

# **Cost Reduction and Manufacture of the SunSine<sup>®</sup> ac Module**

**Final Subcontract Report  
11 June 2001**

G. Kern and M. Russell  
*Schott Applied Power Corporation  
(Formerly Ascension Technology, Inc.)  
Waltham, Massachusetts*



**NREL**

**National Renewable Energy Laboratory**

1617 Cole Boulevard  
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Contract No. DE-AC36-99-GO10337

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NREL Technical Monitor: H.Thomas

Prepared under Subcontract No. ZAX-8-17647-03



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## List of Abbreviations and Definitions

AWG	American Wire Gauge
CM	contract manufacturer
ECO	engineering change order
EMI	electromagnetic interference
FCC	Federal Communications Commission
FLT	fundamental limit of technology
GFI	ground fault interrupter
HALT	highly accelerated lifetime test
HHC	hand held controller
IEEE	Institute of Electrical and Electronic Engineers
IR	infrared
LISN	line impedance stabilization network
MH	man-hours
MHz	megahertz
MOSFET	metal oxide semiconductor field effect transistor
MTBF	mean time between failures
NEC	National Electrical Code
NREL	National Renewable Energy Laboratory
NY SIR	New York, Standard Interconnect Requirements
POA	plane of array
PTC	PV USA test conditions, 1000 W/m <sup>2</sup> , 25°C ambient temperature, 1.0 m/s wind speed, 1.5 air mass
PV	photovoltaic
PWM	pulse width modulation
RMS	root mean square
RTV	room temperature vulcanization, usually a silicone adhesive
SMT	surface mount technology
STC	standard test conditions, 1000 W/m <sup>2</sup> , 25°C cell temperature, 1.5 air mass
THD	total harmonic distortion
UL	Underwriters Laboratories
ZCS	zero current switching, a type of soft switching
ZVS	zero voltage switching, a type of soft switching

## 1.0 Executive Summary

This report summarizes the progress made by Ascension Technology in the Cost Reduction and Manufacturing Improvements of the SunSine<sup>®</sup> ac Module. This work was conducted under NREL subcontract No. ZAX-8-17647-03. The project was a two-phase effort consisting of investigations into improving inverter packaging, soft switching, circuit optimization, design for manufacturing, manufacturing processes and pilot production manufacturing. Significant cost reduction of the product has been achieved.

The main goal of this project was to reduce cost and improve the manufacturability and reliability of the SunSine<sup>®</sup> ac module, which consists of a SunSine<sup>®</sup> inverter mounted on a PV laminate. This work has also boosted the performance and enhanced marketability by adding customer-valued features. Ascension Technology has accomplished these advancements by cost reductions or design modifications in the following areas:

- Die-cast aluminum enclosure and base plate;
- Soft switching for cost reduction and efficiency gains;
- Circuit board and component optimization for performance gains and size reduction;
- Streamlined inverter assembly & production testing;
- Streamlined inverter/module assembly.

As a result of the effort in these areas, Ascension Technology's objectives were to achieve the following:

- 40-50% reduction in inverter manufacturing costs,
- 40% reduction in inverter size from 169 to 100 square inches;
- 4% increase in peak inverter efficiency from 87 to 91% at full power;
- UL listing, FCC certification, and export safety and emissions requirements;
- establish a production capability of 5,000 SunSine<sup>®</sup> inverters/year through manufacturing improvements and production line design improvements;
- less than 1 failure per 1,000 units at time of installation/turn-on;
- a 5 year warranty; and
- a rating of 250 W<sub>ac</sub> at PTC for the SunSine<sup>®</sup> ac Module.

Accomplishments during this project include:

- Inverter production costs reduced 32% in the pilot production run.
- Inverter production costs anticipated to be reduced a total of 36% in future production runs.
- 45% reduction in inverter footprint (in contact with module) from 169 to 93 square inches, and based on inverter enclosure lid, an overall reduction in size from 169 to 125 square inches (lid of new unit is larger than base), a 26% reduction;
- 2.3% increase in inverter efficiency from 85.7% to 88.0% at full power;
- The SunSine<sup>®</sup> ac module passed UL Listing, including testing to IEEE Std. 929-2000, IEEE-C62.41-1991, IEEE-C62.45-1992, and NY State SIR requirements.
- The SunSine<sup>®</sup> ac module was verified to comply with FCC Class B EMI limits.
- 4 failures per 214 units at time of installation/turn-on;
- a 5 year inverter warranty and 20 year PV warranty; and
- a rating of 235 W<sub>ac</sub> at PTC for the SunSine<sup>®</sup> ac module.

Other accomplishments not specifically targeted:

- Successful implementation of soft switching.
- The data is inconclusive if soft switching is the optimal approach for this inverter design.

- Power circuit board sized reduced 57% from 90 to 39 square inches.
- Power circuit board component count reduced 26% from 282 to 208 components.
- Total inverter parts count reduced 30% from 442 to 310 parts.
- Transformer efficiency improved 1.4%.
- We have decided to eliminate burn-in testing from the production process, removing a major bottleneck in production capacity, the remaining bottleneck in production capacity will be final assembly.
- The conformal coat process was successfully tested using the HAST test process.
- Two casting prototypes were developed. The final design was optimized for the ac module application.
- We have learned how to design and create prototype aluminum castings at a moderate cost.
- Potential export markets have been identified, including safety and emissions requirements.
- We have decided to focus on getting the product ready for U.S. markets first, and will address international markets second.
- The inverter has been designed so that it may be easily modified to work in international voltage and frequency versions.
- Enclosure cost reduced 80% over the previous design.
- A successful production run of 500 enclosures was completed.
- Initial pilot production of 110 units was completed and shipped.
- A functional test fixture was developed for testing the SunSine<sup>®</sup> inverter power boards.
- A calibration and IEEE 929 test fixture was developed for testing the SunSine<sup>®</sup> inverters.
- A new ac module connector design completed with 48% cost reduction over the previous design.
- HALT testing was completed on five samples of the final SunSine<sup>®</sup> inverter power board, revision G.

## **2.0 Background**

Ascension Technology first began development of the module-scale inverter in 1991. When integrated with a large PV module, the inverter produces utility-compatible ac power without any balance of system issues or overhead. The module-scale inverter is the ac PV Module's user interface, eliminating system-integrator compromises between module and inverter specification and eliminating user access to live dc voltages. Restricted access to the dc voltages provides enhanced safety during installation, service and operation of PV systems. The first prototypes were developed and tested under research funds from the New England Power Service Company and Sandia National Laboratories.

During this subcontract, Ascension Technology, a division of Applied Power Corporation, addressed the PVMaT goals of manufacturing improvements directed toward innovative, low-cost, high-return and high-impact PV products.

Ascension Technology began this subcontract with NREL in April 1998 with goals to reduce significantly the cost of the SunSine<sup>®</sup> inverter, enhance its performance, and streamline and expand the manufacturing process. The primary goal was to reduce costs, thereby allowing the units to be sold at a lower price. Secondary goals were to enhance performance and improve marketability by adding features that customers require or desire. Finally, Ascension Technology has worked to increase their manufacturing capacity, to allow higher volumes and lower costs as the market expands.

## 3.0 Tasks

The following is a summary of the Tasks for this project. The project consisted of two phases. Phase I comprised Tasks 1 through 5. Phase II comprised Tasks 6 through 11.

### 3.1 Task 1 - Power Electronics Improvements

Soft switching is a class of switch-mode power circuit design techniques used to reduce losses and device stresses incurred during switch transitions and to reduce electromagnetic emissions. Passive or active elements may be used to reduce either the voltage across a switch during a switch transition, called Zero Voltage Switching (ZVS), or the current through a switch during a switch transition, called Zero Current Switching (ZCS). While the extra circuit elements necessary to achieve soft switching impose extra cost and electrical losses, these are usually offset by increased reliability due to lower operating temperatures, reductions in heat removal, less EMI filtering hardware, and decreased component stresses. However, some soft-switching approaches actually increase component stresses.

#### 3.1.1 SunSine<sup>®</sup> Inverter Topology

Before one can explain the need for soft switching, one must first explain the overall topology of the SunSine<sup>®</sup> inverter. The inverter is actually a combination of two power converters in series. The first converter is a dc/dc converter with high bandwidth output current control. This is a buck converter consisting of C1, Q1, D1 and L1 seen in Figure 1. Q1, the main switching MOSFET, is pulse width modulated (PWM) to control the output current of L1 to match a half-sinewave reference signal. The PWM signal switches Q1 at 50 to 100 kHz and is considered a self-commutated converter. Accurate high bandwidth control of L1 current is what allows the unit to achieve low harmonic distortion in the inverter output current. Many commercially available inverters do not have such high bandwidth control and may have difficulty meeting the new IEEE Std. 929-2000 and UL 1741 harmonics requirements at the high order harmonics. These requirements become mandatory for the production of listed inverters in the U.S. as of November 7, 2000.

The second power converter in the SunSine<sup>®</sup> inverter is a current-fed H-bridge dc/ac inverter. MOSFETs Q2, Q3, Q4 & Q5 comprise this converter. Switching of the H-bridge MOSFETs is controlled by a voltage-frequency detect circuit. This circuit has a logic level (0 or 5V) output depending on the polarity of the utility voltage waveform. The output changes state at the zero crossing of the voltage waveform. This circuit is designed to minimize the impact of multiple zero crossings and noise from the utility voltage. This signal controls operation of the H-bridge MOSFETs, hence this part of the inverter is line-commutated. The H-bridge MOSFETs are also controlled by a second signal, a shutdown signal from the microprocessor. The microprocessor can shutdown operation of the power MOSFETs in microseconds.

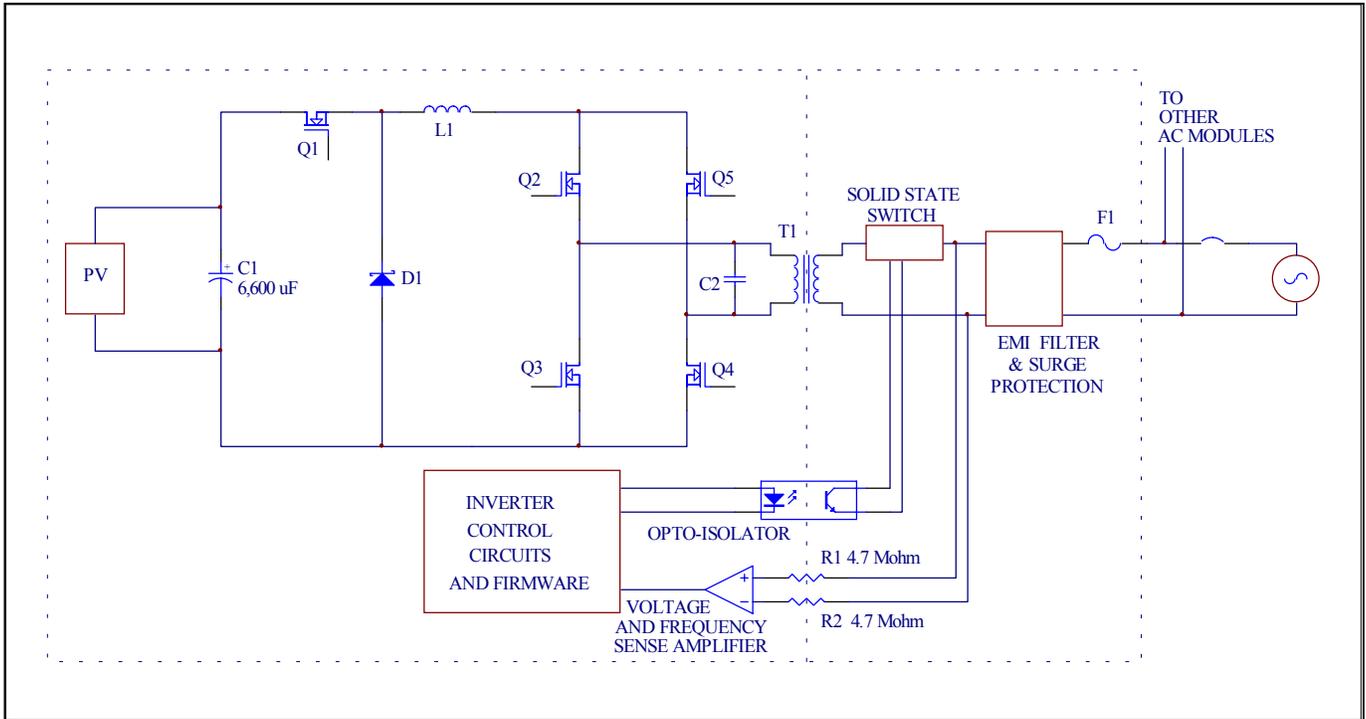


Figure 1. SunSine<sup>®</sup> ac module power topology

The output of the H-bridge dc/ac inverter is connected to a filter capacitor, C2. The voltage at C2 is a nominal  $24V_{ac}$ . Transformer T1 is a 60-Hz, (or 50-Hz for international versions) 24:120 volt transformer, designed and tested for isolation up to  $4,000 V_{ac}$ , and provides isolation between the PV input circuit and the ac output circuit of the inverter. In series with the transformer output is a solid-state relay, isolated from the low voltage control circuits by an opto-isolator rated for  $5,300 V_{ac}$  isolation. The purpose of the solid-state relay is to provide a second means of inverter shutdown and to remove power from the transformer at night. Otherwise, standby losses of the transformer at night would be about  $3.0 W_{ac}$  continuous.

On the utility side of the solid-state switch is the connection for voltage and frequency sensing. This is done through a high input impedance differential amplifier. The input impedance of 4.7 megohm is sufficient to meet UL isolation requirements between the PV input and the ac output of the inverter. The resistors are rated for continuous  $2,500 V_{ac}$  operation.

