CONTRACTOR REPORT

SAND97-0329
Unlimited Release
UC-1290

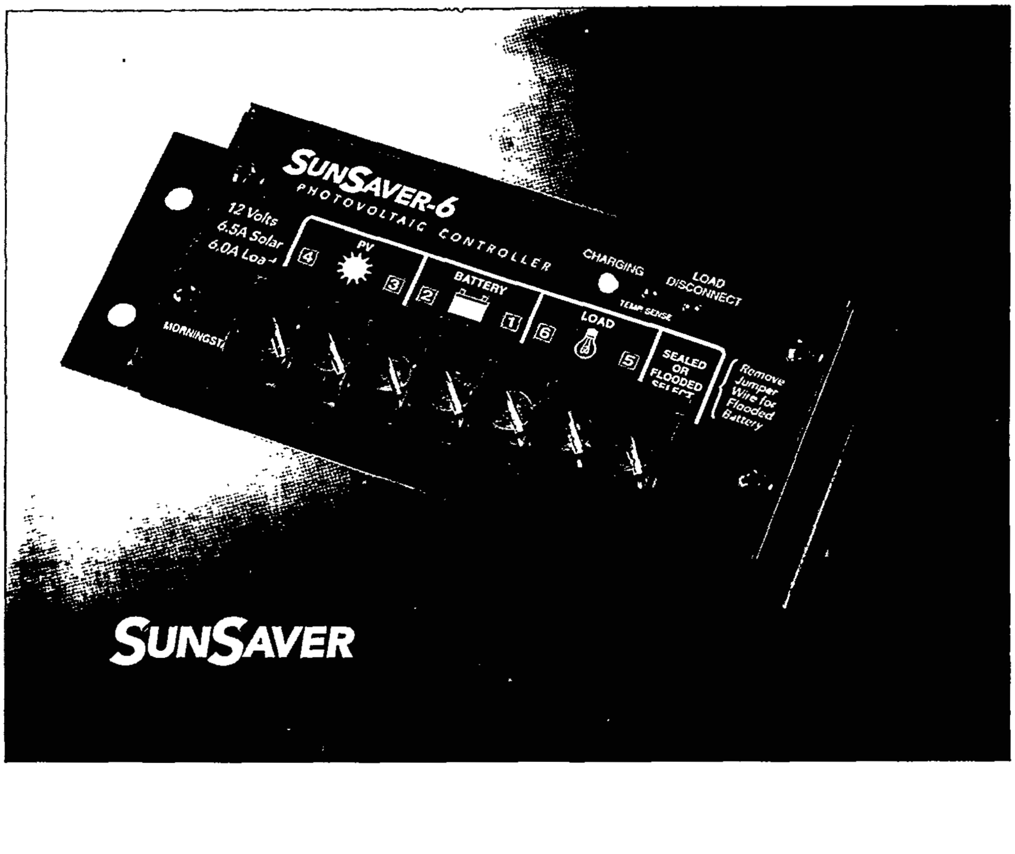
A Pulse-Width Modulated, High Reliability Charge Controller for Small Photovoltaic Systems

Kenneth Gerken
Morningstar Corporation
2911-A Olney Sandy Spring Rd.
Olney, Maryland 20832

Daniel Welsh, PhD, P.E.
Morningstar Corporation
2311 Ninth Street
Encinitas, California 92024

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of Energy
under Contract AM-9938B

Printed February 1997



Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal Rd
Springfield, VA 22161

NTIS price codes
Printed copy: A04
Microfiche copy: A01

DISCLAIMER

SAND97-0329
Unlimited Release
Printed February 1997

Distribution
Category UC-1290

A Pulse-Width Modulated, High Reliability Charge Controller for Small Photovoltaic Systems

Kenneth Gerken
Morningstar Corporation
Olney, Maryland

Daniel Welsh, PhD, P.E.
Morningstar Corporation
Encinitas, California

Contract # AM-9938B

Abstract

This report presents the results of a development effort to design, test and begin production of a new class of small photovoltaic (PV) charge controllers. Sandia National Laboratories provided technical support, test data and financial support through a Balance-of-System Development contract. One of the objectives of the development was to increase user confidence in small PV systems by improving the reliability and operating life of the system controllers. Another equally important objective was to improve the economics of small PV systems by extending the battery lifetimes. Using new technology and advanced manufacturing techniques, these objectives were accomplished. Because small stand-alone PV systems account for over one third of all PV modules shipped, the positive impact of improving the reliability and economics of PV systems in this market segment will be felt throughout the industry. The results of verification testing of the new product are also included in this report. The initial design goals and specifications were very aggressive, but the extensive testing demonstrates that all the goals were achieved. Production of the product started in May at a rate of 2,000 units per month. Over 40 Morningstar distributors (5 U.S. and 35 overseas) have taken delivery in the first 2 months of shipments. Initial customer reactions to the new controller have been very favorable.

CONTENTS

LIST OF FIGURES

ABBREVIATIONS

ASIC	application-specific integrated circuit
BOS	balance-of-system
CAD	computer-aided design
CE	European mark of conformity
CQI	continuous quality improvement
EMC	electromagnetic compatibility
EMI	electromagnetic interference
FET	field-effect transistor
FITS	predicted values from a regression equation
FSEC	Florida Solar Energy Center
GENRAD	brand name for computer tester
HTRB	high temperature reverse bias
IC	integrated circuit
LVD	low-voltage load disconnect
MCM	multichip modules
MOSFET	metal-oxide-semiconductor field-effect transistor
MOV	metal-oxide varistors
MTBF	mean time between failure
MTS	temperature sensor
PCB	printed circuit board
PV	photovoltaic
PWM	pulse-width modulated
SHS	solar home systems
SMD	surface-mount devices
SMT	surface-mount technology
SOC	state-of-charge
THT	through-hole technology
TQM	total quality management
TVS	transient voltage suppressor devices

EXECUTIVE SUMMARY

Small stand-alone photovoltaic (PV) systems account for over one third of all PV modules shipped today. These one and two-module systems form the foundation for the commercial PV market, and most people are familiar with PV by way of these small systems.

A development project to advance the technology for small PV charge controllers was awarded to Morningstar under the U.S. DOE Balance-of-System Development Program - Phase 2. The two major objectives of this development project were to:

- increase the reliability of small PV controllers
- reduce the operating costs of small PV systems

Although charge controllers are responsible for only 5% of the PV system cost, they are the most complex system component and the most troublesome. More important, the charge controller has the most impact on the operating life of the battery. An improved PV controller can reduce the 20-year costs of a PV system by 20% to 40%.

The opportunity to produce a high quality PV charge controller at globally competitive costs was available through advanced electronics and manufacturing technologies. Four technical objectives were established to define this development project and measure the results. A summary of each objective follows.

1. IMPROVE RELIABILITY

Virtually all small PV controllers today are very simple devices. Most are built by hand. The high incidence of controller failures is a major concern of system integrators and large users of PV.

For this project, improving the standard of reliability was a prerequisite for success. Sophisticated engineering models were combined with advanced power electronics to accomplish this goal.

A series configuration with 1500-watt transient voltage suppressor devices at the PV and load terminals protects the circuit from lightning and overvoltage transients, which are a primary cause of failure. The other historical failure mode was resolved with a thermal design that prevents the field-effect transistor (FET) switch from overheating. Thus, a large safety margin is provided for harsh operating conditions.

Extensive testing and analysis projects a failure rate for the resulting commercial product, called SunSaver, to be less than 2 failures per 1,000 units, and an operating life in excess of 15 years.

2. EXTEND BATTERY LIFE

As PV cell costs continue to fall, the battery in a stand-alone PV system becomes an increasingly large part of the system costs. Battery life now has the greatest impact on the viability of a small PV system's economics.

A PV system presents a unique and complex challenge for charging batteries. The controller must manage a rapid, yet safe, recharge under a very diverse range of system conditions. The common on/off PV controllers that have been used for 20 years may only maintain a 55% to 60% charge state.

The SunSaver's design incorporates a highly effective pulse-width modulated (PWM) constant voltage charging algorithm. With a 20-mV accuracy and 25-msec response time, the PWM duty cycles are stable under the most extreme conditions. In addition, the controller can be field selected for sealed or flooded batteries, and the battery charging is adjusted for temperature changes.

This unique PWM design results in lower system voltage drops, less heating, and highly effective charging of the battery. Testing has confirmed this to be an ideal charging algorithm for PV batteries. The PWM charging algorithm has significantly increased PV battery capacity compared to traditional on/off charging, and thus should increase battery cycle-life.

3. AUTOMATED PRODUCTION

To meet the reliability and battery charging objectives, up to 37 components had to be added to the design. To remain competitive in international markets, a large initial investment in surface-mount technology (SMT) and fully automated production was required.

A world class ISO 9002 contract manufacturer was selected to produce the SunSaver. The SMT design resulted in a dramatic increase in circuit density and electrical performance, while reducing costs by 35%. Additional cost savings resulted from automated assembly on a Universal SMT line and automated testing with a GENRAD computer station.

Another benefit of this assembly approach is consistently high quality levels. The SMT equipment can place parts at accuracies better than .0006 inch.

4. VERIFICATION TESTING

The design evolved through 15 months of development and testing. The final preproduction prototypes were subjected to extensive circuit and system level testing in the lab and on PV systems.The controllers were also tested in a Morningstar environmental chamber for 800 cycles from -30°C to +85°C. Finally, the SunSavers passed a series of rigorous electromagnetic interference (EMI) tests to be certified for the Eurpean Mark of Conformity (CE).

As detailed in the report, the design that resulted from this development program accomplished each technical objective. The resulting commercial product, the SunSaver, advances the technology, value and performance of small PV controllers up to the level of the PV modules.

The product started shipping in May 1996 at a rate of 2,000 units per month. Over 75% of the new controllers are shipping directly overseas. Initial market reaction has been very positive.

1.0 INTRODUCTION

This report presents the results of a development project to advance the technology for small PV system controllers. The cost-shared development project was awarded to Morningstar under the U.S. DOE Balance-of-System (BOS) Development Program - Phase 2. The purpose of Phase 2 of the Program is to increase the reliability of BOS equipment and reduce the operating costs of PV systems.

