton, New Hampshire, to pursue a multi-level program under a Photovoltaic Manufacturing Technology (PVMaT) solicitation. This program was targeted at design innovation, standardization, and modularity, with the goal to deliver low-cost AC PV systems to the utility-interactive market. One significant result of this program is that Solarex filed a U.S. patent application on the new module frame and mounting system that was developed with support from PVMaT. Solarex has already started to manufacture this new combination framing and array mounting system, and a number of residential-scale installations are already in place in the field. The major AES accomplishment under this program was the development of a reliable, FCC-compliant AC module inverter fully listed by Underwriters Laboratories (UL). The inverter passed various environmental tests, including those required by UL (the same temperature and humidity cycling tests that PV modules require), and is now in commercial production.

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