Next are the EMI filter and surge protection components. These components filter conducted emissions from entering or exiting the inverter and are generally effective in the frequency range of 0.45 to 30 MHz. Also included is surge protection to minimize the probability of conducted line surges damaging or affecting inverter operation.

Finally, each inverter is fused, F1, to prevent any component failures from affecting the rest of an ac module system. The only time F1 would open is due to component failure in the inverter. The fuse, F1, is not user-accessible or serviceable.

### 3.1.2 Soft Switching

So where does soft switching come in? Soft switching is used when Q1 turns on. A special circuit is used to control the voltage across Q1 so that Q1 turns on with zero voltage switching, ZVS. Figure 2 shows the voltage that controls operation of the MOSFET,  $V_{gs}$  Q1, and the voltage across the MOSFET output,  $V_{ds}$  Q1. This ZVS

technique is achieved by an auxiliary circuit that draws the main voltage across the switch ( $V_{ds}$ ) down to zero before the control signal ( $V_{gs}$ ) is activated.

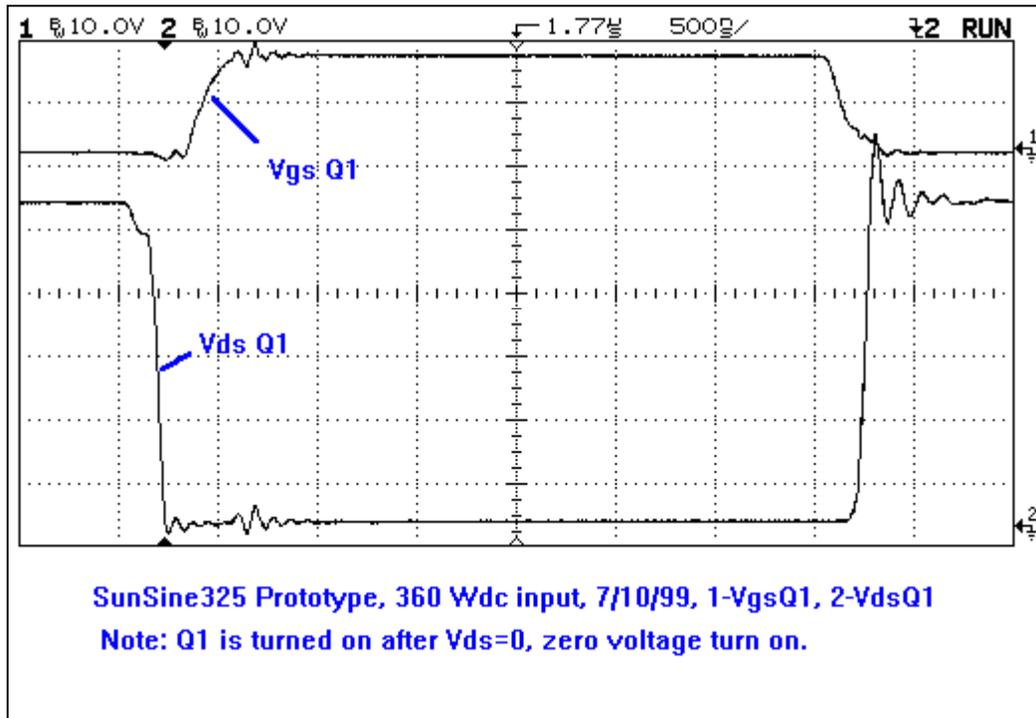


Figure 2 Transistor waveforms during soft switching ( $V_{gs}$  is the control signal,  $V_{ds}$  is the voltage across MOSFET Q1. “SunSine<sup>®</sup> 325” is the company’s internal name for this new product.

Figure 2 also shows the turn-off transition of Q1. The current waveform is not shown in Figure 2. If it were it would show that Q1 was already off during the turn-off transition. Extra capacitance has been added to the circuit to slow down this transition, to prevent electromagnetic interference that can be generated by steep  $dv/dt$  waveforms.

### 3.1.3 Impact on Efficiency and EMI

The initial impact of implementing soft switching was to allow an increase in inverter efficiency from 85.7% to 90.8% at 300 Wac output. Some of that increase in efficiency came as a result of a reduced number of EMI filter components and about 1.6% of the increase in efficiency was due to a change in the transformer design and use of some more efficient MOSFETs in the design. Therefore, it is estimated that about 3.0% of the increase in efficiency was due to use of soft switching.

However, this full power efficiency of 90.8% was measured before the product was put through the FCC Class B testing. During this testing, it was found that soft switching reduced the amount of EMI energy in the radiated band of 30 to 1,000 MHz but increased the amount of energy in the conducted band of 0.450 to 30 MHz. The soft switching has a circuit that resonates at about 5 to 10 MHz. This low frequency energy coupled into the aluminum casting of the inverter quite well, making it very difficult to pass the FCC conducted limits. Changes were made to the soft switching circuits to reduce the amount of EMI energy generated, but unfortunately those changes consumed additional energy thus lowering the efficiency of the inverter. In the end, in order to pass the FCC limits,

the full power efficiency of the inverter had dropped from 90.8% to 88.0%, nearly negating all of the gains of implementing soft switching in the first place.

Soft switching also has a more complicated power topology and control requirements than a straight buck converter would have. The added components for soft switching add cost to the inverter design. It is hard to say if a soft switching or a hard-switched design would be the optimal approach for this inverter when the issues of cost, complexity and efficiency are considered. The data from this project are not conclusive on that question.

3.1.4 Task 1 deliverables completed

D-1.3 Report summarizing rationale for selection of soft-switching approach and prototype performance results.

3.1.5 Task 1 results summary

- Successful implementation of soft switching.
- The data is inconclusive if soft switching is the optimal approach for this inverter design.

**3.2 Task 2 – Circuit Board Optimization**

The power circuit board was optimized. The basic circuit was redesigned such that most of the circuit elements were available as standard products from multiple vendors. This has the effect of reducing part prices. The redesign process has made extensive use of surface mount technology (SMT) components. These parts are less expensive, better for use in automated assembly lines, and take up less room on the board. The new inverter uses 90% surface-mount components. There are 187 SMT components and 21 through-hole components. The presence of large components in the inverter dictates some manual insertion during assembly, but this has been minimized in the new design.

3.2.1 Inverter Circuit Improvements

Reducing the size of the main circuit board was a major goal of this task. The redesign was conducted by test and analysis of the circuit, and improvements in component quality and control technique. Numbers that summarize the results of this work can be seen on Table 1, and a picture of the old design next to the new board appears in Figure 3. The reduced size of the circuit board helps to reduce the size of the enclosure as well. Summary numbers for the inverter are presented in Figure 4.

<b>Table 1. Comparison of Circuit Board Versions</b>			
<i>Component</i>	<i>Original SunSine<sup>®</sup> 300</i>	<i>New SunSine<sup>®</sup></i>	<i>% reduction</i>
Board Size	90 in <sup>2</sup>	39 in <sup>2</sup>	57%
Circuit Board Component Count	282	208	26%

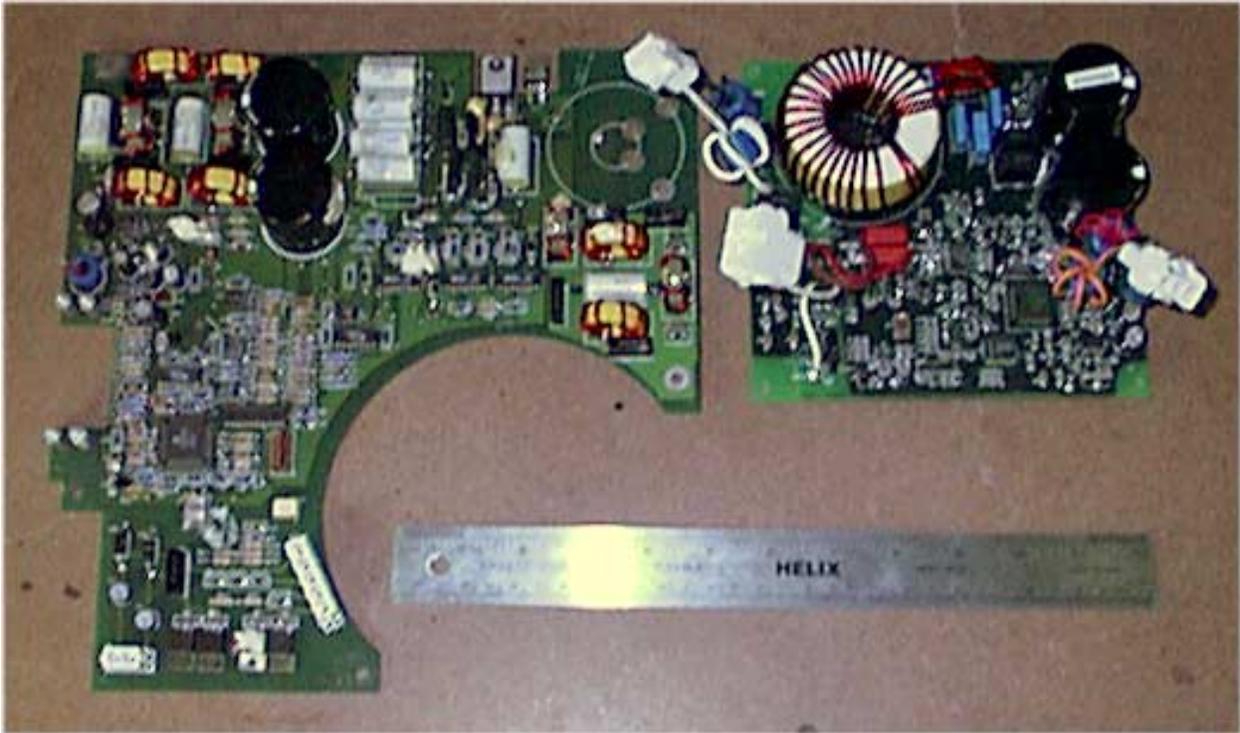


Figure 3. Circuit board of old and new SunSine®.

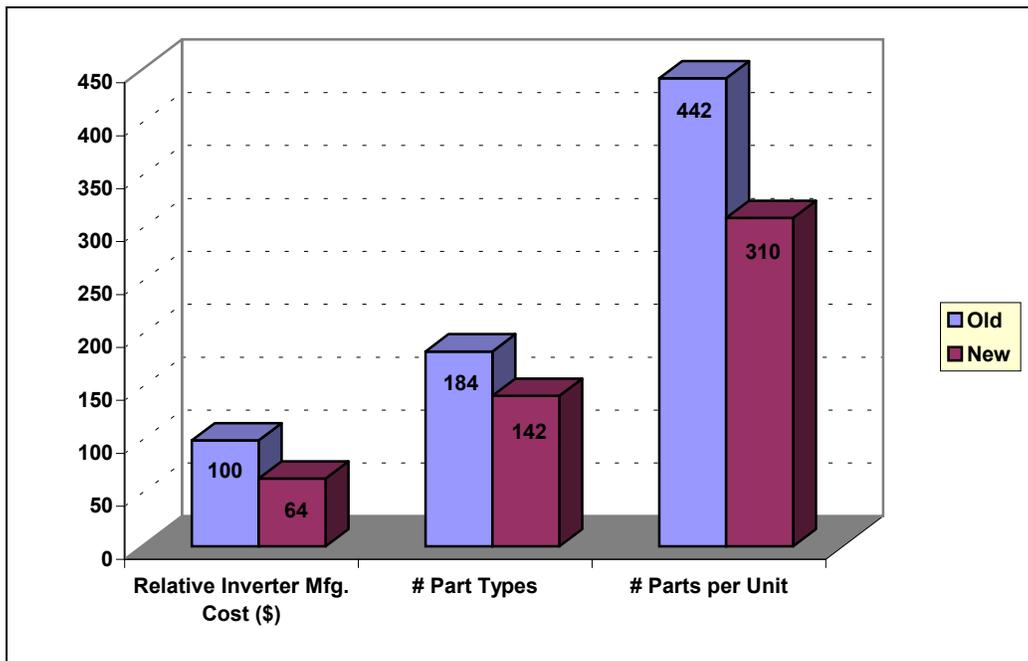


Figure 4. Inverter cost and parts count reductions.

### 3.2.2 Capacitor Lifetime Estimates

One of the failure modes in dc/ac inverters can be failure of the electrolytic storage capacitors. These capacitors are used to filter the difference between the dc-input power and the ac output power, as well as to reduce ripple current from switching operation of the converter. These capacitors contain a liquid electrolyte that evaporates over time. The rate of evaporation is a function of capacitor temperature. A rudimentary model of capacitor temperature versus ambient temperature, wind speed and POA irradiance has been constructed. Data from one year of operation of a single-axis tracking system in Tempe, Arizona was used as input to the model to determine how much capacitor life was lost per year of operation. Based upon this preliminary model, various capacitors were evaluated to determine what kind of lifetime we could expect in this environment. Our goal is to achieve a capacitor lifetime of 20 years. Using the model and the specific data of the capacitors selected, a capacitor lifetime of 26.7 years is expected in an application such as mentioned above. Locations where temperatures and average irradiance are lower can expect longer lifetimes for the capacitors.

The model was created from test data collected on an operating unit at the NREL Outdoor Test Facility. The PV module temperature, inverter case temperature, and internal capacitor temperatures were monitored during operation. In addition, POA irradiance, ambient air temperature, wind speed and ac output power of the unit were also monitored. An empirical model of capacitor temperature was created versus POA, ambient air temperature and wind speed. This model was then applied to one year of data from a single-axis tracking system located in Tempe, Arizona.