The charge controller in small stand-alone PV systems is the primary driver of system reliability and battery life. An advanced controller will affect the system performance more than any other component, and an improved controller can potentially reduce 20-year system costs by 20% to 40%.

Small stand-alone PV systems today account for over one-third of all PV modules shipped. Therefore, improvements to the controller will have a positive influence on a major segment of the industry. Because small controllers have lagged behind the dramatic technology gains of the PV modules, there exists an excellent opportunity to increase user confidence and improve the economics for PV systems through new technology.

BACKGROUND

As PV module costs fall, the BOS components become more significant to the total system cost. However, comparatively few resources have been applied to PV system controllers, especially the small controls (rated under 10 amps of PV current).

It is well documented that BOS components in general, and small controllers in particular, suffer from reliability and performance problems. The DOE National Photovoltaics Program Plan points out that "few designs for mechanical or electronic BOS have been optimized for photovoltaics."[1] And, a 6-month worldwide market research effort by Morningstar in 1993 identified PV controllers as the BOS component most in need of improvement.

There are a number of reasons why small PV controllers have not advanced with the rest of the PV industry, which include the following:

- Controllers only account for about 5% of the total PV system cost, so the market for controllers is small (see Figure 1).
- Most small controllers are only simple ON/OFF charge regulators, and most of these are hand-built in local, protected markets.
- PV applications and marketing channels are both highly diverse, so it is difficult to supply "standard" small PV controllers.
- Given the downward cost pressure on PV systems, the market niche for higher cost controllers is very small.

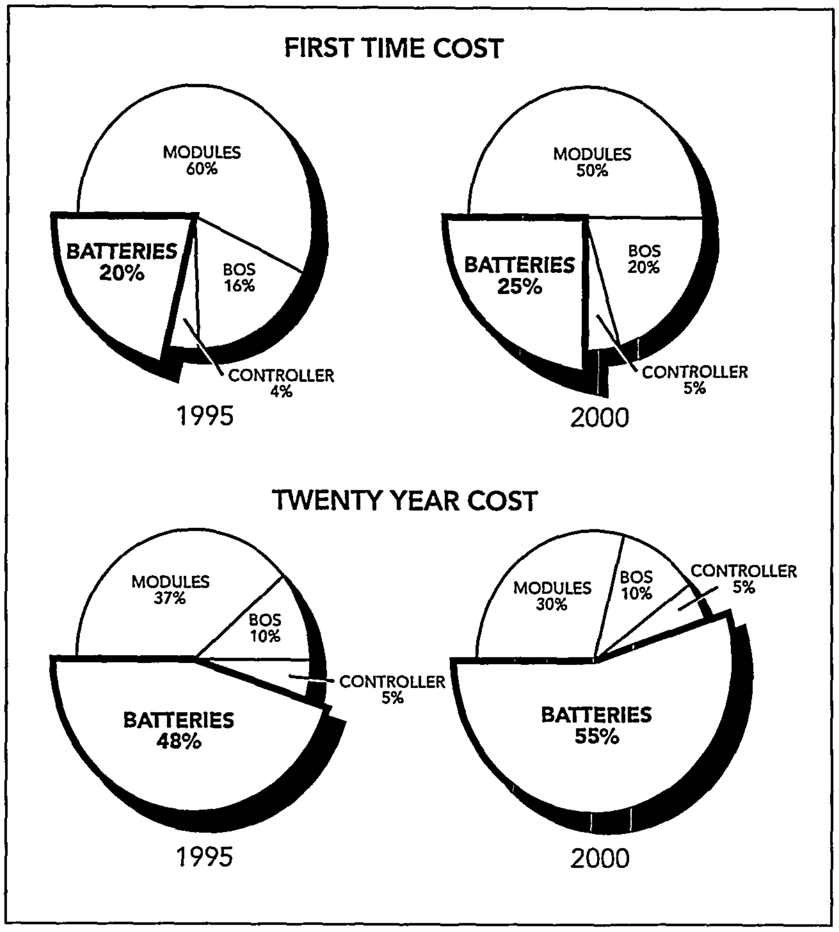


Figure 1. PV System Cost Breakdown.

As noted in Figure 1 above, the battery is rapidly becoming the largest life-cycle cost component in the system. There is a growing awareness of the impact that battery life has on the system economics. Also, as the volume of PV system installations increases, there is a growing emphasis on the high costs to repair or replace failed PV controllers. As PV becomes more widely accepted and the technology matures, users have been demanding more value and quality in their PV systems.

The challenge for this project, therefore, was to improve the quality and performance of small PV controllers without causing an increase in cost. The competitive structure of the international PV markets precludes any increase in the controller price.

TECHNOLOGY OPPORTUNITY

As noted above, most small PV controllers use old technology and are built by hand. Thus, there existed an opportunity to provide a higher quality and higher value controller at competitive prices through technology.

Power electronics and surface-mount devices (SMD) have advanced rapidly in the past few years. Morningstar's preliminary designs for small PV controllers indicated that significant improvements could be achieved at competitive prices using advanced technology, such as SMD and automated production. Morningstar has access to international distribution channels to enable a sufficient volume for automated production.

This development project was awarded to pursue this opportunity. Sandia provided financial support and technical assistance. Sandia's extensive battery/controller test data and experience was invaluable to the development of this advanced controller.

PROJECT OBJECTIVES

The unique operating environment of a PV system requires a highly specialized controller design. The technical objectives were clear, but the costs presented a serious constraint.

Four major technical objectives were defined to ensure the success of this development project. These were measured and tracked closely throughout the 1-year project period. The four project objectives follow:

1. Reliability
   The primary requirement of the design and technology was to reduce controller failures to less than 0.2%, and increase controller operating life to 15 years or more.

2. Extend Battery Life
   The method for battery charging must produce a significant increase in PV battery lifetimes. Improved battery life must be consistent across all diverse PV system applications.

3. Automated Production
   Manufacturing of the product would utilize the latest assembly and test equipment to ensure consistent product quality, and to keep the product cost competitive.

4. Design Verification Testing
   Extensive testing to demonstrate that the objectives and controller performance are achieved. The testing also provides a foundation of performance data for future design evolutions.

PROJECT RESULTS

Each of the project objectives noted above were broken into specific goals to manage all critical areas of the project. All the goals were met or exceeded as demonstrated in the test data. A summary follows.

1. Reliability (Five Goals)
   The design significantly improves lightning and overvoltage protection by adding 1500 watt TVS devices to the PV and load terminals, and by switching in a series configuration (Goals 1 & 2). The third goal produced a thermal design that holds FET junction temperatures under 94°C in worst-case conditions. The environmental design will support a 15-year life (Goal 4). The fifth goal details the calculations and analyses that project a failure rate of less than 0.2% and an operating life of over 15 years.

2. Extend Battery Life (Seven Goals)
   The final design incorporates a PWM, constant voltage algorithm that is much more effective charging a PV battery (Goal 1). Some interesting potential benefits of pulse charging are discussed in Goal 2. A number of charging control parameters necessary for extending battery life are reviewed, and these include a 20 mV accuracy and 25 msec response time (Goal 3), a sealed/flooded battery type select (Goal 4), a standard temperature compensation function (Goal 5), and a solid state LVD feature (Goal 6). Finally, the charging functions that affect the critical finishing charge are presented in Goal 7.

3. Automated Production (Five Goals)
   To maintain consistently high-quality levels and remain cost competitive, five goals were established for the assembly and QA testing. First, a world-class production facility was selected (Goal 1). Then, the product cost was reduced about 35% (Goal 2) by using surface-mount technology (Goal 3) and automated assembly on a Universal SMT line and automated testing on a GENRAD computer system (Goal 4). Finally, the high yields and high quality required to hold costs down require a Total Quality program as discussed in Goal 5.

4. Design Verification Testing (Five Goals)
   Morningstar has a well-equipped test facility that was dedicated to this project. A six-page functional test matrix provided the management tool and record for most non-circuit testing, and the results are discussed. A set of test data is included in the Appendix. The design was also tested at a licensed laboratory and passed CE certification. Finally, environmental chamber testing at Morningstar and other ongoing tests are discussed.

SUMMARY

As described in the following report, the design resulting from the development effort accomplishes each technical objective and goal. The final commercial product, called SunSaver, is an advanced PV controller rated up to 10A. Full specifications and product features can be found in the included SunSaver brochure.

The SunSaver is expected to raise the standards for PV charge controllers up to the level of the PV modules. This will provide a much stronger platform for healthy growth of the PV industry in the critical 1 and 2-module stand-alone segment.

2.0 MAJOR OBJECTIVES

2.1 FIRST OBJECTIVE: RELIABILITY

Due to the remote locations of many stand-alone PV systems, reliability is the first fundamental requirement for a successful system. Today, the balance-of-system (BOS) components are responsible for 99% of PV system repair problems,[2] and in small battery-based PV systems the controller is the cause of most failures.

Morningstar's research indicates that large users must replace about 10 percent of their PV controllers per year due to sudden premature failures. PV system installers and distributors worldwide complain that frequent visits to sites to replace controllers is costing far more than they can afford. As other elements of their PV business mature, warranty work becomes an increasing portion of their overhead.

There are also numerous papers that describe how BOS failures (and controllers in particular) are slowing the growth of PV projects. For example:

- "PV technology has often been touted as reliable and virtually maintenance free. Rightly or wrongly, failures of BOS components are perceived by users and governments as a failure of PV technology."
  The World Bank, Washington, D.C. USA[3]

- "Conservative estimates of the immediate market potential for SHS [Solar Home Systems] in the Philippines give figures of approximately 150,000 units... Technical problems with SHS were observed primarily in connection with failures of the charge regulator. ... the financial viability of the SHS is rather sensitive to the re-investment costs for these components."
  GTZ, Germany[4]

- A new PV controller introduced into the Zimbabwe market in 1994 experienced a 65% failure rate in the first year.
  PV Distributor, Zimbabwe

Therefore, the first major objective of the SunSaver project was to improve the standard of reliability for small PV controllers. Five goals were established to ensure that the critical requirements for reliability were satisfied in the design. These goals were developed to resolve the historical patterns of failures in the field. The first two goals deal with the high levels of exposure to transient overvoltage conditions typical in PV systems. Goal #3 models thermal design factors. The remaining goals discuss protection from harsh environmental conditions and summarize reliability/lifetime calculations.