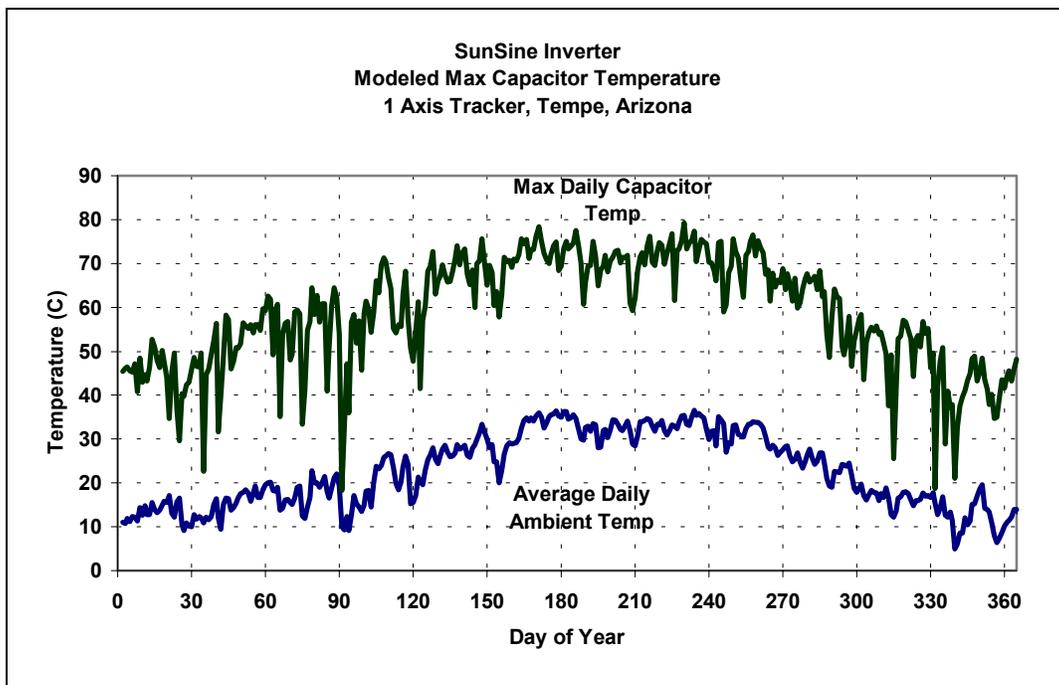


Figure 5. SunSine<sup>®</sup> ac module, modeled capacitor temperature for one year of operation in a single axis tracker located in Tempe, Arizona.

Figure 5 shows the measured average daily ambient temperature on the bottom of the graph and the modeled maximum capacitor temperature for each day of the year. In this application, it is interesting to note that the maximum capacitor temperature does not exceed 80°C. However, the capacitors have a rating of 105°C, so operation is well within the design margin of the capacitors.

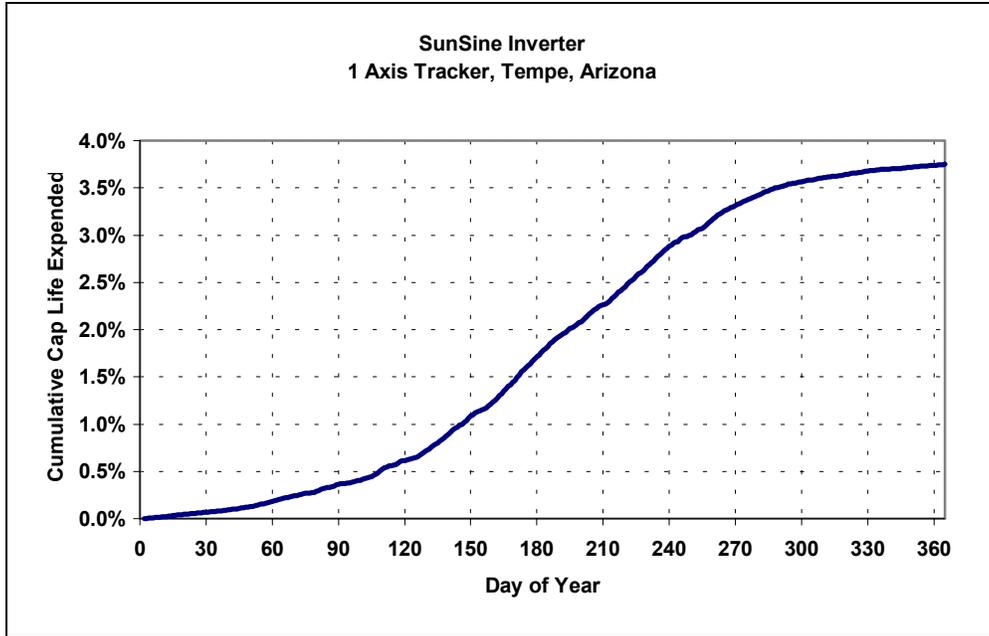


Figure 6. Rate of loss of capacitor life versus day of year.

Figure 6 shows that over the course of one year the capacitors will lose about 3.75% of their life during that year. As would be expected, most of that loss of life, or rather loss of electrolyte, occurs during the summer months when the operating temperatures are highest.

### 3.2.3 Transformer Improvement

As part of the improvement process, the transformer was redesigned. The new transformer exhibits higher fixed losses leading to a lower efficiency at low power, but lower conduction loss than the old transformer. The result is that the inverter will obtain higher efficiency at high power ratings. This is summarized in Figure 7. The crossover point of the two curves is near the 50% rating point for the inverter. The effects of this change on energy production will vary from site to site, but clearly the new transformer will help the ac module to achieve a higher output rating at STC and PTC conditions.

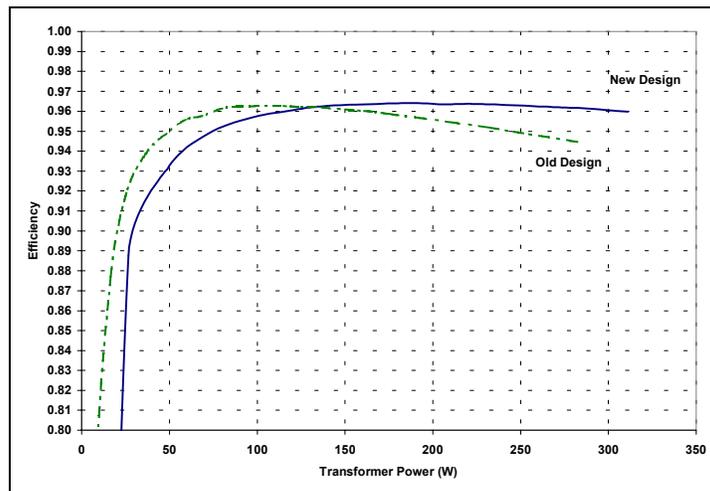


Figure 7. Old and New Transformer Efficiency

The new transformer design is simpler, maintains nearly the same dimensions as the old design and while heavier by about 2 pounds boasts a temperature rise characteristic reduced by 37%. At 275 Wac output, the new transformer increases inverter efficiency by about 1.4%.

### 3.2.4 Inverter Efficiency

It is difficult to separate the impact that soft switching has on inverter efficiency from other changes that have been incorporated into the inverter design. A test of inverter efficiency was performed on the new SunSine<sup>®</sup> inverter, Rev. C, and the old inverter, a production unit of the SunSine<sup>®</sup> 300. The efficiency of each unit was measured from zero to full output power at a fixed input voltage of 51.0 volts. This voltage corresponds to the maximum power voltage of the PV laminate at STC conditions. These two inverter versions were tested with exactly the same test setup so that a comparison of efficiency would be as accurate as possible.

One reason for doing a comparison is that there is some uncertainty in the absolute accuracy of our test setup. Measurement of efficiency is rather difficult to do with absolute precision. The test equipment, however, is very good at producing repeatable results.

At 275 Wac, the new inverter design was 4.7% more efficient than the SunSine<sup>®</sup> 300 inverter. At 300 Wac, this improves to 5.2%. This increase in performance at the higher power levels is achieved with some loss of efficiency at the lower power levels. The improvement has been achieved through changes in the transformer design, the implementation of soft switching in the power conversion stage and in a reduced number of components needed for EMI reduction.

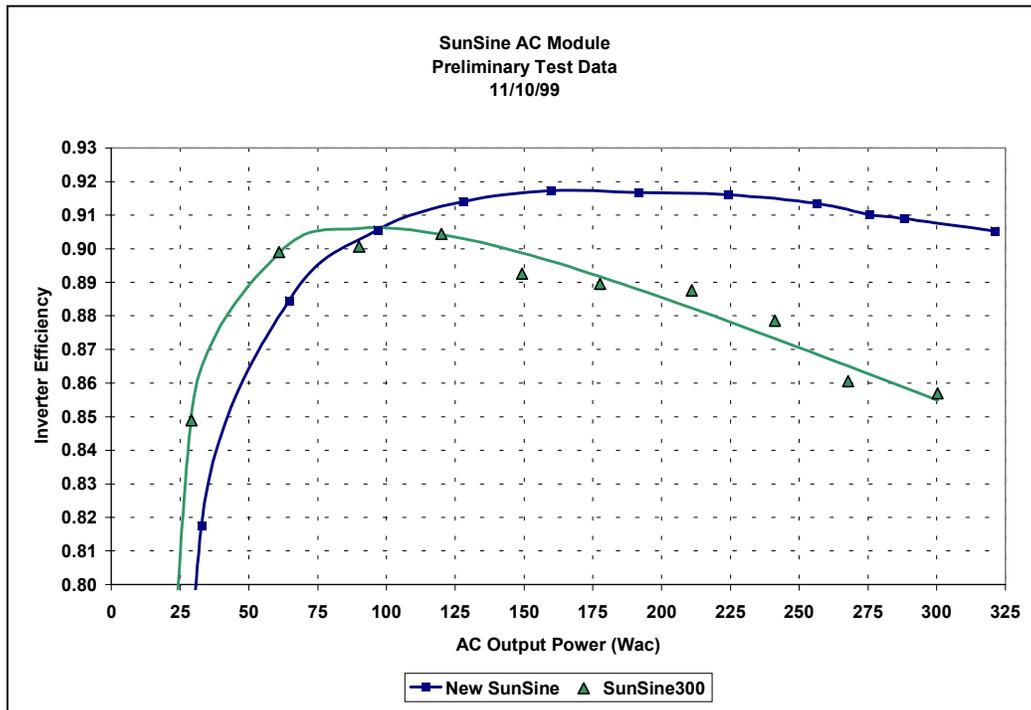


Figure 8. Comparison of inverter efficiencies: SunSine<sup>®</sup> 300 and a preliminary SunSine<sup>®</sup>, Version C.

However, inverter efficiency dropped considerably after making modifications needed to pass FCC Class B EMI limits. This was discussed in section 3.1.2 and will not be repeated here. Figure 9 shows the final inverter efficiency curve for inverter version G.

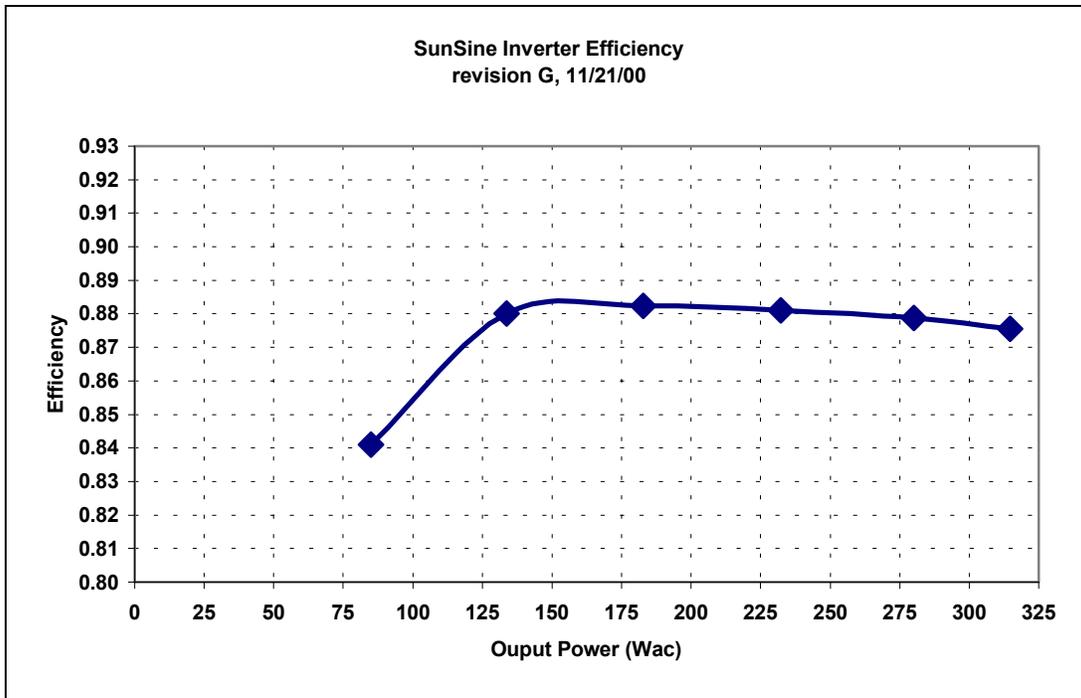


Figure 9. Final SunSine® Inverter Efficiency Curve

### 3.2.5 Task 2 deliverables completed

D-1.7 Prototype ac module delivered to NREL for performance testing.

### 3.2.6 Task 2 Results Summary:

- 2.3% increase in inverter efficiency from 85.7% to 88.0% at full power.
- Power circuit board sized reduced 57% from 90 to 39 square inches.
- Power circuit board component count reduced 26% from 282 to 208 components.
- Total inverter parts count reduced 30% from 442 to 310 parts.
- Transformer efficiency improved 1.4% at full power.

### **3.3 Task 3 – Manufacturing Process Improvements**

Inverter assembly has been simplified. There are fewer parts involved and hence fewer manual operations. Connectors are easier to access during assembly due to the new orientation of the circuit board. The heat sink interface between the power semiconductors and the casting has been simplified by use of a special potting compound. Meetings were held with critical component vendors and production management to review the first prototype of the new inverter. These meetings generated feedback to the design process and the majority of the issues raised have been addressed to make the unit as easy as possible to manufacture. A review of the documentation needed to support manufacturing was also conducted.

A review of an automatic dispensing conformal coat process was conducted. A sample inverter, coated using this method, was subjected to a Highly Accelerated Stress Test, HAST. In this test, the unit was subjected to 110 °C temperature at 85% relative humidity for 200 hours. This test is conducted with power applied to most of the electrical circuits. When the unit was returned from the test it was found to still be operational, with no significant

defects in the unit. However, since this process was verified, the design was modified to use a potting compound to encapsulate the power board instead.

Encapsulation of the power board provides mechanical support for the larger components on the power board. Without the potting, those components would need to be secured to the power board by other means. Encapsulation also protects the components against rapid thermal transitions as can occur during shipment of the product. Encapsulation also provides for thermal heat transfer from the hot power components on the bottom of the board to the aluminum casting while at the same time providing very good electrical insulating properties.

### 3.3.1 Production Capacity

Burn-in testing used to be the bottleneck in the production process. But now that burn-in testing has been removed from the process, it is not entirely clear where the bottleneck really is. During the pilot production, when things were running smoothly, about 40 units were being built per week. This comes out to an annual rate of 2000 units per year. In that case, the limiting factor was really the amount of labor being applied to the process, not any specific process related delay. One possible bottleneck in the production process is that we only have one calibration and IEEE 929 test station. That test station is operated manually and takes about 15 minutes to test each unit. At that rate, 32 units can be tested per day, or 160 units per week, or 8,000 units per year. So at this point in time, the calibration test station is not a significant bottleneck in production.

The PV modules come from ASE Americas, Inc., where they will soon have a production capacity of 20,000 ASE-300-DG/50 300W PV modules per year. The circuit boards come from a contract manufacturer who could easily produce about 125 boards per week (estimated), or 6,250 per year, without significantly affecting their other customers. The die cast contractor will be able to fabricate between 250 to 500 units per day, so this represents a capacity of 50,000 to 100,000 units per year. So by choosing our critical component vendors wisely, we should be able to avoid bottlenecks in our supply chain. Further details about the production process will be covered as part of Tasks 8 and 9.

### 3.3.2 Task 3 deliverables completed

D-1.1 Report summarizing planned process modifications and anticipated improvements.

### 3.3.3 Task 3 Results Summary

- We have decided to eliminate burn-in testing from the production process, removing a major bottleneck in production capacity, the remaining bottleneck in production capacity will be final assembly.
- The conformal coat process was successfully tested using the HAST test process.

## **3.4 Task 4 – Smaller Packaging for SunSine® Inverters**

The original enclosure used for the inverter was from a low-yield sand casting process. As mentioned in Section 3.1, the new circuit board permits the design of a smaller casting, and the per unit cost of the previous casting inspired the search for a better process. A new vendor has been found, working from a die-cast process that promises higher yields and lower cost. Higher tolerances and better surface finish quality are also improvements available from the die-cast process. Figures 9 and 10 show the old and new prototype castings.

The prototype casting developed during Phase I was much larger than the final version. This is because our initial approach in designing the casting was to see if we could use the same design for multiple product versions. Those versions would have included products for U.S. and international markets, ac module and string inverter applications, and 320- $W_{ac}$  and 500- $W_{ac}$  ratings. After the prototype was completed we realized that there would be significant penalties for trying to design one casting for so many product versions. That, combined with our

decisions on export markets, has led us to focus on the domestic ac module. The final casting design was optimized to take advantage of the much smaller circuit board design.

During the design process we have improved our ability to generate casting prototypes. A design firm and prototype casting vendor was contracted who can produce the design drawings and prototypes with very good quality and turn around time. A stereo lithography prototype of the design was made and provided to a prototype casting vendor who fabricated several prototype castings in aluminum. The prototype castings are made in a process that is fast and reasonably close to what can be done in die casting at a moderate cost. The purpose of making such prototypes was to prove out the packaging concept for thermal, structural, watertight integrity and other UL and performance related issues.



Figure 10. First casting prototype for the SunSine<sup>®</sup> inverter. Note the separate wiring compartment and the use of a gasket seal around most of the enclosure. Plenty of room was included so that inverters up to 500W could be built with this design. This was not the final design used.

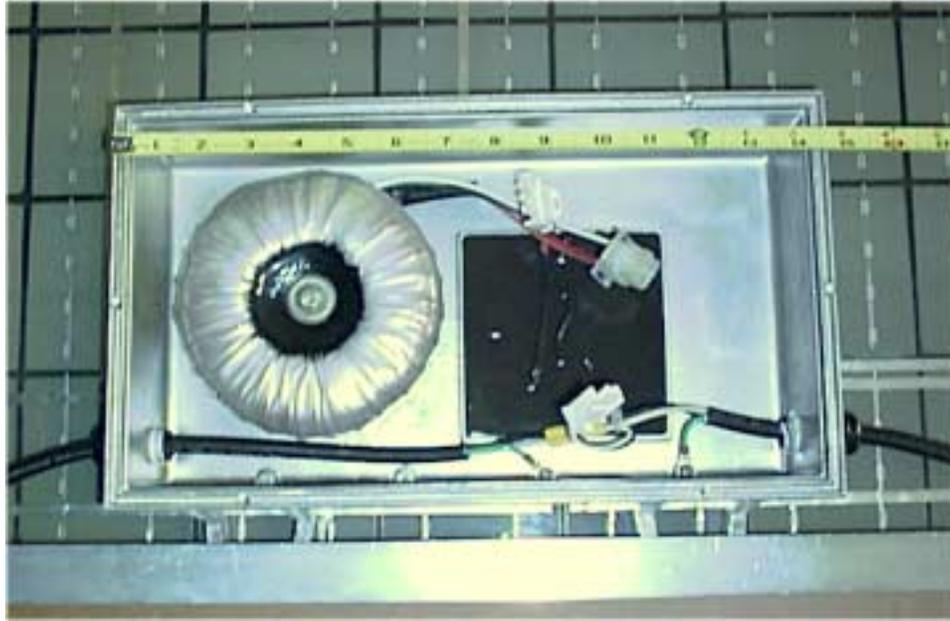


Figure 11a. New SunSine<sup>®</sup> casting base mounted on PV Laminate

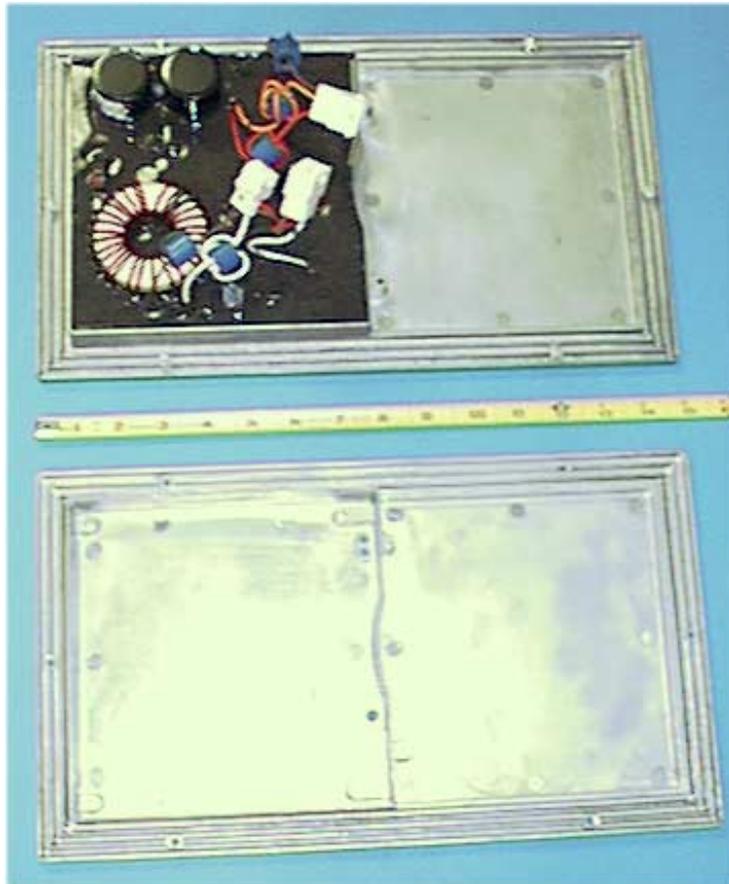


Figure 11b. New SunSine<sup>®</sup> casting design with lid and base assembly shown side by side.

Figure 11 shows the new casting design. A gasket-less sealing method is used between the lid and base that is effective for tilt angles up to 60 degrees. In the few cases where tilt angles greater than 60 degrees are needed, a silicone sealant can be applied between the upper edges of the lid and the base. The new design also includes mounting brackets that attach directly to the PV frame. These brackets provide a second means of attachment to the laminate so that the securement of the inverter to the laminate is very secure. The use of mounting brackets also provides a path for ground continuity between the frame and the inverter casting which would otherwise have to be provided by a separate ground wire.

The inverter base is also secured to the rear of the laminate with a special adhesive to hold it in place. Many features were designed into the casting so that assembly of the inverters would require a minimum of operations. Threaded conduit holes are provided for the Heyco strain reliefs on the output cables. Grounding screw points are provided at multiple locations within the casting so that each ground wire can be terminated separately.

#### 3.4.1 Task 4 deliverables completed:

D-1.2 Summary of enclosure design specifications and relative improvements.

D-1.6 High quality digital photographs of enclosure prototype.

#### 3.4.2 Task 4 Results Summary:

- Two casting prototypes were developed. The final design was optimized for the ac module application.
- We have learned how to design and create prototype aluminum castings at a moderate cost.

### **3.5 Task 5 – Export Versions of the SunSine<sup>®</sup> ac Module**

The purpose of this task was to determine if there are appropriate export markets for the new SunSine<sup>®</sup> ac Module. If so, to determine the requirements for selling into those markets. The markets considered include, the United States, Canada, China, Europe, the United Kingdom, Australia, and Japan.

The requirements for the U.S. and Canada are very similar. Both operate at 120V 60Hz. Listing for safety is required and can be done through Underwriters Laboratory (UL). The listing marks are UL and UL-C. FCC Class B is the required level of EMI protection. Interconnect requirements are set by the new IEEE Std. 929-2000. The requirements for selling products in China are somewhat difficult to meet. They typically require a high degree of in country content in products sold in their markets. Direct import of inverters or ac modules into China would be difficult to develop. Interconnect voltage and frequency is typically 220V 50Hz.

Europe includes Austria, Denmark, Germany, Italy, the Netherlands, Portugal, and Switzerland. The interconnect voltage is typically 230V 50Hz. Europe is marked by intense local competition and widely varying interconnect standards. Germany requires a specific impedance detection method for anti-islanding protection. This method would be quite costly to implement and would only be applicable to Germany. UL is working to harmonize UL 1741 with the European standards. At present, CE marking is required for safety and EN 55022 also known as CISPR 22 B, is required for EMI protection. The United Kingdom and Australia have similar requirements as Europe. Their interconnect voltage is 240V, 50Hz. In the U.K., CE marking is required and C-tick is required in Australia for safety. EN 55022 applies to EMI protection in the U.K. and Australia. So the safety and EMI requirements are similar to Europe.

Japan has been very proactive with respect to grid-tied PV. The interconnect voltage in Japan is 100V 50/60Hz. Half of the island operates at 50 Hz and the other half at 60 Hz. An ac module introduced into Japan should allow operation at either frequency. The transformer used in the U.S. version can also work in Japan without modification. The maximum output current of the ac module would remain the same but this means the maximum output power would have to be reduced. Fortunately there is sufficient headroom in the inverter design to allow

this. The SunSine<sup>®</sup> ac module could be de-rated for operation in Japan to a maximum output of 275 W<sub>ac</sub>. Other specifications would be slightly modified due to normal operation at a lower voltage. The benefit is that the same hardware could be used for both Japanese and U.S. markets. The only difference would be in the programmable setpoints programmed into the unit.

During the course of Phase I we decided to focus on U.S. markets, to optimize the product for our own domestic markets. Attempting to design one product for world markets at this point would impose added cost to units sold in the U.S. and slow down getting the new product into production. Only after establishing a solid customer base in the U.S. and increasing market share of domestic grid tied PV markets will we consider export markets.

### 3.5.1 Task 5 deliverables completed

D-1.4 Outline of manufacturing process documentation.

D-1.5 Powerpoint presentation summarizing markets surveyed, market requirements, and performance specifications.

### 3.5.2 Task 5 Results Summary

- Potential export markets have been identified, including safety and emissions requirements.
- We have decided to focus on getting the product ready for U.S. markets first, and will address international markets second.
- The inverter has been designed so that it may be easily modified to work in international voltage and frequency versions.

## **3.6 Task 6 – Design for Die-Cast Enclosure and Base Plate**

The final design of Task 4 was completed. Prototypes of the design were fabricated and 2-D drawings were made and sent out to three possible die-cast vendors for quotations. Each of the three vendors quoted setup charges, per piece prices, and minimum order quantities. The vendor with the lowest piece price was selected and an order placed for 500 sets of lids and bases.