There are other reliability features of the SunSaver design that are not discussed in this report. These include features such as reverse polarity protection and a 25% overload capability to reduce the failures from abuse and operator error. Details of the circuit design, such as negative traces designed to carry 50 amps of current, are also outside the scope of this report.

The goals discussed below focus on some of the most difficult failure problems with PV controllers. Reliability must be designed into the product to account for all worst-case operating conditions. The overall reliability goal for this development effort was established at 2 failures per 1,000 units and a 15-year operating life. Calculations are provided in Goal #5 to support these figures. The results of the development work are described in the following 5 goals.

RELIABILITY GOAL #1: LIGHTNING AND OVERVOLTAGE PROTECTION

Temporary overvoltages occur in power systems for a variety of reasons, but lightning causes the most severe overvoltages. This is particularly true with PV systems due to the exposed locations and system connecting cables.

Large PV systems typically employ numerous protective elements in the system that may include a lightning rod, an earthing system, shielding of cables, and surge arrestors at various points in the system.[5] However, these protections are seldom incorporated into small 1 and 2-module PV systems.

Because there is less system-level protection, small PV controllers are more susceptible to damage by voltage transients. Overvoltage transients will punch through the gate-source oxide layer of the power switching FETs, and this results in a microscopic hole that permanently destroys the device. In small PV systems, the burden for protection against destructive voltage transients generally falls entirely on the controller.

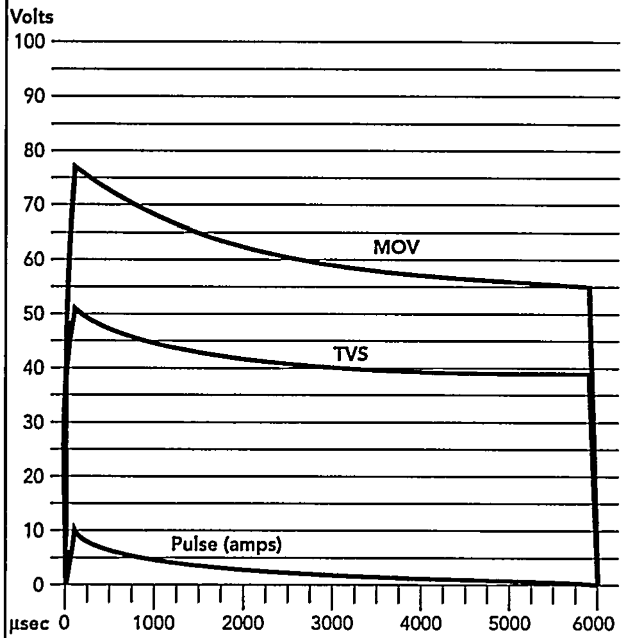
Morningstar market research revealed that large users (e.g., telecom and oil/gas) often replace over 10% of their small controllers each year due to storms. This is unacceptable and indicates that the conventional methods for protecting FETs in small PV controllers are not adequate.

For this project, an analysis was conducted of methods to protect the circuit, and the FETs in particular, from surge voltages. Most small PV controllers use metal-oxide varistors (MOV), and these were compared to a higher cost solution using silicon avalanche transient voltage suppressor devices (TVS). Both devices work by shorting the transient current.

A comparison of TVS and MOV devices was done for the SunSaver design (see Figures 2 and 3). Two-industry standard pulse shapes for moderate lightning were used. The impulse waveform is specified by its rise time and duration, and these pulse shapes are used in industry tests by manufacturers to define device performance curves. Both TVS and MOV devices were selected from the same manufacturer (Semitec[6/7]) to ensure compatible specs for comparisons.

The two devices were first selected for dc standoff voltage. This is the maximum operating voltage before the protection device will begin to conduct. This voltage must be selected for absolute certainty that under all normal operating conditions the protection device will not begin to conduct current to ground (i.e., the standoff voltage rating must be above PV module Voc with all temperature, accuracy, tolerance and aging factors considered).

AT&T Standard



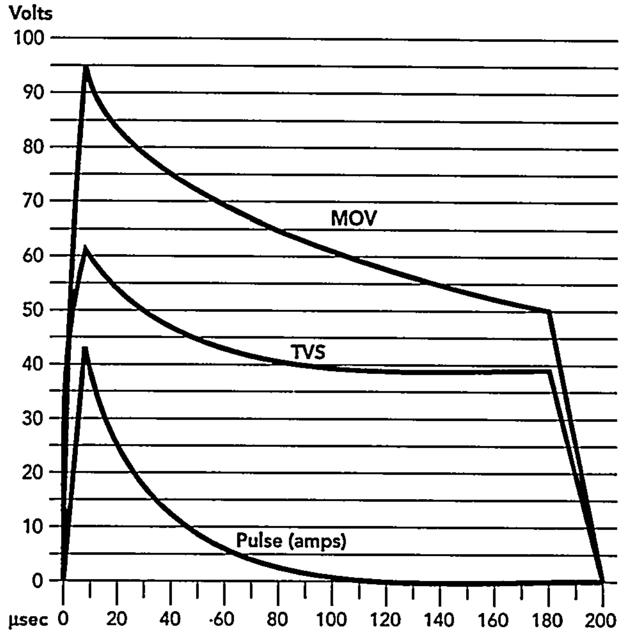
Amps:	Rise	Fall	Peak	Repetitions
	10μsec	1000 μsec	10 amps	3000

Device:	Size	Part Number	DC Standoff Voltage	Max Clamping Voltage
TVS	1500W	Z 6039	31.6V	51
MOV	15mm	Z 15L390	31.0V	77

Time μsec	Pulse amps	TVS volts	MOV volts
0	0.00	0	0
2	2.00	40	60
4	4.00	43	66
6	6.00	46	72
8	8.00	49	74
10	10.00	51	77
200	8.50	50	76
600	6.50	48	73
1000	5.00	45	68
2000	2.50	41	62
3000	1.20	40	58
4000	0.60	39	57
5000	0.30	39	56
5900	0.10	39	55
6000	0.00	0	0

Figure 2. Transient Overvoltage Protection (10/1000 Pulse).

IEC801-5 Level 1



Amps:	Rise	Fall	Peak	Repetitions
	8μsec	20 μsec	43 amps	5

Device:	Size	Part Number	DC Standoff Voltage	Max Clamping Voltage
TVS	1500W	Z 6039	31.6V	61
MOV	15mm	Z 15L390	31.0V	95

Time μsec	Pulse amps	TVS volts	MOV volts
0	0.00	0	0
2	10.00	46	77
4	21.00	52	80
6	32.00	57	86
8	43.00	61	95
12	34.00	59	87
16	27.00	57	82
20	22.00	53	80
40	11.00	47	78
60	5.50	43	70
80	2.50	40	63
100	1.20	39	60
120	0.60	39	57
140	0.30	39	54
160	0.15	39	52
180	0.07	39	50
200	0.00	0	0

Figure 3. Transient Overvoltage Protection (8/20 Pulse).

Having selected the device, the clamping voltage must then be capable of holding the induced transient voltages below the rated damage threshold of the FET. The clamping voltage will increase with larger currents, and the clamped voltage value is given for each of the two defined pulse shapes (i.e., 10 amps and 43 amps).

Finally, the sizes of the TVS (1500 watts) and the MOV (15 mm) were selected as the smallest devices required to meet Morningstar specs. These will handle the majority of lightning events, and only a near-strike would generate enough energy to destroy the device.

SIGNIFICANT CONCLUSIONS:

1. The selected FET (International Rectifier part IRFZ44S or equal) is rated for 60 volts, 50 amps, and 0.028 ohm Rds. The selected FET is also a rugged power metal-oxide-semiconductor field-effect transistor (MOSFET) with an avalanche capability for high dv/dt conditions of microsecond durations.

   For high reliability and long operating life, the circuit design should ensure that transient surges will not exceed 60 volts. In addition, use of 50-volt FETs or FETs without avalanche capability should be considered unacceptable.

2. The 10/1000 pulse is a common test waveform and used in AT&T transient voltage tests. This pulse shape is shown with a rise time of 10 μsec to reach 10 amps. Protection provided for this pulse follows:

   - TVS: Maximum voltage as clamped by the device is 51 volts. There is no chance of FET or TVS failure.
   - MOV: Maximum clamped voltage is 77 volts. This exceeds the 60 volt FET rating by a significant margin. There will also be degradation of the MOV from this pulse, and future pulses will likely reach even higher voltages.

3. The 8/20 pulse is another common test waveform defined by IEC801-5 level 1 specifications. Protection provided for this pulse follows:

   - TVS: It can be seen that the voltage rises to 61 volts at the FET for about 2 microseconds. However, it will be explained in the next section (Goal #2) that the SunSaver series design will limit this voltage across the FET to 49 volts. Again, this is well below the FET rating.
   - MOV: Maximum clamped voltage is 95 volts, which is 35 volts above the FET rating. Further, this overvoltage condition occurs for nearly the entire duration of the pulse, which will fail the FET. There will also be significant degradation of the MOV.

4. MOVs degrade with each transient event. They are made from a zinc oxide material, and the granular interfaces will overheat and begin to short with each transient.[8] When the selected MOV exceeds 77 volts, the damage will be such that the MOV specs are changed by more than 10 percent. The TVS does not degrade with transients.

5. As noted above, a 15-mm size MOV was selected by Morningstar. However, most small PV controllers use MOVs smaller than 15 mm, and these push the clamping voltages significantly higher. For example, a leading German supplier uses a 10-mm MOV, which would increase the clamping voltage for the 8/20 pulse to 110 volts. Another leading supplier uses a 5-mm MOV, which increases the voltage to 120 volts (twice the rating of the FET).

6. Location of the protective device is critical to this analysis. The SunSaver locates transient protection devices virtually touching the terminal posts of the PV and load (note that the SunSaver brochure photos show old prototype boards). The devices are soldered to 2-ounce copper plating on the boards.