Three degrees of draft had been designed into the base unit. However, there were still some problems when it came time for the initial production of the bases. The single biggest problem was that the bottom portion of the base would separate from the walls of the part when the die cast machine ejected the part. Work was done to strengthen the interface between the walls and the bottom of the base. Extra ejector pins were also added to the die to even out the pressure forcing the part out of the die. The other problem that was experienced was one of schedule. One of the tooling shops involved in machining the die had had some labor problems at the same time as a high volume of work. This impacted the setup of the die cast process, but eventually the die cast vendor worked out the problems.

The final cost of the lid and base casting is 20% of the price for the SunSine<sup>®</sup>300's sand-cast housing and base plate. This is a reduction in enclosure cost of 80%. In addition, the quality of the die cast pieces is much higher than we could ever get from the sand cast process. The initial run of 500 sets of lid and base castings was completed successfully. Figure 11 shows the final lid and base castings.

3.6.1 Task 6 deliverables completed

D-2.2 Deliver high quality digital photographs of the new die-cast enclosures.

3.6.2 Task 6 Results Summary

- Enclosure cost reduced 80% over the previous design.
- A successful production run of 500 enclosures was completed.

**3.7 Task 7 –Integration, Testing and Listing / Certification**

The results of tasks 1 through 5 were combined to achieve a final inverter design. The design underwent UL, HALT, FCC-EMC, and surge testing. In the course of that testing, the design was modified to meet the following criteria.

<b>Table 2. SunSine<sup>®</sup> ac Module Test Specifications</b>
UL 1741, Safety IEEE Standard 929-2000, Interconnect NY State SIR, Interconnect IEEE-C62.41-1991, Surge Testing IEEE-C62.45-1992, Surge Testing HALT, Reliability FCC Class B, EMC

3.7.1 UL Listing

The SunSine<sup>®</sup> ac module was tested to UL-1741 by Underwriters Laboratories. The results of the individual UL tests are listed below.

*Rain Testing* *Passed*

The unit may be used in systems with tilt angles from 0 to 60 degrees. In systems with tilt angles greater than 60 degrees, including vertical orientation, application of a silicone sealant between the inverter lid and base is required. Since very few systems have such steep tilt angles, we felt this was the best approach. This testing was conducted in UL’s Northbrook, IL facility.

*Temperature Test* *Passed*

The SunSine<sup>®</sup> ac module will have a 60°C ambient temperature rating. This is the same temperature rating as the ASE-300-50/DG PV module. In an ac module application, since the inverter is 88% efficient at full power, this means the inverter can be connected to PV with a rating up to of 330 W<sub>dc</sub> STC. The inverter was placed in a temperature chamber and operated until temperature readings stabilized in a series of temperature tests. At the end of the tests while the unit was still warm, a hi-pot test was run at 1,500 V<sub>ac</sub>. During this test, no component may exceed its maximum temperature rating. Sixteen thermocouples were located throughout the inverter and monitored continuously by a data acquisition system.

*Dielectric Voltage Withstand Tests*

*Passed*

In these tests a high voltage is applied between the dc input and ground, the ac output and ground and between the dc input and ac output. These tests ensure that the input and output circuits are well isolated from chassis ground and each other and is one of the most important safety tests UL does. For the SunSine<sup>®</sup> ac module, UL requires a test potential of 1,240 V<sub>ac</sub> to be applied for 60 seconds without breakdown. This test is applied multiple times throughout the test program. We performed all of these tests at a test potential of 1,500 V<sub>ac</sub>. This way we can use this same set of test data to meet international test requirements if we decide to introduce the unit for international markets.

After one of the tests, the overload test, we increased the dielectric test potential to 2,800 V<sub>ac</sub> and passed. This is the highest voltage our hipot tester will generate, so the actual limit may be even higher. The peak voltage of a 2,800 V<sub>ac</sub> test is 3,960 volts. The ability of the unit to withstand such a high voltage should allow the unit to survive high surge levels such as are tested in the IEEE Surge testing.

*Output Ratings*

*Passed*

This is a series of tests conducted to verify that the unit operates at the same conditions indicated on the product label. For example, output power and power factor are measured at 25%, 50% and 100% of rated output. The power factor measured was 0.99, 0.99 and 1.00 respectively.

*Harmonic Distortion*

*Passed*

Output current THD and individual harmonics will vary depending upon temperature of the unit. Measurements of THD ranged from 1.8% to 2.5%. The unit also passed the individual harmonic limits of IEEE Std. 929-2000.

*DC Injection*

*N/A*

Since the unit includes an isolation transformer, this test was determined to be not applicable.

*Voltage & Frequency Waveform Variation*

*Passed*

This is a sequence of waveform tests that ensure the unit will shutdown in over or under voltage or frequency conditions within predetermined time limits. The voltage and frequency trip set points are verified in this series of tests. The default steady state operating limits of the unit are 106 to 132 V<sub>ac</sub>, and 59.3 Hz to 60.5 Hz, in compliance with IEEE Std. 929-2000. NYSERDA is adopting these limits as well. The trip set points are adjustable by qualified service personnel in case we have future customers with different operating requirements. Those adjustable setpoints are not accessible to the end user.

*Anti-islanding Tests*

*Passed*

This is a series of tests conducted at 25%, 50% and 100% of inverter rating with loads at 25%, 50%, 100% and 125%. The inverter uses Sandia Voltage Shifting (SVS) and Sandia Frequency Shifting (SFS) for anti-island protection. A total of 44 trip tests was conducted and the time to shutdown recorded. The longest time to shutdown measured was 0.184 seconds (11 cycles at 60 Hz), the pass/fail limit is to shutdown within 2.000 seconds, so we were well within the limit. The unit shutdown faster than 0.100 seconds (6 cycles) in 37 out of 44 tests.

*Grounding Impedance*

*Passed*

A 25 A<sub>ac</sub> (and 30A<sub>ac</sub> for Canada) current is passed through the grounding system of the wires, frame and inverter casing. Voltage drop is measured to allow computation of grounding resistance. The SunSine<sup>®</sup> was less than the

0.10 ohm limit. This test was conducted using 16-gauge wire since some product configurations may use 16-gauge wire.

*Strain Relief* *Passed*

Each of the cable types proposed for use with the product was tested. A 35 lb. weight was attached to the output cable for one minute to ensure the cable is properly secured.

*Inverter Securement* *Passed*

The inverter is secured directly to the module frame by two mounting brackets and with a sealant/adhesive between the inverter case and module substrate. This test was conducted at room temperature on both a double-glass module and a single-glass module. The inverter weights 20 lbs. so an additional 60 lbs. is applied to the inverter case for one minute attempting to break the attachment to the module. A new material is being used for the sealant/adhesive since the previous material is no longer available.

By using two methods of attachment to the module, we believe we have solved the problems previously experienced with inverter securement. The inverter securement test is also repeated on test samples conditioned by the temperature cycle and humidity cycle tests as part of those tests.

*Loss of Control Circuit* *Passed*

The power supply to the control circuit was disabled and the inverter is supposed to shutdown. In some designs it is possible that this test would be destructive, but in our design, the inverter returns to normal operation when control power is restored.

*Output Short Circuit* *Passed*

While the inverter is running at full power, a short circuit is applied to the ac output. Output current of the inverter is measured on an oscilloscope to determine how long it takes for the inverter to shut down and the magnitude of the output current. In our case the inverter shutdown within 34 milliseconds and the output current did not exceed the normal output current rating of 2.66 A<sub>ac</sub>.

*DC Input Miswiring* *N/A*

It was determined that this test is not required for the ac module since the dc input is factory wired.

*Overload Test* *Passed*

The temperature and output current limiting features of the inverter were disabled. Hardware limits within the inverter limited output current to about 350 W<sub>ac</sub>. This test ran for 7 hours without failure of the unit and was followed by hi-pot tests at 2,800 V<sub>ac</sub>.

*Component Shorts and Opens* *Passed*

The inverter design was evaluated to determine the two worst-case component failures. Since the design of this inverter is so similar to the SunSine® 300, it was determined that only two tests were needed. In each case a single fault is forced in the inverter. Operation of the inverter is monitored to ensure that no unsafe condition develops.

### *Temperature Cycle Test*

*Passed*

This test comes from UL 1703 and applies to ac modules. The inverter and module are conditioned by the temperature cycle test and after the test must pass a dielectric withstand test. The securement of the inverter is also conditioned by the temperature cycle test, after which the inverter securement test is performed on the test sample. Two samples were tested for inverter securement, one on a double-glass module and one on a single-glass module.

### *Humidity Cycle Test*

*Passed*

This test comes from UL 1703 and applies to ac modules. The inverter and module are conditioned by the humidity cycle test and after the test must pass a dielectric withstand test. The securement of the inverter is also conditioned by the humidity cycle test, after which the inverter securement test is performed on the test sample. Two samples were tested for inverter securement, one on a double-glass module and one on a single-glass module.

### *IEEE Surge Tests*

*Passed*

Although not presently mandatory by UL, we did the IEEE C62.41 and IEEE C62.45 tests. These tests are required for NY SIR and will soon be adopted by UL 1741. These tests were conducted at UL's facilities in Northbrook, IL.

### 3.7.2 FCC Class B Verification

FCC testing was completed after numerous rounds of design modification and test. The final result, however, uses a minimum of extra components for EMI filtering. We learned a great deal about how EMI is generated and is emitted from this product. Some of the emissions are particularly difficult to mitigate and do not respond to 'normal' approaches in EMI filtering. This is why this testing took somewhat longer than originally anticipated.

For example, there are no Y caps in this design. A Y cap filter is a pair of capacitors that go from line-chassis and neutral-chassis on the 120-volt ac connection. Their purpose is to provide a low impedance path for EMI energy to return to chassis ground before conducting out the line/neutral wires.

Y caps, however, have several negative points. First, since they are connected between line and neutral to ground, they are a component that can be damaged due to surges between line and/or neutral and ground. Second, they allow some amount of leakage current to flow in the ground connection. In an ac module system, where multiple modules are installed, this leakage current adds up and can be a source of nuisance tripping for GFI protectors. Even if the steady state leakage current is insufficient to trip a GFI, a small surge could easily pass through the Y caps and cause a GFI to trip. Right now, GFI protectors are not required by the NEC. But who knows, some day they might be. There are already installations in the field where GFI protectors are improperly used on ac module systems.

By eliminating Y caps in the EMI design, these possible pitfalls are avoided.

GFI breakers are not recommended for the ac module systems. GFI breakers are not tested by UL for use in backfeed systems, which ac module systems certainly are.

### 3.7.3 HALT Testing

HALT testing was performed on the inverter's power boards and lid assemblies at about the same time as the UL testing. The process of HALT testing will be presented in more detail as part of Task 11. Operating and destruct limits for the bare power boards are indicated in the table below.

An operating limit is a point at which the unit no longer operates within specification. For example, under most conditions when the unit exceeded an operating limit, the inverter continued to generate power. But some aspect of its operation was outside of its specified performance envelope. Most typically, the output current waveform

exceeded the harmonics limits if IEEE 929-2000. When the applied stress returns to normal conditions, the unit recovers from the operating limit fault.

A destruct limit is a point at which the unit no longer operates within specification and when the stress is removed, the unit does not recover. All of the destruct limits found in this testing caused the unit to cease power generation and the unit stopped operating.

SunSine <sup>®</sup> Inverter Power Board Not potted HALT operating and destruct limits	
Destruct Limits	
Low Temperature	< -100°C
High Temperature	+130°C
Vibration	40 G <sub>rms</sub>
Operating Limits	
Low Temperature	-80°C
High Temperature	+90°C
Vibration	35 G <sub>rms</sub>

Most of the testing was done on non-potted boards. The reason is that potting of the boards protects the boards and prevents possible failure modes from showing up. We wanted to see as many of the possible failure modes as possible. After we finished the test sequence with non-potted boards, we had some time left to test one potted sample. The potted sample was tested in a combined cycle environment where thermal stress, thermal transient stress and vibration are combined in one test sequence. The results are summarized below.

SunSine <sup>®</sup> Inverter Potted HALT Combined Cycle Test Summary	
Number of thermal cycles	7
Low temperature setpoint	-60 °C
High temperature setpoint	+70 °C
Vibration	0 to 55 G <sub>rms</sub>
Temperature transitions	16 °C / min.

Due to limited time, we were not able to determine operating and destruct limits of the potted test sample. During the combined cycle testing, there were some intermittent trips of the unit, but the unit always recovered and resumed normal operation.

### 3.7.4 Task 7 deliverables completed

D-2.3 Deliver prototype SunSine<sup>®</sup> ac modules to Sandia and NREL for testing.

### 3.7.5 Task 7 Results Summary

- The SunSine<sup>®</sup> ac module passed UL Listing, including testing to IEEE Std. 929-2000, IEEE-C62.41-1991, IEEE-C62.45-1992, and NY State SIR requirements.
- The SunSine<sup>®</sup> ac module was verified to comply with FCC Class B EMI limits.
- The SunSine<sup>®</sup> ac module was tested under the HALT test protocol.

### **3.8 Task 8 – Pilot Production Manufacturing Assessment**

Inverter production costs have been reduced by 32 percent during this PVMaT project. This impacts the total ac module production cost as a reduction of 22 percent. Problems were experienced during pilot production with respect to yields, and as a result we are changing contract-manufacturing vendors for the inverter power boards. A total of 161 units have been shipped as of early December 2000, with more to come from this initial run of about 250 units.

#### **3.8.1 Pilot Production Quantity**

Two and a half years ago when this project began, an initial pilot production run of 110 units was envisioned. In the time since then, demand for the product had increased so much so that it was felt a greater number of units should be produced as part of the pilot production run. Therefore the quantity to build for the pilot production run was increased from 110 to a total of 250 units. For contractual purposes, we considered completion of the first 110 units to constitute completion of the pilot production for the purposes of the NREL subcontract.