   In contrast, a leading Spanish supplier inserts 0.9-inch MOV leads into the terminal block. The resulting voltage induced by the 8/20 pulse will add an additional 10 volts to the MOV clamping voltage.

7. A TVS can theoretically respond to a transient threat in one picosecond. The MOV will turn on in a few nanoseconds. The rise time for an IEC 801-2 pulse waveform is 0.7 to 1 nanosecond. Depending on the characteristics of the transient, the MOV may allow a greater voltage overshoot of 30 to 50 volts.[9]

8. The TVS is a solid-state device with very precise electrical characteristics. However, the tolerances of the MOV with its granular construction are much less accurate.

9. The TVS is rated for 1,500 watts at the 10/1000 pulse, and this rating increases to 18,000 watts for the 8/20 pulse. While the TVS can take unlimited 250-amp pulses of the 8/20 waveform, the MOV is rated to withstand only two of these pulses.

10. The TVS is rated to dissipate 2 watts in a steady-state mode, and the MOV is rated for 0.1 watt (10-mm MOV rated for 0.05 watt).

11. MOVs are significantly lower in cost.

12. The TVS has a minimal effect on the rest of the circuit. The MOV has far greater capacitance than the TVS.

SUMMARY:

Electrostatic discharge and electronic overstress account for approximately 60% of field failures of integrated circuits (IC's) alone.[10] In order to effectively suppress incoming transients, the protective device must dissipate the impulse energy, respond fast enough to prevent the rising edge of the impulse from entering the system, and hold the voltage low enough to prevent damage to the circuit. In addition, to achieve a 15-year operating life, the device must not degrade over time.

It was decided for the SunSaver design to utilize 1,500-watt TVS devices at both PV and load terminals for the following reasons:

- Superior protection of the FETs
- Lower clamping voltages
- No degradation over time
- Tighter tolerances and better predictability
- Faster response to transients
- The circuit is susceptible to load transients as well as surges from the PV cables

MOV devices are "unsuitable as board level protectors for most modern integrated circuits"[11] due to high clamping voltages and degradation to a permanent low impedance state. The use of TVS devices with the ProStar has proven to be extremely successful, and reliability of the SunSaver from transient events is expected to be equally high.

RELIABILITY GOAL #2: SERIES VS. SHUNT DESIGN

Every aspect of the circuit was investigated for the effects of transient pulses. Transients have many causes other than lightning, and it is very difficult to design for a 15-year operating life when considering how much exposure a PV controller will have to transient pulses.

In an effort to further strengthen the SunSaver design, Morningstar researched the merits of a series design vs. a shunt configuration. While a series design is inherently safer than a shunt, virtually all PV controllers rated under 10 amps are shunt configurations. This is because the FETs in a shunt design are much easier to switch, and the circuit is significantly lower in cost.

In a reliability analysis of an 8/20 pulse as described above, the TVS would clamp the circuit to 61 volts. However, in a series design the resulting voltage across the PV FET would only be 49 volts as shown in Figure 4.

As can be seen, the series FET is between the 61-volt transient and the 12-volt battery. This produces only 49 volts across the FET, which is well within its 60-volt rating.

The shunt design, however, places the FET directly between the positive leg and ground. This produces the full 61 volts across the FET. In addition, the Schottky diode becomes a second component to be stressed by the transient (to 49 volts since it is in the series path).

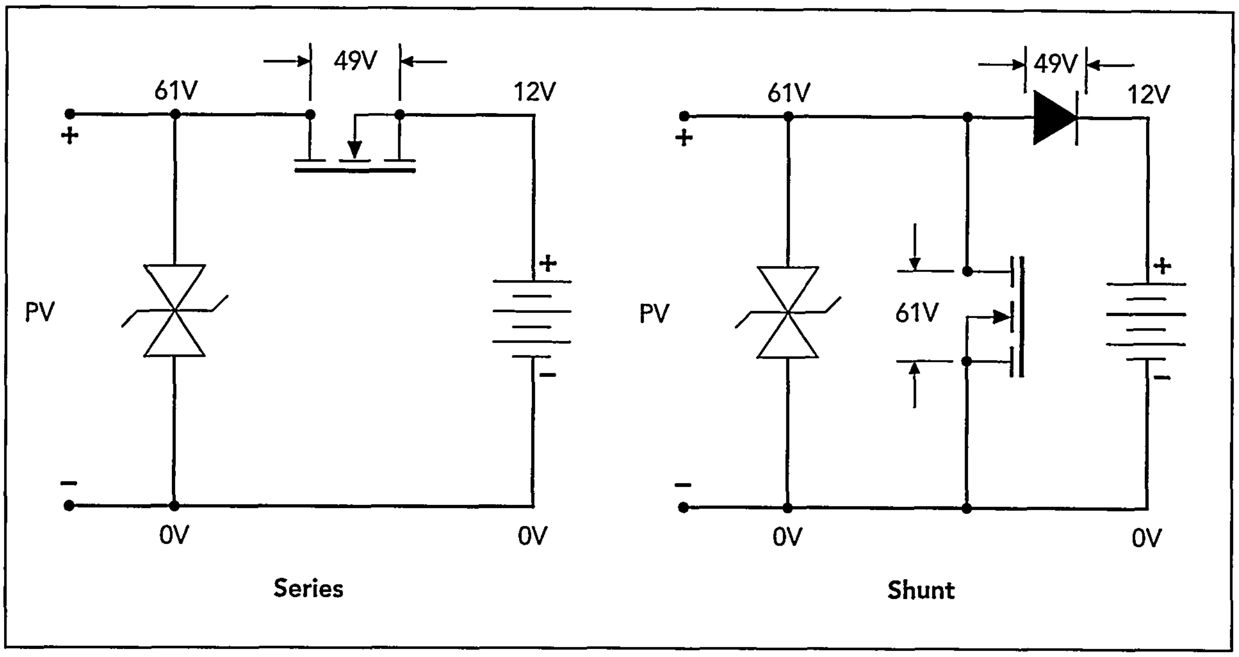


Figure 4. Transient Overvoltage Stress.

From this analysis alone, the series design offers a much greater degree of protection. There are also many other advantages of a series configuration that include the following:

- the series FET has less voltage applied across it during all phases of operation when compared to the shunt FET
- the shunt FET incurs more stress during charging because it is in a high temperature reverse bias standoff position
- a series design allows the troublesome Schottky diode to be eliminated, which provides numerous benefits including:
  - less heating of the circuit
  - lower voltage drops
  - FET lifetime is much greater than the Schottky
  - eliminates reverse leakage through the Schottky
- less switching noise in a series design
- all switching is done in the positive leg for maximum user safety
- greater precision in battery charging (see Battery Goal #7)
- pulse charging is possible (see Battery Goal #2)

The SunSaver design was a shunt configuration for the initial 7 months of development. Converting to a series design added 18 parts and added significant cost to the product. This was a difficult decision given the price constraints for small controllers. However, after months of cost/benefit analyses, it was clearly demonstrated that the advantages of a series design are compelling.

RELIABILITY GOAL #3: THERMAL DESIGN

After lightning and other transient-related failures, the next most common cause of PV controller failure is heat. These controllers carry full array and load currents through the circuit boards, and most have thermal problems.

The thermal cycling common to all PV controllers results in fatigue stressing of device materials, and high temperatures will accelerate corrosion and electromigration. The many processes leading to failure are accelerated by temperature in an exponential manner. As defined by the Arrhenius equation, a 50% increase in temperature can reduce device life by a factor of 50.

The PV controller is particularly subject to thermal stress due to the unique aspects of the PV application. These include daily thermal cycling, highly varied and often uncontrolled environments, and frequent overload conditions.

Failures from these very harsh thermal conditions are common in small PV controllers. These failures are typically caused by:

- components not rated for the actual service temperatures
- excessive steady-state operating temperatures
- hot spots due to poor or unbalanced design
- excessive FET junction temperatures
- inability to dissipate transient overloads

These controllers often suffer from extremely harsh service. For example, many controllers heat the circuit board close to its glass transition temperature, which places enormous stress on the traces and solder joints.

To account for all these conditions and failure modes, the SunSaver design was developed to a very rigorous thermal model. This model is based on the following operating conditions for each day:

- full array power charging for 12 hours at 60°C ambient
- 50% PWM duty cycle for 6 hours at 60°C ambient
- full load power operation for 6 hours while charging
- full load power at night for 6 hours at -40°C ambient

This daily profile places a minimum 100°C temperature change on every component each day. It guarantees that each component operates at full power both hot and cold in every day of service. This model assumes the worst-case conditions and maximum stress for design purposes.

This full 3D model of the internal heat flow was a critical design tool that guided all aspects of the SunSaver design. All parts of the model were constructed to be conservative. For illustration, elements of the model included:

- failure rates not to exceed 0.1% in 5 years
- loads included incandescent, inverter, motor, fluorescent, power supplies
- conduction from the heat sink to the mounting surface was assumed to be zero
- overloads of 125% for 5 minutes at 60°C ambient
- transients at 10 times rated current for 10 msec that occur 10 times each day
- calculations based on 1 ounce of copper for board traces

As the design progressed, the model and entire design cycle were iterated against measured performance of prototype units. The final designs had thermocouples embedded in the potting material to directly measure operating temperatures of the board traces, FET's and other devices (see Test section).

The results of the worst-case performance of four SunSaver units tested on actual PV systems are shown below. This is compared to the values predicted by the thermal model:

PARAMETER AT 25°C	MODEL	TEST
Array current	10.0A	11.0A
Load current	10.0A	10.2A
Heat sink temp	46.9°C	45.4°C
Voltage drop A	362mV	342mV
Voltage drop B	40mV	13mV
Voltage drop C	201mV	158mV
Voltage drop D	40mV	11mV
Resistance A	36.2mΩ	31.1mΩ
Resistance B	4.0mΩ	1.2mΩ
Resistance C	20.1mΩ	15.5mΩ
Resistance D	4.0mΩ	1.0mΩ
Power dissipated	6.43W	5.63W
FET junction temp	+52.7°C	+34°C

As expected, the thermal model used for the design proved to be conservative based on actual testing. For example, the 2-ounce copper used in the production boards significantly reduced the trace resistance and board heating as compared to the model. This was done intentionally to assure a good thermal margin in the final design.