As of early December 2000, a total of 161 units have been shipped. Another 16 are completed and await shipment with a remaining 73 at various stages in process.

#### **3.8.2 The Production Process**

The key elements of the production process are outlined below. Comments are added to identify places where significant improvements have been made or where problems still exist in the process.

##### *Parts Procurement*

The following components are ordered and delivery is scheduled to coincide with when they will be needed in the production schedule.

- Electronic components. Lead times are typically 8 to 12 weeks but in today's strong economy, it is not uncommon to find some components with lead times as long as 24 or 36 weeks.
- Mechanical components.
- Printed Wiring Boards.
- Potting Compound.
- Castings.
- Transformers.
- Output Cables.
- PV Laminates.

##### *SS325 Power Board Assembly*

The heart of the ac module is the Power Board. This is the single most important and also the most complex subassembly in the unit.

- Cable and connector prep. Three connection cables for the power board are prepared prior to Power Board assembly. The cables are used for dc input power, transformer connection and ac output power.
- Parts inventory. Production does not begin until all parts are on hand and ready for assembly.

- Top side solder paste application. Solder paste is applied to a bare board through a type of screen-printing process. Here the solder paste is applied to the pads on the board for the SMT components that are about to be placed on the board.
- Top side SMT part placement. A total of 156 SMT components are placed on the top side of the board.
- Top side solder re-flow. The board is placed in an oven which melts the solder paste under controlled conditions to form a solid solder bond to the board.
- Wash. The boards are then washed to clean them of any solder process residues.
- Bottom side solder paste application.
- Bottom side SMT part placement. A total of 31 SMT components are placed on the bottom side of the board.
- Bottom side solder re-flow.
- Wash.
- Hand placement and soldering of components. A total of 21 through hole components, three of which are cable assemblies, are placed and soldered on the top side of the board. Four additional components were added manually as part of two ECOs to this batch of boards.
- Wash.
- Functional Test, Test 1. The board is placed in a functional test fixture and powered up. Various signals are probed to ensure proper operation of the board.

#### *SS325 Diode Board Assembly*

- Cable and connector prep. One output cable is used for this assembly.
- Parts inventory.
- Hand placement and soldering of components. Six SMT diodes and one cable assembly is soldered to the board. This is easily done by hand since the board is so simple and the components are large.
- Wash.

#### *Inverter Lid Assembly*

- Clean the Lid. The aluminum die cast lids typically have some small amount of flashing material remaining on them, which needs to be knocked off before assembly can proceed.
- Mount the SS325 Power Board. The board is mounted to the die cast lid with four screws.
- Install Light Pipes. One light pipe is used for the red LED and two are used for the IR Data Port, to transmit light from the power board through the potting material to the outside of the lid.
- Add clear RTV and let cure. Clear RTV is added between the light pipes and the LED or IR transceiver to for a seal against the black potting material and still allow light to pass.
- Add potting material. The two-part potting compound is mixed in a predefined ratio and dispensed into the lid.
- Cure potting material. Each lid is placed in an oven at 85°C to 95°C and allowed to cure for about 2 ½ hours. The oven has capacity to cure up to 27 lids at a time.
- Hi-pot test, Test 2. A hi-pot test is performed to ensure proper electrical isolation between the dc input circuit, ac output circuit and chassis ground on the lid assembly.
- Calibrate the Lid Assembly, Test 3. The lid assembly is calibrated to ensure accurate ac voltage measurement, ac current measurement and clean sine wave operation. In addition, IEEE 929 voltage and frequency trip tests are conducted to ensure compliance with IEEE Std. 929-2000.

### *Inverter Base and PV Assembly*

- Drill 2 holes in PV frame for the inverter mounting.
- Mount the base to the PV laminate.
- Install the diode board.
- Install the output cables.
- Install the transformer.
- Pot the diode board area.
- Install the Lid assembly.
- Hi-pot Test, Test 4. Per UL1741, the hi-pot test is the last test performed on the unit before final shipment.
- Ship finished unit.

### 3.8.3 Test Station Results

The following results are based upon data available at the time of this report. Even though all 250 units have not yet been completed, we believe sufficient data has been collected to determine efficacy of the following tests.

#### *Functional Test, Test 1*

The requirements of this test evolved during the 2½ years of this project. The purpose of this test is to determine if the SS325 Power Board is working properly or not. The test consists of mounting a Power Board on the test fixture. It is then connected to appropriate power supplies and a transformer. A Hand Held Controller (HHC) is used to communicate with the diagnostic features of the Power Board and is used to control the unit under test. An oscilloscope is connected for observation of the output current waveform of the inverter.

The test begins by turning on dc power to the unit. HHC communications is established over the IR Data Port. 12 dc voltages are probed and recorded from the unit under test. These voltage readings provide indication of proper operation of various parts of the board under test. ac power is then turned on. The red LED should then come on solid. Six ac voltages are probed and recorded, again to ensure proper operation of portions of the circuit. HHC commands are then entered to jump start past the 5-minute turn on delay to get the board to start dc/ac power conversion. Output current is then observed to rise to a predefined level with the correct number of LED flashes and the sinewave as observed on the scope is checked. ac and dc power are then turned off. If all indications were within specified limits, the unit passes and moves on to the next step in the process. If indications were not normal, then some further inspection of the board is performed to determine the cause of the problem and corrected if possible, followed by a retest.

Up to this point a total of 252 boards have been tested through this station. Of those, 197 have passed this test and 55 have failed. This indicates a yield of 78.2 percent up to this point. The boards that failed this test have been reviewed and the failures can be categorized as follows.

- 26 Obvious Assembly Process Errors. This is 10.3% of the total and is typically one of the following problems.
  - Component in backwards.
  - Wrong value component used, such as a resistor.
  - Missing component.
  - Component not properly placed on the pads.
  - Circuit board defects.

- 20 Probable Assembly Process Errors. This is 7.9% of the total. These are cases where one or more components on the board have failed. It is believed that these are mostly failures caused by lack of proper static precautions that have caused the components to fail.
- 3 Design Errors. This is 1.2% of the Total. This is a known error that has been incorporated into the next revision of the Power Board and can be fixed on these boards as well by changing one component value.
- 6 TBD. This is 2.4% of the Total. In these boards the cause of failure has not been determined.

Most of these boards can be repaired and sent back through the test so that the ultimate yield should approach 92 percent.

Certainly it would be preferable to reduce or eliminate the first two error modes. Changes to the entire process are being considered so that higher yields, and ultimately lower costs can be achieved. But those changes are outside the scope of the NREL contract and will be considered as we move forward with our next production run.

#### *Hi-pot test, Test 2*

A hi-pot test is performed to ensure proper electrical isolation between the dc input circuit, ac output circuit and chassis ground on the lid assembly. A total of 187 units have been put through this test with no failures, and therefore a yield of 100%.

#### *Calibrate the Lid Assembly, Test 3*

The lid assembly is calibrated to ensure accurate ac voltage measurement, ac current measurement and clean sine wave operation. In addition, voltage and frequency trip tests are conducted to ensure compliance with IEEE Std. 929-2000. By its very nature, this test also ensures proper functional operation of the unit after it has been potted.

During an audit of the test process, it was determined that test time per unit was 10 to 15 minutes. A significant amount of time is wasted waiting for the unit to increase output to full power. The slow rise in output power is due to the design of the dc power supply in combination with how the inverter performs maximum power tracking. Without getting into the details, this can be corrected easily by changing to a different type of dc power supply. This should save about 5 minutes from the test time.

A total of 187 units have passed through this test station. Of those, 10 units have failed the test. The most common failure mode is the result of poor or inoperable IR Data Ports. This has been traced back to improper application of RTV on the light pipes during Lid Assembly. About one half of the failed units can be reworked and retested, giving an ultimate yield of about 97.3%.

#### *Hi-pot Test, Test 4*

A total of 177 units have passed through this test station. Of those units there have been zero failures, a yield of 100%.

#### *Total Process Yield*

The total process yield is the number of completed finished units which pass all of the tests divided by the number of units initially started in production. At the time of writing of this report, that number was 177 units out of 252, or 70.2%. However, there remain a number of units still in process which need to be reworked. We expect 40 more units to be completed, bringing the total process yield up to 86.1%.

### 3.8.4 Production Costs

The most important goal of this entire project has been to make significant reductions in the cost and price of the ac module so that ac module PV grid tied systems become more affordable to our customers. At the same time it is important to maintain the quality and reliability of the SunSine<sup>®</sup> ac module.

In the original SunSine<sup>®</sup> 300 ac module, the inverter portion of the unit was entirely manufactured under the control of Omnion on a turnkey basis. Our cost for that inverter was 1.00x.

In the new SunSine<sup>®</sup> ac module, our modus operandi has changed such that we now perform much of the test and assembly of the unit ourselves, with a smaller fraction of the inverter assembly being subcontracted out. The figure below shows a breakdown of the inverter and ac module costs on a per unit basis relative to the cost of the SunSine<sup>®</sup> 300.

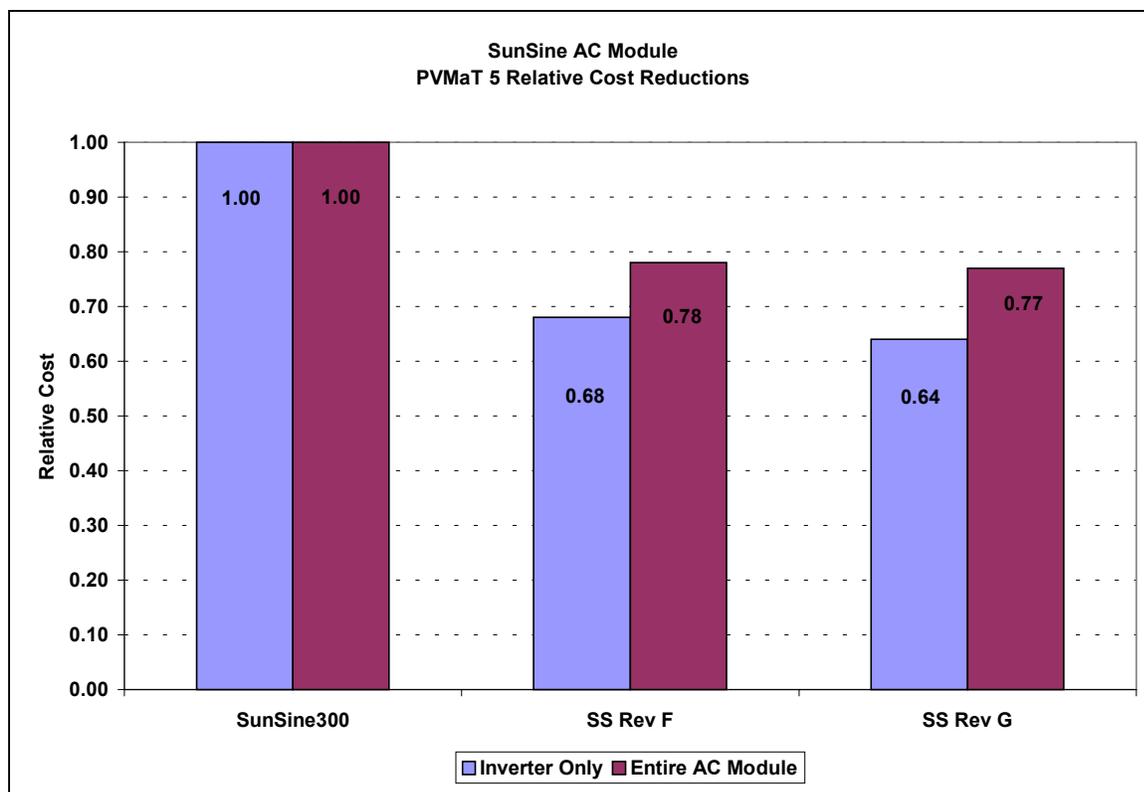


Figure 13. SunSine<sup>®</sup> ac module, inverter and module cost reductions relative to the original SunSine<sup>®</sup> 300 design.

The pilot production run is labeled as ‘SS Rev F’. The cost to produce the new SunSine<sup>®</sup> inverter is 68% that of the cost for the original SunSine<sup>®</sup> 300, a drop of 32%. When combined with the total costs to produce the ac module, this represents a drop of 22% in cost of the entire ac Module. An additional 4% drop in inverter cost is anticipated for the next inverter run, revision G. So that the final inverter cost is anticipated to have been reduced 36% from that of the SunSine<sup>®</sup> 300 design.

### 3.8.5 Quality and Ease of Manufacture

The only significant problems we have had with respect to ease of manufacture and quality have been at the contract manufacturer (CM) building the Power Boards. In that case, the CM was a startup operation where our boards were the very first boards built on a brand new production line. Since these boards were built, the CM has decided to return all of the production line equipment and change over to yet another brand of production line equipment. Because of the problems we have had with this CM, we are in the process of changing CMs to one with a mature production process and well-established quality procedures.

The one thing that we cannot do ourselves and must contract out is that of building the Power Boards. The capital cost of a production line can be anywhere from \$1M to \$2M per line, and requires a very particular expertise that does not exist within our company.

### 3.8.6 Production Time

Outside of the items that are subcontracted, our total labor content per unit is 0.75 MHs. This breaks down as 0.25 MH for the calibration and IEEE 929 testing and 0.50 MH for the assembly of the inverter onto the PV laminate. An additional 0.35 MH would be needed for potting the Lid Assembly, but up to now that has been done at the CM.

### 3.8.7 Task 8 deliverables completed

- D-2.4 Deliver final SunSine<sup>®</sup> ac modules to Sandia and NREL for testing.
- D-2.5 Deliver pilot production report.

### 3.8.8 Task 8 Results Summary

- Initial pilot production of 110 units was completed and shipped.
- Inverter production costs reduced 32% in the pilot production run.
- Inverter production costs anticipated to be reduced a total of 36% in future production runs.

## **3.9 Task 9 – Manufacturing Test Fixtures**

Two test fixtures are used in the process, a functional test fixture for the inverter power boards and a calibration and IEEE 929 test fixture for testing the inverter lid assemblies.

### 3.9.1 Power Board Functional Test

The requirements of this test evolved during the 2½ years of this project. The purpose of this test is to determine if the SS325 Power Board is working properly or not. The test consists of mounting a Power Board on the test fixture. It is then connected to appropriate power supplies and a transformer. A Hand Held Controller (HHC) is used to communicate with the diagnostic features of the Power Board and is used to control the unit under test. An oscilloscope is connected for observation of the output current waveform of the inverter.

The test begins by turning on dc power to the unit. HHC communications is established over the IR Data Port. 12 dc voltages are probed and recorded from the unit under test. These voltage readings provide indication of proper operation of various parts of the board under test. ac power is then turned on. The red LED should then come on solid. Six ac voltages are probed and recorded, again to ensure proper operation of portions of the circuit. HHC commands are then entered to jump start past the 5-minute turn on delay to get the board to start dc/ac power conversion. Output current is then observed to rise to a predefined level with the correct number of LED flashes and the sine wave as observed on the scope is checked. ac and dc power is then turned off. If all indications were within specified limits, the unit passes and moves on to the next step in the process. If indications were not normal,

then some further inspection of the board is performed to determine the cause of the problem and corrected if possible followed by a retest.

Since a number of voltages are probed from the board, a bed of nails test fixture was built, see Figures 14 and 15. However, we were unable to get the fixture pins to line up properly with the test points on the board. One problem we had was that the test points were on the bottoms of vias. If there were a small deviation, as small as 0.010", the test point would enter the via hole as the board was placed, but then be pulled off center. Eventually this would cause the pin to stick and no longer provide proper spring action. Because time was short, and customer shipments were already overdue, we decided to go to a manual hand probing approach. In this case the person doing the test would probe by hand the signals that needed to be measured. At least the number of points being probed was manageable -- only 18 points.

Another reason we attempted to build the bed of nails test fixture ourselves was that the contract manufacturer (CM) chose not to provide that service after initially indicating they could. But startup problems at the CM kept delaying work on such a fixture until it was too late to shop out the work, so we made an attempt at building the fixture.



Figure 14. Bed of Nails Test Fixture with board.



Figure 15. Bed of nails test fixture, close up.

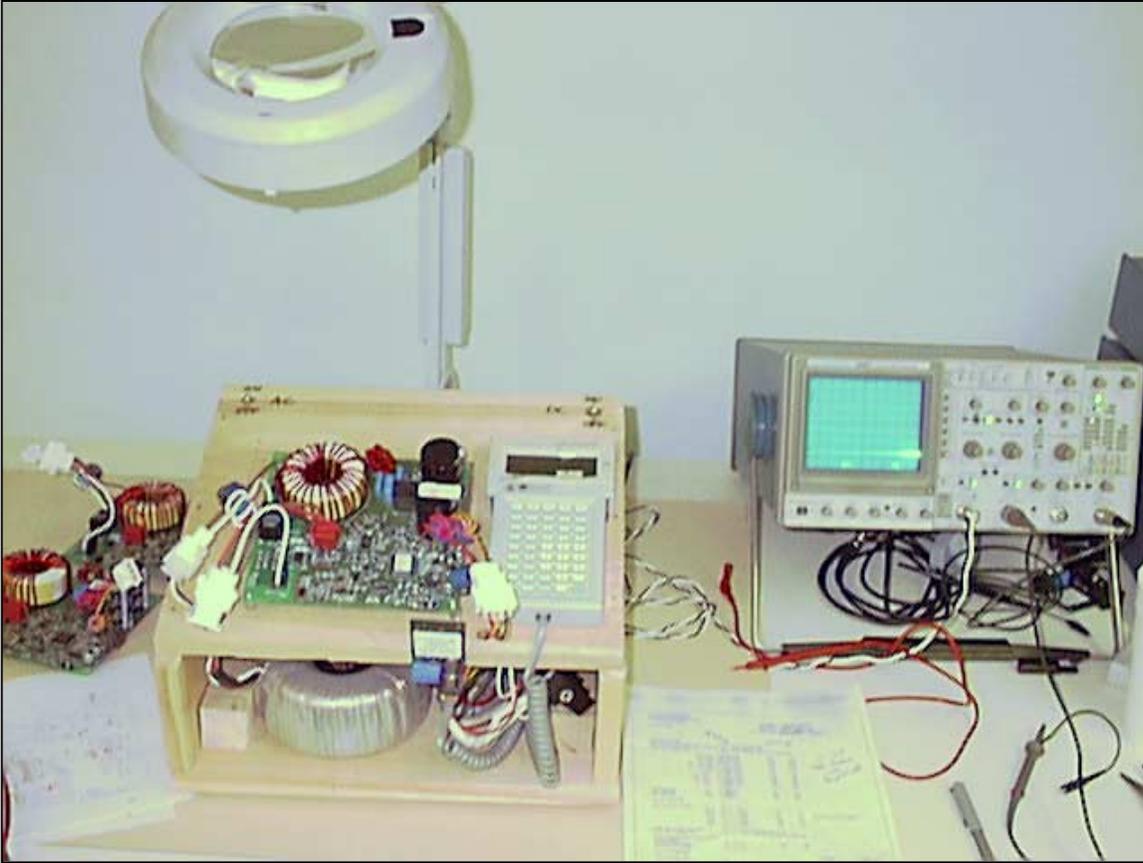


Figure 16. Functional Test Station.

Figure 16 shows the final functional test station setup. The setup includes a power supply in the bottom of the box, a hand held controller for communication with the power board and a scope for viewing the output current waveform. Some of the information below was also provided in the D-2.5 Pilot Production Report, but is copied here for convenience due to its relevance.

As of this report, a total of 252 boards have been tested through this station. Of those, 197 have passed this test and 55 have failed. This indicates a yield of 78.2 percent up to this point. The boards that failed this test have been reviewed and the failures can be categorized as follows.

- 26 Obvious Assembly Process Errors. This is 10.3% of the total and is typically one of the following problems.
  - Component in backwards.
  - Wrong value component used, such as a resistor.
  - Missing component.
  - Component not properly placed on the pads.
  - Circuit board defects.
- 20 Probable Assembly Process Errors. This is 7.9% of the total. These are cases where one or more components on the board have failed. It is believed that these are mostly failures caused by lack of proper static precautions that have caused the components to fail.
- 3 Design Errors. This is 1.2% of the total. This is a known error that has been incorporated into the next revision of the Power Board and can be fixed on these boards as well by changing one component value.
- 6 TBD. This is 2.4% of the Total. In these boards the cause of failure has not been determined.

Most of these boards can be repaired and sent back through the test so that the ultimate yield should approach 92 percent.

Certainly it would be preferable to reduce or eliminate the first two error modes. Changes to the entire process are being considered so that higher yields, and ultimately lower costs can be achieved. But those changes are outside the scope of the NREL contract and will be considered as we move forward with our next production run.

### 3.9.2 Inverter Calibration and IEEE 929 Test

The lid assembly is calibrated to ensure accurate ac voltage measurement, ac current measurement and clean sine wave operation. In addition, voltage and frequency trip tests are conducted to ensure compliance with IEEE Std. 929-2000. By its very nature, this test also ensures proper functional operation of the unit after it has been potted.

During an audit of the test process, it was determined that test time per unit was 10 to 15 minutes. A significant amount of time is wasted waiting for the unit to increase output to full power. The slow rise in output power is due to the design of the dc power supply in combination with how the inverter performs maximum power tracking. Without getting into the details, this can be corrected easily by changing to a different type of dc power supply. This should save about 5 minutes from the test time.

A total of 187 units have passed through this test station. Of those, 10 units have failed the test. The most common failure mode is the result of poor or inoperable IR Data Ports. This has been traced back to improper application of RTV on the light pipes during Lid Assembly. About one half of the failed units can be reworked and retested, giving an ultimate yield of about 97.3%.

### 3.9.3 Burn In Testing

Burn-In testing is not done on the SunSine<sup>®</sup> inverter for two reasons. First, we have found no data from industry colleagues or vendors, which indicate that burn-in testing would weed out potential product failures. In fact, most contract manufacturers today do not do any kind of burn-in testing. We are told that the main reason why burn-in testing is no longer common practice is that the quality of components has increased significantly beyond that of years ago when burn-in testing was more common.

The second reason for not doing burn-in testing is one of time and cost. A burn-in test station was used for the SunSine<sup>®</sup> 300 inverters. The station cost about \$10k and could test ten inverters in eight hours. This was a real bottleneck in the production process, and so it was decided the best thing to do was simply to eliminate that test.

### 3.9.4 Hi-pot Testing

Hi-pot testing is applied to the inverter to ensure a sufficient amount of insulation/isolation is provided between the dc input, ac output and chassis ground. Our hi-pot test involves application of 1200 Vac for a minimum of one second between the two circuits being tested. If an excess amount of current is drawn, typically 5mA, it indicates a breakdown in the electrical insulation in the product and is a fail condition. This is a very common test applied to most all UL Listed products. There is no specific test fixture required for the test so no photograph is provided. Hi-pot testing is done on the inverter lid assembly, and on the final finished unit's ac output. The UL requirements for hi-pot testing are provided in UL 1741.

### 3.9.5 Task 9 deliverables completed

D-2.6 Deliver test fixture report.

### 3.9.6 Task 9 Results Summary

- A functional test fixture was developed for testing the SunSine<sup>®</sup> inverter power boards.
- A calibration and IEEE 929 test fixture was developed for testing the SunSine<sup>®</sup> inverters.

### **3.10 Task 10 – Development of New, Lower-cost Quick Connectors**

A new lower cost quick connector was needed for the SunSine<sup>®</sup> ac module. The macro pulse connectors which had been used were expensive, had some technical weaknesses, and the company that made them was very difficult to work with putting the supply of connectors in question. A search was conducted to determine if a suitable connector could be found from existing connector companies.

All of the connectors that were found were designed to have a power source on one end and a load on the other. This is the common ac power application for outdoor power connectors. In that application, only one side of the connector system need to have the conductors guarded from inadvertent human contact. In our application with ac modules, there is a power source at both ends of the connection. In this case, both sides of the connector need to be guarded. One problem that exists with the macro pulse connectors is the snap lock ring on the outside of the connector. This part is made with plastic and has an internal spring mechanism to engage the snap lock. This mechanism is subject to damage, and once damaged, the entire cable must be replaced. The cost and inconvenience to replace a cable is quite high and so we were motivated to find a more reliable means of connection.

In conducting the search of connector companies, we found one company who was interested in modifying their existing product line to meet our special needs. That company is Lumberg. In addition to solving the two problems listed above, our cost for the new connector is now 48% less than the macro pulse connector system. Another added benefit is that the cable used by the Lumberg connector uses a smaller wire gauge and is a more flexible cable, making it easier to work with. The macro pulse cables used 12 AWG wire and were very stiff and harder to work with. The new Lumberg cables come with a European wire size, which is between 16 and 14 AWG, and is quite appropriate for use in small ac module systems. Larger ac module systems will need ac source circuit combiner boxes with fuses to step up to larger branch circuit wire gauges. Finally, the new Lumberg connector comes with a more rugged Aluminum coupling ring. Figure 17 is a view of the new Lumberg connectors.



Figure 17. The new Lumberg ac module connector system.

### 3.10.1 Task 10 deliverables completed

D-2.7 Deliver prototype of connectors to NREL.

### 3.10.2 Task 10 Results Summary

- A new ac module connector design completed with 48% cost reduction over the previous design.

## **3.11 Task 11 – HALT Verification Testing of Pilot Production SunSine® ac Module Inverters**

This was the second and final HALT test performed during this project. The only significant destructive failure found during HALT testing of the SunSine® inverter power board was an internal failure in the large electrolytic filter capacitors. This failure mode was precipitated by application of vibration stress of approximately 20 Grms. No other relevant destructive failure modes were found.

HALT testing is not designed to provide data to indicate how long a product will operate under normal conditions, sometimes called mean time between failure, MTBF. However, one possible failure mode of the inverter is loss of electrolyte in the large storage capacitors. Using models built from empirical test data and historical PV system performance data, we estimate capacitor life to be 26.7 years. Our goal was to achieve a capacitor life of at least 20 years.

We believe based upon these tests that this inverter design is fairly mature and void of significant defects. It will continue to be our challenge to ensure a production process that provides a stable and high quality product, with solid performance with respect to reliability.

### 3.11.1 Power Board Revision G

The changes incorporated in Power Board revision G are as follows.

The board thickness was increased from 0.062” to 0.125”. The reason for this is that the thinner board had too much flex because of the heavy power components attached to the board. Since most of the parts on the board are surface mount, there was some concern that excessive flexure of the board would cause cracks in either the components or the solder bonds to the board. No direct evidence was found to support this theory, but the company felt it would be best to take a conservative approach here.

Footprints for some of the surface mount diodes were not properly sized for the diodes. The result was that it was more difficult to achieve a good solder bond between the diodes and the board. The footprints for these parts were enlarged to allow for a greater tolerance in part placement and to allow for a better solder fillet to be achieved.

Vias located on component pads were interfering with the smooth application of solder paste. Therefore, all vias were moved so that there no longer are vias on any of the solder pads, preventing interference with the paste operation.