The verification testing was also done under very conservative conditions. For example, many tests were done from -30°C to +60°C ambient conditions. Another example is the rough wood mounting surface that was used for test units to disrupt laminar flow of air behind the controller heat sink.

"Real world" actual conditions will seldom reach the levels used in the model or the testing. The result is an assurance that under worst-case conditions the maximum FET junction temperature will only be 34°C over ambient. At the 60°C ambient condition used for the design, the FET will never exceed 94°C. This is well below Morningstar's target threshold of 115°C. Given the exponential nature of temperature effects, the reliability and operating life of the SunSaver controller will be significantly increased.

RELIABILITY GOAL #4: ENVIRONMENTAL DESIGN

Photovoltaic controllers are commonly installed outdoors and can be exposed to the most harsh conditions on earth. This applies most to controllers for small PV systems. In addition, smaller systems often place the controller in a battery box so that it is also exposed to corrosive battery gasses.

The SunSaver specification called for a 15-year life, so the design had to suffer no degradation from worst-case conditions. A good example is an Abu Dhabi summer in Saudi Arabia. The ambient temperatures can be over 55°C in the shade[12], and humidity is typically very high. The sand in some areas has a very high salt content, and fine sand particles are blown by high winds into every "sealed" enclosure.

To ensure a 15-year life under these conditions, it was first necessary to fully encapsulate the circuit board. An epoxy potting material was selected. Full contact between the potting material and the board is assured by the case design and assembly process, which eliminates voids and air bubbles in the potting.

The potting material was custom formulated with the following properties:

- 90 Shore A hardness - softer material to reduce stress on the components and assembly
- 10.0 BTU-in/hr-ft2-°F thermal conductivity - efficiently conducts heat from the board to the case
- 41 x 10^{-6}/°C linear coefficient of thermal expansion - closely matches the board assembly and case properties so all components expand at similar rates
- -40°C to +150°C service temperature

Next, an extruded aluminum case was designed to withstand marine environments. The material is 6063-T5 aluminum with a hard-coat electrolytic anodized finish. The hard-coat anodize was selected over a cheaper organic anodized finish because it is much more durable.

The label is also aluminum, with a clear 1-mil Tedlar overlamination to protect from the weather and U.V. sunlight. The label is fastened to the case with four passivated stainless steel screws.

The 7-screw terminal is a tri-barrier case design using polypropylene UL rated material. The screws are nickel plated brass, and the terminal material is tin over nickel. The jumper material is tin plated brass. This terminal is designed by the manufacturer for marine applications. Morningstar conducted a 3-month salt test for various terminals, and all hardware corroded severely except this one selected for the SunSaver. There was no evidence of any corrosion on the selected terminal at the end of the test.

Finally, the SunSaver was designed and tested for both high and low ambient temperatures. The high temperatures are of more concern for operating life. As discussed in Reliability Goal #3, the SunSaver was tested extensively to the thermal models, and the SunSaver operates well within all the thermal design margins.

RELIABILITY GOAL #5:
15-YEAR LIFETIME AND FAILURE ANALYSIS

Reliability is defined as the probability of failure-free performance under a specified environment for a given period of time. Morningstar's design goal for all controllers is two failures per 1,000 units, and a 15-year operating life.

The projected 5-year failure rates for the SunSaver with a 95% confidence level are:

- SunSaver-6 <0.1% (1 per 1,000)
- SunSaver-10 0.2% (2 per 1,000)

This part of the report describes the analysis and methods used to calculate the SunSaver's expected reliability and operating life. A mean time between failure (MTBF) figure is sometimes quoted for PV controllers, but this method of failure analysis has little meaning for modern solid-state devices. The failure analysis used by Morningstar is based on a thorough analysis of the PV system environment and the resulting electrical and thermal stresses on the circuit.

SOLID STATE ELECTRONIC FAILURE MODES

The lifetime of a SunSaver in the field will be dominated by two factors: transient overvoltage exposure and electronic component operating lifetimes. The protection against transients has been discussed in the first two reliability goals. It is expected that the transient protection will prove to be highly effective based on the design, the extensive transient testing, and the field performance of the ProStar. The incidence of overvoltage failures with the ProStar in the first year is less than 0.05 percent.

Regarding the operating lifetimes of the devices, solid-state electronics have a failure profile that is often described as the bathtub curve. There is first an infant failure region, followed by a long period of random failures, and finally the wearout region. The goal of Morningstar's reliability analysis is to assure that the random failure period lasts 15 years or longer, and the random incidence of failure is below 2 per 1,000 units.

INFANT FAILURES:

All the SunSaver components are high quality, and many are tested by the manufacturer before shipment. All SunSavers are tested at high power after production to eliminate weak parts. The infant failures should be minimal, but all electronic devices suffer some incidence of this. These failures will generally occur in the first tens of hours of operation.

RANDOM FAILURES:

The random failure rate is very low for modern electronics. Switches, poorly soldered components, and misuse of the controller will typically cause the majority of failures during this period. This operating period can last for millions of hours if the device is operated under low stress conditions.

WEAROUT FAILURES:

The transition to the wearout region is fairly rapid. In a wearout mode, components begin to fail because of physical changes resulting from long-term heating and cooling, exposure to moisture and other irreversible processes. Most of the failures are voltage, temperature and humidity related.

Most of the SunSaver components operate under low stress and should have operating lifetimes approaching 20 years before significant wearout begins to occur. The FETs have the greatest stress, and these devices will limit the operating life of the SunSavers. Very simply, if the FETs are run hotter, operate in high humidity, or are exposed to voltage stress, they will enter the wearout phase of life much sooner.

FAILURE MECHANISMS

FET manufacturers extensively test their devices. International Rectifier tests 25 to 50 thousand FETs every 3 months. This generates statistical reliability data that is very useful in calculating product performance.

The five failure mechanisms for FETs that apply to PV charge controllers follow:

a) High Temperature Reverse Bias (HTRB):
The slow degradation of the standoff voltage due to migration of ionic contaminants in the FET junction. This affects the FET's ability to block the PV array voltage while in PWM (in a series design, but a shunt design will leak to ground).

b) Gate Stress:
Rupture of the thermally grown gate oxide layer in the FET. This is the long-term effect of turning the FET gate on and off at operating temperatures and voltage.

c) Power Cycling:
Fatigue of the silicon/metal interfaces and metal/metal interfaces. This is important for electronic equipment turned on and off, and similar to the stress of the sun rising and setting each day.

d) Temperature Cycling:
Fatigue of the silicon/metal interfaces and metal/metal interfaces. These failures are due to the thermomechanical stresses from thermal cycles and operating extremes the FETs experience each day. For PV systems, this is a major source of stress.

e) Temperature Humidity Bias:
Ingression of water molecules into the die, and cathodic corrosion of the aluminum bonding pads. These failures begin to occur in extreme operating environments.

RELIABILITY MODEL

Each of the above failure mechanisms must be evaluated, since different physical conditions could cause the FET to prematurely age and wear out too soon. Because the operating conditions of PV systems are so diverse, a full-time worst-case model was developed for the switching and cycling reliability calculations.

The model examines the PWM FETs, the night isolation FETs, and the load FETs for cumulative stress and damage. The model is based on full-power battery charging for 4 hours per day, and PWM at 50% duty cycle for 8 hours per day, with full rated current and 60°C ambient temperatures.

a) HTRB:

- Isolation FETs 12 hours per day at 15 volts.
- PWM FETs blocking 15 volts (PV Voc - battery) for 8 hours/day during PWM, ambient temp = 60°C, maximum current.
- Load FETs blocking battery voltage only during LVD, no cumulative time.

b) Gate stress:

- Isolation FETs 12 hours per day at 12V gate drive, 60°C ambient, and carrying full rated current.
- PWM FETs on 8 hours per day at 12V, 60°C, full current.
- Load FETs on 24 hours per day at 12V, 60°C, full current.

c) Power cycling:

- Isolation and PWM FETs for 1 cycle per day with a net 80°C temperature change.
- Load FETs for 2 cycles per day with a net 60°C temperature change during each cycle.

d) Temperature cycling:

- All FETs undergo an 80°C temperature cycle each day.

RELIABILITY CALCULATIONS

Using statistical reliability data for the FETs, the reliability model described above, and the specific design parameters of the SunSaver, a predicted operating period of time to cause a 0.1% failure rate can be calculated.

Some failure modes yield a projected operating life far in excess of the 15 to 20 years expected for the circuit. This means that the stresses for that failure mode are much lower than would be required to fail up to 0.1% of the controllers, and it is likely that very few SunSaver controllers will fail in this mode.

A summary of the calculations follows:

a) HTRB:
This calculation determines the maximum FET junction temperature that would be allowed to maintain failures below 0.1% in a 5-year period. Because the isolation FETs are blocking at much lower temperatures, only the PWM FETs are relevant for this calculation.

The total blocking time for 1,000 SunSaver-10 controllers over a 5-year period is 1.4E+07 hours (43,830 hours x 1,000 units x 2 FETs x 4/24 hours/day).
Using FET statistical failure data for failures per billion operating hours divided by the total blocking time, a figure of 71.4 FITS is calculated. This can be used in manufacturers' failure data tables to determine the maximum allowable FET junction temperature to assure failure rates less than 0.1%.

The maximum allowable FET junction temperature is 115°C. As described in the thermal model (Reliability Goal #3), the SunSaver FET should not exceed 94°C at an ambient temperature of 60°C. This provides a good margin to ensure that HTRB stresses are well below those allowable for a 0.1% failure rate.

b) Gate Stress:
From the reliability data, a 0.1% failure rate for 12V gate drive at 100°C temperature variation is 1.0E+08 hours. Note that the SunSaver model assumes 80°C variations in the worst-case, so some margin is built into this calculation.