An attempt was made to build a bed of nails fixture for the Power Board to aid in functional testing of the boards. This attempt failed due in part to the fact that test points were collocated with via holes. In those cases any small error in location of the test point pin and the via hole would cause the pin to bend when the board was placed on the test fixture. Because of this, it was decided to remove via through holes from the test point locations. Test points were also enlarged from 0.050” diameter to 0.075” diameter and placed on a 0.025” grid with greater clearance from other test points or features on the board. All test points are located on the bottom side of the board so that a single sided test fixture may be used for probing the test points.

Via hole sizes were reduced from 0.040” to 0.028” and were tented over by solder mask. The purpose of this is to aid in vacuum pull down during bed of nails testing.

There were two ECOs applied to the version F boards. One was to increase the power rating of one of the power supply resistors and the other was to add a Vcc supply supervisor circuit for the microprocessor. Those changes had been added to the boards by hand in version F. For version G, those components were changed to surface mount components and added to the board design, thus easing the assembly process.

### 3.11.2 Highly Accelerated Lifetime Testing (HALT)

HALT is a testing protocol applied to a product to uncover potential failure modes in a fairly short amount of time. Ideally, the goal is to get the product to perform to the fundamental limits of technology, FLT. Extreme stresses are applied to the product in order to bring out failure modes far quicker than they would otherwise occur under normal operating conditions. The goal is NOT to replicate the stress environment that the product sees under normal use. Because of this, HALT testing itself does not provide a quantitative means of determining expected product lifetime under normal use conditions.

One of the results of the HALT testing will be a determination of the operating and destruct limits of the product under each of the static stresses, cold step, hot step and vibration. The definition of those two limits is as follows.

#### *Operating Limit*

If an operating limit is exceeded, the product will no longer be expected to operate normally. If the applied stress is then reduced to be within the operating limit, the product will return to normal function.

#### *Destruct Limit*

If a destruct limit is exceeded, the product is no longer expected to operate normally. If the applied stress is then removed and brought within the operating limits, the unit will still no longer continue to operate normally. This is a limit beyond which the product is not expected to recover.

Operating limits are normally found before reaching destruct limits. But in some cases operating and destruct limits will be the same.

The basic HALT test process consists of the following steps. The stresses are applied in an order of what is typically least destructive to that, which is typically most destructive so that the most test time can be obtained from each test sample.

#### *Cold Step Stress*

The product is placed in a temperature chamber where air temperature and product temperature can be controlled. High rate airflow ducts are directed onto the product to allow for rapid and accurate control of product temperature. In our case the product temperature sensor was located directly on the main microprocessor in the middle of the board. The product temperature is lowered in 10°C increments with a dwell of 10 minutes at each temperature. The product is continually monitored to determine if it is operating normally or not. The cold step testing continues until either the product reaches a destruct limit or the limit of the chamber is reached. The chamber limit is -100°C.

### *Hot Step Stress*

This test is similar to the cold step stress except that temperature is increased by 10°C increments until either the product reaches a destruct limit or the limit of the chamber is reached. The chamber limit is in the range of +150°C to +200°C, well above the expected limits of our product.

### *Rapid Thermal Transitions*

Hot and cold setpoints are determined which are slightly inside the upper and lower temperature operating limits. The test begins at room temperature then the product is cooled to the lower setpoint. The product temperature can transition as fast as 60°C per minute during the ramp down to the cold setpoint. The product then dwells at this setpoint for 10 minutes after which the product is heated up to the high temperature setpoint. Again the rate of change of temperature can be as high as 60°C per minute during this transition. Again, the product dwells at this high temperature setpoint for 10 minutes. One cold and hot dwell with two transitions constitutes one cycle. Multiple cycles are performed, typically five. During this test the product is monitored continually to determine if it is operating normally or not.

### *Vibration*

The vibration step stress is done at room temperature. A six-axis shaker table is used to apply the vibration stress. The vibration includes both linear motion as well as rotational motion, and that is how 6 degrees of freedom are achieved. The product is rigidly fixtured to the table to ensure good energy transfer from the table to the product. The vibration setpoint is controlled via a feedback sensor directly attached to the table. The setpoint is an RMS measurement with a bandwidth of about 2kHz. The product response is measured with three separate acceleration sensors, one for each linear axis. The response of those sensors is recorded at various table vibration setpoints. Just like with the hot and cold step stresses, vibration is increased in predefined steps with a 10 minute dwell at each step.

### *Combined Environment Stress*

Combined environment combines hot and cold temperatures with high thermal transitions and vibration. The rapid thermal transition profile is followed, with an initial vibration setpoint of 0 Grms. At the beginning of each cycle, the vibration is increased by a fixed amount. This continues until the product fails.

### 3.11.3 Product Monitoring

During the testing the product was monitored for normal operation as follows. The output current waveform was monitored on an oscilloscope. The output current was also monitored for conducted EMI through a LISN and Spectrum Analyzer. Output current THD was monitored with a BMI Power Profiler. Input dc voltage and current were also monitored. Communication with the power board was also monitored over the IR Data Link using a Hand Held Controller. This data link provided diagnostic information such as board temperature, programmable setpoints and other internal diagnostic data. A number of signals were connected to a data logger, which recorded six voltages on the power board itself. Twenty signals from the board were brought out to a switch box and connected to the oscilloscope for visual inspection.

We believe that monitoring of this many signals from the product gave us a very high level of test coverage. We could see when signals were beginning to drift, well before normal operation of the unit was affected. Access to these signals also gave us the ability to determine possible root cause of failure in some cases while the unit was exhibiting abnormal operation. Many times, it can be very difficult to determine root cause after the fact when the unit is sitting on the bench.

### 3.11.4 Number of Test Samples

During this testing there were a total of five test samples used. Three of those test samples were bare Power Boards and two of the test samples were Power Boards potted in the Lid Assembly. Generally, the way the testing goes is one test sample is placed in the chamber and testing continues until that unit reaches a destruct limit. At that point, the unit is removed and another test sample is placed in the chamber. In the mean time, the unit that failed is debugged and repaired if possible. Over the course of four days of testing, all five test samples were taken to a destruct limit. The four days of testing was completely used, otherwise we might have used even more test samples.

Bare board test samples were used in this testing for several reasons. First, it is not the intent of the testing to replicate actual operating conditions. Second, it is much easier to debug and repair bare boards rather than potted samples. Third, we believe that the potting material acts to protect the boards and therefore would mask potential failure modes during the testing. Instead, our intent was to find as many possible failure modes as possible. Near the end of the testing, we then used the potted test samples just to verify that the potting did not add any additional failure modes beyond what had already been found with the bare boards.

### 3.11.5 Results

During this testing the following operating and destruct limits were found.

SunSine <sup>®</sup> Power Board HALT Test Results		
Temperature	Lower Destruct Limit	< -100°C
	Lower Operating Limit	-90°C
	Upper Operating Limit	+100°C
	Upper Destruct Limit	>+120°C
Vibration	Upper Operating Limit	15 Grms 40 Grms <sup>1</sup>
	Upper Destruct Limit	25 Grms > 40 Grms <sup>1</sup>

Note 1. With the large filter capacitors isolated from the vibration.

These limits were found using the bare board test samples. The low temperature destruct limit was not found because -100°C is the limit of the test chamber. The inverter continued to operate at that temperature, but not within specifications. We were not able to determine the upper temperature destruct limit because when the unit reached +120°C, the inverter function ceased to operate. We were unable to mask the cause of that operating limit and so hot step stress testing was stopped.

During vibration, we found that the large filter capacitors failed at 25 Grms. The failure was that the capacitors would form an open circuit somewhere on the inside of the capacitors. We believe this is a fundamental limit of technology for this model of capacitor. The large capacitors (C48,C49) were then removed from the board and mounted in a location free of vibration stress. They were wired to the board so the board could continue to operate. Testing was then continued up to 40 Grms to see if there were any other components on the board susceptible to vibration stress. Testing was stopped at 40 Grms because time was needed to continue the rest of the test protocol.

SunSine <sup>®</sup> Power Board HALT Test Destruct Failures	
<i>Serial No.</i>	<i>Failure</i>
BDR0042001	C48, C49 internal open circuit at 20 Grms.
BDR0042002	C48, C49 internal open circuit at +90°C 12 Grms during combined cycle testing.
BDR0042003	C48, C49 internal open circuit at 20 Grms.
BDR0042004	D25 solder joint failure, at +80°C 12 Grms. This was a potted unit.
BDR0042006	Test fixture signal wires melted causing unit to fail during combined cycle testing when air temperature of chamber overshoot to +150°C. This was a potted unit.

Only one of the destruct failures listed above is significant, namely open circuit failure of the large capacitors, C48 and C49. The failure of the D25 solder joint was due to insufficient use of solder during soldering of the component. This is not relevant because these test samples were prepared manually in the Boulder lab and do not reflect the production soldering process. The last failure mode, that of melting of the test fixture wires, is also not relevant. Those wires were only present for monitoring of signals from the Power Board and are not normally present in the product. It is unfortunate that the two failures found while testing the potted units were both artifacts of manual preparation of the test samples and are not reflective of the product itself.

In all cases, after the HALT testing had been completed, the test samples were repaired and resumed normal operation. In this way, we know that there were no other destructive failures imposed on the test samples.

### 3.11.6 Expected Product Lifetime

HALT testing itself actually provides no data from which to determine product lifetime or mean time to failure. That is not the purpose of HALT testing. However, one of the possible failure modes of the product is a loss of capacitance in the large filter capacitors, C48 and C49, due to evaporation of electrolyte. This failure mode is well understood to be temperature dependant. As temperature rises, the rate of evaporation increases as well. It was our goal to choose capacitors that would have at least a 20-year life in even the most extreme system environments. Data was collected on operating units and correlated to ambient air temperature and POA irradiance. From this data a model was developed to predict capacitor temperature given wind speed, POA irradiance and ambient air temperature. This model was then applied to one year of data from a single-axis tracking system located in Tempe, Arizona. Based upon this model, it was found that in one year of operation, the capacitor would lose 3.75 percent of life due to loss of electrolyte. This correlates to an expected life for the capacitors of 26.7 years.

Most real world applications will not be as severe as the Tempe single-axis tracker and so even longer life should be expected from the capacitors. It should be noted that this failure mode of the capacitors is NOT the same as the failure mode found during the HALT testing. HALT testing does not predict how long it would take for the vibration failure mode to show up in real world conditions.

### 3.11.7 Task 11 deliverables completed

D-2.8 Deliver HALT test report.

### 3.11.8 Task 11 Results Summary

- HALT testing was completed on five samples of the final SunSine<sup>®</sup> inverter power board, revision G.

#### 4.0 Patents Pending

During the course of this project, two patents were applied for that apply to the SunSine<sup>®</sup> ac module. One is on the functional design of the SunSine<sup>®</sup>'s enclosure, and the other is on methods associated with the utility interface. The nature of the patent process is that it takes 12 to 24 months to find out if an application is approved and issued as a patent. Since the outcome of the patent application process is not guaranteed, we have chosen not to disclose the specific content of those patents.

#### Addendum

During the fall of 2000 and through the spring of 2001, SunSine<sup>®</sup> ac modules have been shipped and installed in the following locations:

<b>State Where Installed</b>	<b>Number of SunSine<sup>®</sup> ac modules</b>
Arizona	5
Colorado	1
Hawaii	8
Kansas	1
Massachusetts	98
Maine	1
New Jersey	1
New Mexico	1
New York	22
Oregon	16
Texas	42
Wisconsin	18
Total	214

# REPORT DOCUMENTATION PAGE

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13. ABSTRACT ( <i>Maximum 200 words</i> ) This project was a two-phase effort consisting of technical research and manufacturing development to improve and reduce the costs of the SunSine <sup>®</sup> inverter. Research addressed packaging, soft switching, circuit optimization, manufacturing process improvements, and pilot production manufacturing. Significant cost reductions were achieved. The main goal of this project was to reduce cost and improve the manufacturability and reliability of the SunSine <sup>®</sup> ac module, which consists of a SunSine <sup>®</sup> inverter mounted on an ASE Americas PV laminate. This work has also boosted the performance and enhanced marketability by adding customer-valued features. Ascension Technology has accomplished these advancements by cost reductions or design modifications in the following areas: Die-cast aluminum enclosure and base plate; soft switching for cost reduction and efficiency gains; circuit board and component optimization for performance gains and size reduction; streamlined inverter assembly and production testing; and streamlined inverter/module assembly. As a result of the effort in these areas, Ascension Technology's objectives were to achieve the following: 40%-50% reduction in inverter manufacturing costs; 40% reduction in inverter size from 169 to 100 square inches; 4% increase in peak inverter efficiency from 87% to 91% at full power; UL listing, FCC certification; establish a production capability of 5000 SunSine <sup>®</sup> inverters/year through manufacturing improvements and production-line design improvements; less than 1 failure per 1000 units at time of installation/turn-on; a 5-year warranty; and a rating of 250 W <sub>ac</sub> at PTC for the SunSine <sup>®</sup> ac Module. Accomplishments during this project include: Inverter production costs were reduced 32% in the pilot production run; inverter production costs anticipated to be reduced a total of 36% in future production runs; 45% reduction in inverter footprint (in contact with module) from 169 to 93 square inches; and a 2.3% increase in inverter efficiency from 85.7% to 88.0% at full power. In addition, the SunSine <sup>®</sup> ac module is UL listed, meets IEEE Std. 929-2000, IEEE-C62.41-1991, IEEE-C62.45-1992, and NY State SIR requirements, and was verified to comply with FCC Class B EMI limits. There were 4 failures per 214 units at time of installation/turn-on; a 5-year inverter warranty is offered; and a rating of 235 W <sub>ac</sub> at PTC for the SunSine <sup>®</sup> ac module was achieved.				
14. SUBJECT TERMS: PV; module scale inverter; utility-compatible ac power; ac module; soft-switching; SunSine			15. NUMBER OF PAGES	
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