A SunSaver-10 with LVD will incur 88 hours of gate drive per day in the reliability model. The time to 0.1% failure is then 1.1E+06 days, which is about 3,000 years. Therefore, the gate drive stresses will account for very few failures.

c) Power Cycling:
Statistical data for 100°C temperature change (again, greater than the model), predict 4E+05 cycles to reach 0.1% failures. With 8 cycles per day for a SunSaver-10 with LVD, the lifetime before reaching 0.1% failures is 137 years.

d) Temperature Cycling:
The failure rates for high temperature cycling are folded into the calculations for HTRB and Power Cycling noted above.

SUMMARY

Using the extensive failure data available for the components, together with the SunSaver test data, it is possible to design with a high level of confidence that the desired reliability level has been achieved.

This same failure and lifetime analysis was done for the ProStar controller design. In the ProStar's first 15 months, about 9,000 units have been shipped, and an estimated 7,000 have been installed. There have been 22 failures of the ProStar controller board, which indicates a 0.3% failure rate. However, over half these failures were due to a calibration problem and a troublesome transistor, and both have been eliminated in a board upgrade. This brings the failure rate below 0.2%.

The SunSaver is a more simple design, is better protected from the environment, and reflects lessons learned from the ProStar design. It is expected that the SunSaver failure rate will be better than 0.2% starting with the first units shipped.

2.2 SECOND OBJECTIVE: EXTEND BATTERY LIFE

A Technology Development milestone in the present U.S. DOE PV Program Plan (1996 to 2000) is to "Achieve design lifetimes from batteries in PV systems."[13] This is also the second major objective of the SunSaver development project. Battery performance and operating life must be improved to reduce PV system costs and increase the success of stand-alone systems.

As PV cell costs continue to fall, the battery in a small stand-alone PV system is an increasingly large part of the system cost. Over the life of a PV system the battery will account for over half of the total equipment costs.

Thus, the battery has the greatest impact on the economics of a stand-alone PV system. As can be seen in Figure 5, the battery typically accounts for about one fourth of the initial purchase price of a small PV system. More important than initial purchase cost, however, is the 20-year cost of the battery. If the expected battery life is reduced due to poor charging, the net present value equipment costs of the PV system over a 20-year period can be increased by 30% to 50%.

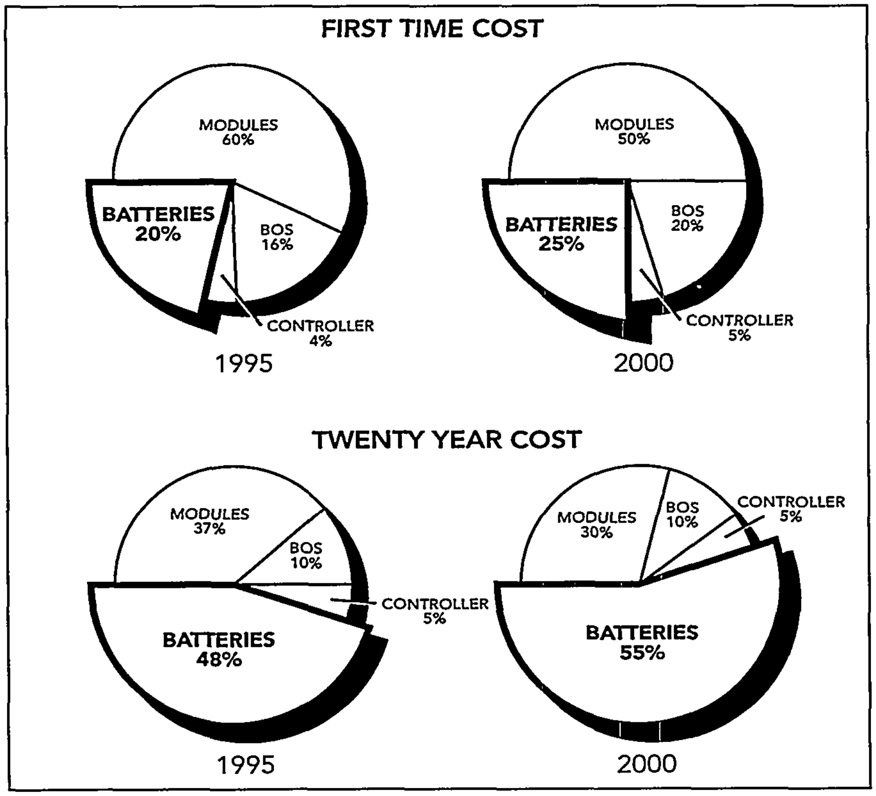


Figure 5. PV System Economics (Small PV Systems – 5 to 10 amps).

The economics of the PV battery often apply to an even greater degree in small PV systems, since these low cost systems typically have the poorest battery performance. The historical problem has been that small system PV battery chargers are generally very simple regulators due to the intense cost pressures at this low end. As the market matures, a growing dissatisfaction with the reduced battery lifetimes has developed. However, more expensive battery chargers have gained very little market share with the 1 and 2-module PV systems.

The underlying and fundamental problem is that charging a battery with a PV system is a unique and very complex process. Although the requirements imposed on the controller are highly variable, special engineering and custom hardware are not affordable at this low end. Therefore, some batteries will perform very well due to a fortuitous match of conditions, but most will fail in less than half their expected life for many reasons. Some of the unique challenges to charging a PV battery include:

- the charging source (sun) goes down each day
- the charging source is limited and highly variable due to weather
- the battery will cycle in a variable manner and must be recharged each day
- the array/load ratios vary a great deal from site to site and from month to month
- local batteries are often used which can vary in charging characteristics
- there are dramatic daily and seasonal variations in the energy output of a PV array
- environmental conditions are often extreme
- temperatures will vary daily, and PV systems are installed in climates ranging from Alaska to Saudi Arabia.
- PV systems are often unattended, or skilled maintenance is not available

Because custom solutions to these challenges will never be cost effective, it was necessary to develop a high-volume, standard charge controller design that would perform in all applications. The strategy for developing the SunSaver was to adapt the charging algorithm used in another higher end controller, ProStar. Since the ProStar is a digital controller that is too costly for small systems, an analog version of the ProStar was developed for SunSaver.

To guide this area of the development, a set of seven goals was established to define an "ideal" PV battery charger for small systems. These goals address the unique aspects of charging a battery with a PV array. The goals also made clear that a substantial advance in technology for small controllers would be required.

BATTERY LIFE GOAL #1:
PWM CONSTANT VOLTAGE ALGORITHM

A 1992 PV battery survey noted that most PV controllers use a simple "ON/OFF regulation mechanism."[14] These controllers interrupt charging early in the charging cycle when a voltage regulation setpoint is reached. To prevent global instability, a hysteresis of a volt is generally used to reconnect the PV array, and this causes the battery voltage to drift down for a period of time before charging can start again. A Sandia study, reported in 1994, found that batteries charged with the standard setpoints will typically average between 55% and 60% state-of-charge (SOC) for a period of years.[15] This causes stratification of the electrolyte and sulfation of the battery plates, thus increasing internal resistance, which further reduces charge efficiency.

A constant-voltage algorithm is a much more efficient method of charging a PV battery. When the battery voltage reaches the regulation setpoint (Vr), the voltage is then maintained at a constant fixed value, which automatically tapers the charging current according to the battery's state of charge.

When the ON/OFF controller reaches the Vr setpoint, the charging current goes to zero for uncontrolled periods of time, and much of the solar energy available for that day is typically lost. With a constant voltage algorithm, current from the PV array is continuously charging the battery. This process is self-regulating in that the current will decay as the battery reaches full charge so that the battery is not overcharged.

The most effective means to achieve constant voltage battery charging is with a pulse width modulated (PWM) control of FET switches in series between the PV array and the battery. This allows for a variable duty cycle that reduces the charging current as necessary to maintain a constant voltage at the battery.

Figure 6 illustrates the pulses that are formed to control the battery charging. These are measured SunSaver PWM pulses that are formed at a fixed frequency of approximately 300 Hz. The bottom pulses show an 80% duty cycle where 8.0 amps of a 10A PV array are charging the battery. The middle set of pulses have reduced the charging current to 5.1 amps, and the top pulses indicate that the current has tapered down to a 25% duty cycle (i.e., 2.5 A of a 10 A PV array is charging the battery).

Only a few PV controllers attempt this method of charging, but the designs have been generally disappointing. The same Sandia study[16] notes that two of these are actually ON/OFF controllers operating at a variable frequency (about 400 Hz). The leading controller in this area, a German product, also has a hybrid design that suffers from a number of similar flaws, including:

- a variable switching frequency
- inability to achieve 0% to 100% duty cycle
- during full charge, a shunting of the PV array for 6 ms per cycle with varying charging intervals

• during regulation, a minimum charging time of 4 ms per cycle with varying shunt periods

• voltage hysteresis of 100 mV

The challenge for this SunSaver development project was to avoid the problems noted above by maintaining a fixed PWM frequency, providing a full 0% to 100% PWM duty cycle, ensuring that the PWM was responsive to system changes, maintaining stability under all conditions, and optimizing the FET switching of the PV power source.

The ProStar controller has accomplished all these objectives, but it is an intelligent, processor-based digital controller. The cost of this approach exceeded the SunSaver budget. Much of the SunSaver development, therefore, was devoted to incorporating all the requirements for a stable, responsive and fully effective PWM control process into a lower cost analog design.

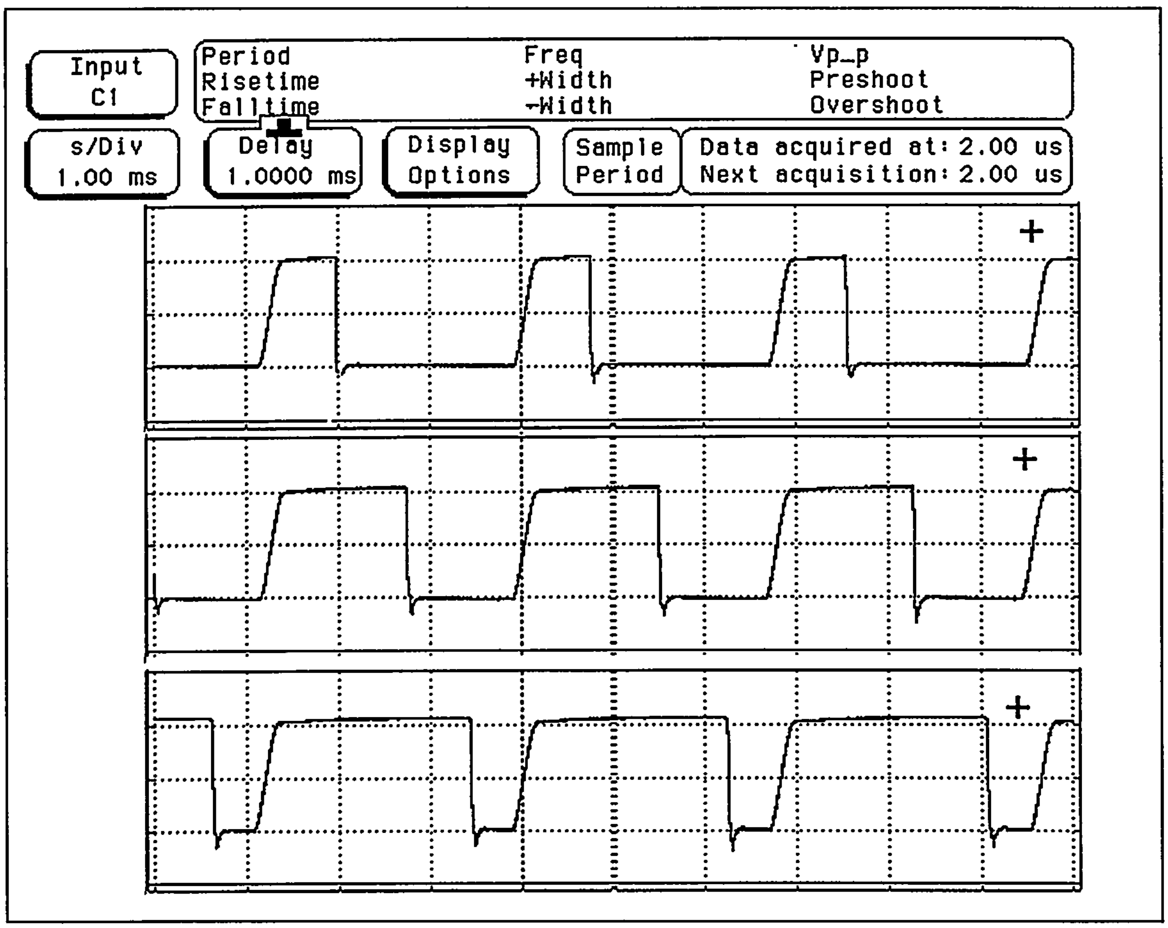


Figure 6. PWM Duty Cycles.

The SunSaver design is extremely successful in this regard. The discussion in Goal #3 describes the stability and response of the FET switching. A full 0% to 100% duty cycle was achieved. The following battery-charging goals will describe the pulse-charging accuracy of the PWM and special features incorporated into the design for very effective PV battery charging.

A battery-charging curve for a SunSaver on test is provided in Figure 7. This shows the classic tapering of the charging current after the Vr voltage is reached. Note the stable battery voltage for the last 6 hours of the day. Also, note the finishing charge, at 1.5 amps over the load, for the last 3 to 4 hours to bring the battery to a 100% charge state.

Another test (Figure 8) shows how responsive the controller is to clouds and changing conditions. Regulation begins about 12:00 noon, but the current tapers more slowly since the battery charge state is slightly lower. Note that when two large clouds interrupt the constant voltage charging, the PWM duty cycle allows more current to flow into the battery to compensate for the lost energy due to the clouds. With an increased charge rate to make up for the reduction in PV energy from the clouds, the total area under the PWM curve (e.g., the total energy to the battery) is the same as if there had been no clouds. The battery will take the current it needs, and it pulled more current to compensate for that lost by the clouds.

BATTERY LIFE GOAL #2: PULSE CHARGING

Morningstar has extensively researched battery pulse-charging techniques, and the company has contracted for consulting studies in this area. Most pulse-charging research is being done to support fast charging and longer battery life for electric vehicles. However, there may be significant benefits that can be extended to PV battery charging.

The potential benefits of charging a PV battery with controlled pulses[17] include:

- compact lead sulfate can be broken up to improve battery capacity and charge acceptance
- charge efficiency can be improved and effects of aging can be reduced
- operating life of the battery can be increased
- higher voltage pulses can punch through resistive coatings between the grid and active material on the plates
- the opportunity for a gas bubble to form can be reduced
- downpulses further improve charge efficiency and reduce gassing

In a PV system, a downpulse (i.e., reverse or discharge pulse) will occur when charging in PWM with a load. Morningstar's research indicates there are good prospects for using pulse charging

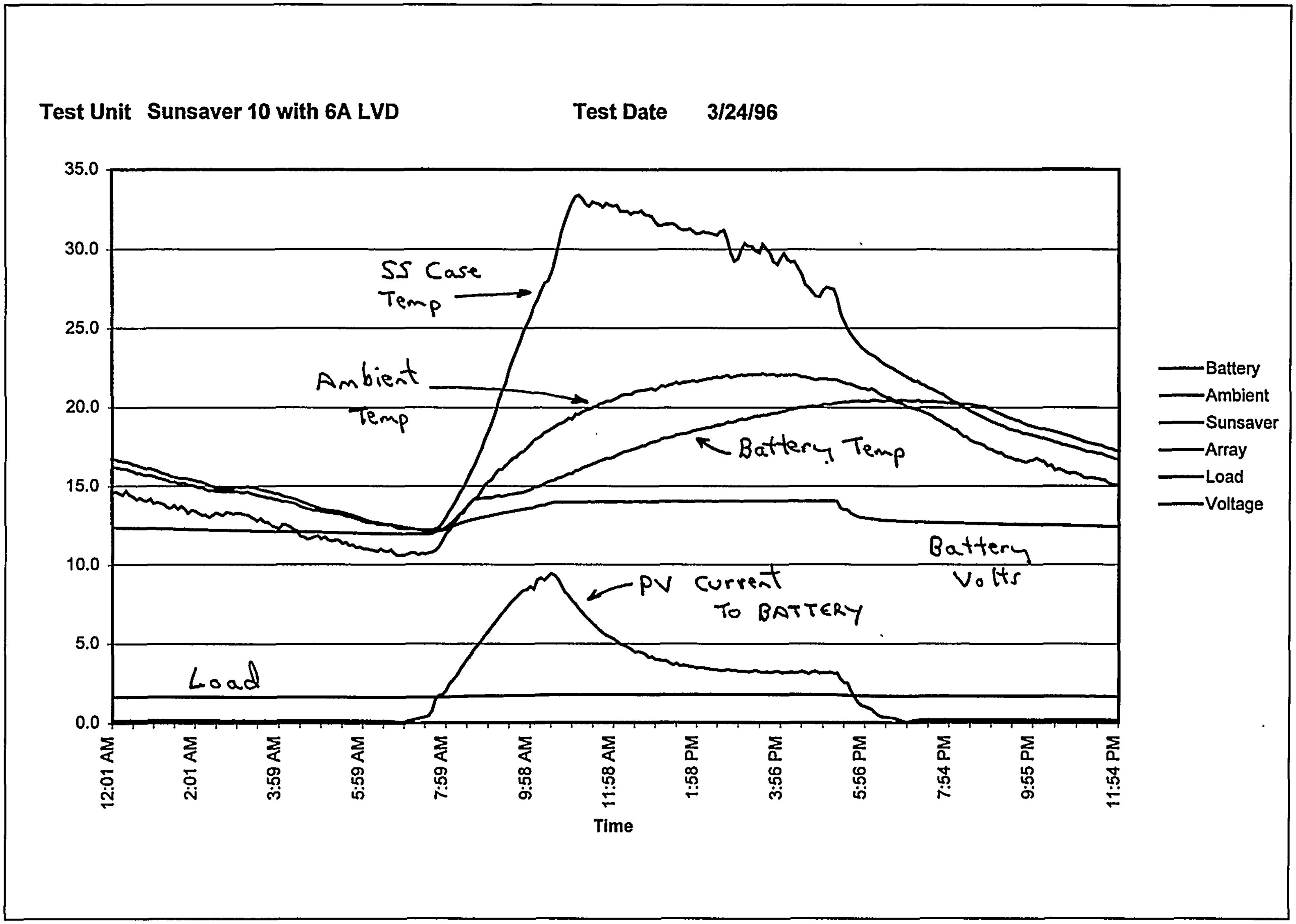


Figure 7. Battery Charge Test Curve (3/24/96).

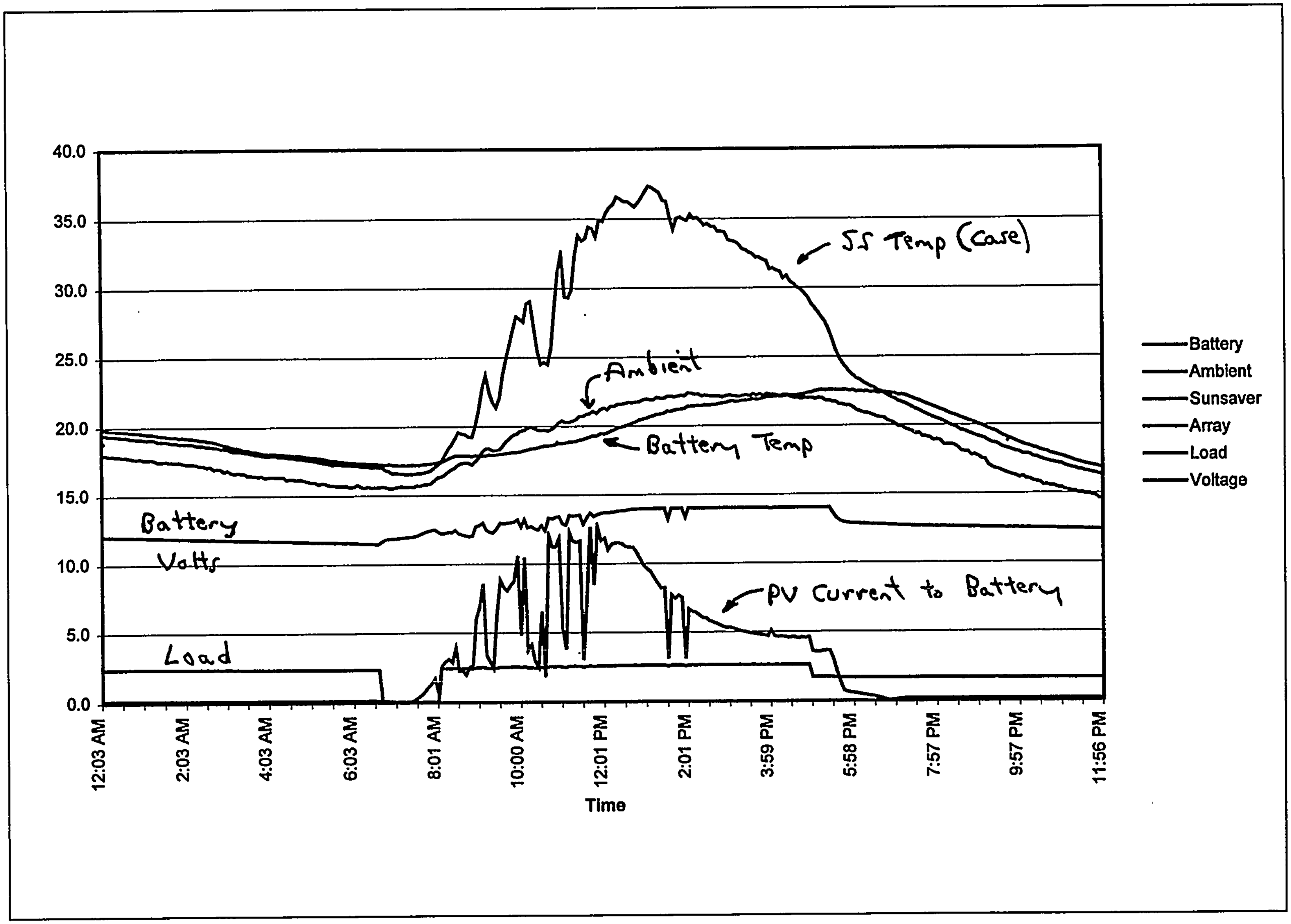


Figure 8. Battery Charge Test Curve (3/23/96).

combined with downpulses to extend battery life in PV systems. The following benefits may be possible:

- the downpulse creates new activation sites, so with subsequent pulses there are more sites available to accept charge
- pulses break through corrosion to prevent capacity loss
- sulfation is reduced
- heating and gassing of the battery during charging are lessened

One especially exciting area of pulsing may offer particular benefits for PV systems. The PWM charge pulses may be short enough in duration to reduce the ability for gas bubbles to form. Further, it seems that a downpulse makes gassing even less likely since it apparently helps to breakup the precurser to a gas bubble.

Meanwhile, during the off time of the PWM pulses, ionic diffusion continues in the electrolyte to equalize the ion concentration. This helps to assure full charging of the battery while avoiding excessive gassing and heating.

To maximize the potential benefits of pulse charging a PV battery, Morningstar is continuing to research the parameters that are important in controlling the performance of battery pulsing, including:

- frequency
- duty cycle
- rise time of the pulse
- waveform of the pulse
- voltage of the pulse
- time and energy of the downpulse

Figure 9 shows clearly the shape of the SunSaver PWM pulse. This can be compared to a pulse typical of other PV controllers. It is possible to shape the pulse in the FET gate drive circuitry to accomplish charging objectives.

These variables were considered in the development of the SunSaver design, and testing of battery charging efficiency is continuing. To optimize the design for potential pulse charging benefits is expected to take a number of years.

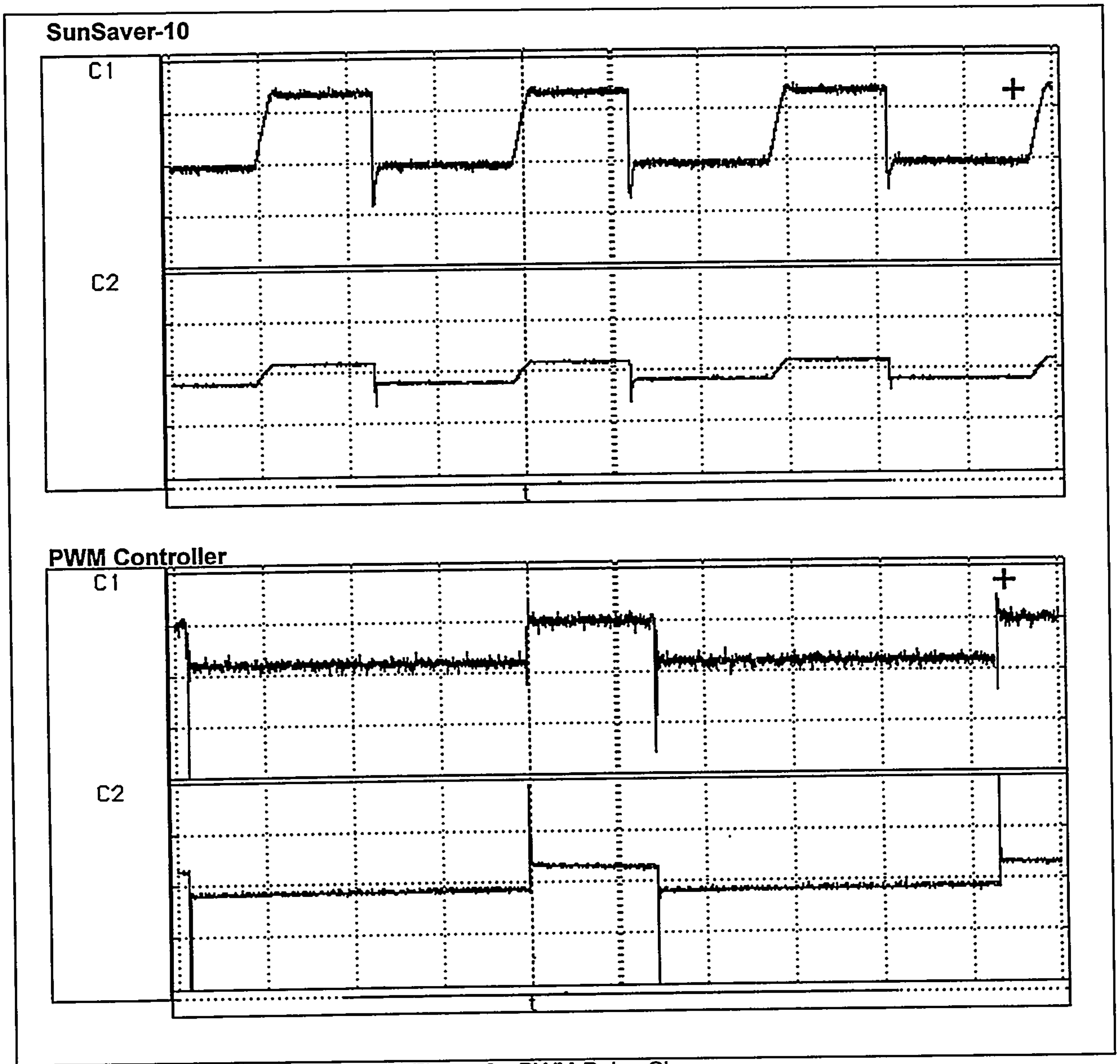


Figure 9. PWM Pulse Shape.

BATTERY LIFE GOAL #3: ACCURACY AND RESPONSE

The PV charge controller must recharge the battery as quickly as possible during the time the sun is available, but it must also avoid heating and excessively gassing the battery. This conflict inherent in PV systems is a primary cause of reduced battery lifetime.

The PV controller must automatically manage conditions typical of PV sites such as the following:

- recharge to recover quickly after a week of rain
- charge at maximum rates during the winter
- safely regulate all day during high solar resource periods
- safely regulate for months if a load is disconnected

Various 2-stage charge schemes were considered to accomplish fast and safe charging, but these were rejected. If the full charge setpoint is raised higher than the gassing point, there is a considerable risk that system conditions will cause the battery to remain for extended periods in overcharge. If the finish charge voltage is reduced below the gassing point, very little current will then be transferred to the battery to bring it to a healthy state of full charge.

With a PWM algorithm, however, there are constant voltage charging values for lead-acid batteries that provide for rapid charging and a safe regulation voltage. These are between 2.35 v/cell and 2.40 v/cell (see sealed/flooded select - Goal #4) where the battery enters the gassing stage.[18] For effective PV charging, the proper constant voltage must be held within a narrow window. This requires a very stable and responsive PWM, and a high degree of setpoint accuracy with tight tolerances.

The SunSaver design includes precision resistor divider networks, tight tolerance components, and a circuit design that responds quickly to changing conditions. The PWM is very stable around Vr under all conditions. Normal variation around Vr is 10 to 15mV, and extreme conditions cause Vr to vary only about 300mV, with recovery in less than 25 msec.

As shown in Figure 10, the load is suddenly increased from 0.6A to 6.5A, and this produces a 25A inrush current. The voltage sags about 300mV, and then fully recovers in less than 25 msec (0.025 second). Also, it can be seen how the PWM duty cycle adjusts from about 5% (almost no charging) to about 90% in the same 25 msec period.

With surface-mount technology and automated production, the manufacturing tolerances are extremely accurate. The sealed battery Vr setpoints for prototype units were typically calibrated to within 8 to 10 mV of the specified value. Based on this, the final product spec was adjusted to ± 12 mV (sealed) and ±55 mV (flooded), which is exceptionally tight. While the first pre-production run calibrated on a GENRAD computer measured a few sealed battery Vr variations up to ±40 mV, this is acceptable since the initial SunSaver target spec for proper battery charging was ±50 mV.

In the first production run, most sampled units were within ±30 mV, and it is expected that this value will improve to ±20 mV. The extremely fast response of the Vr setpoint and a 20 mV accuracy tolerance will exceed the required charging accuracy under the most extreme system conditions.

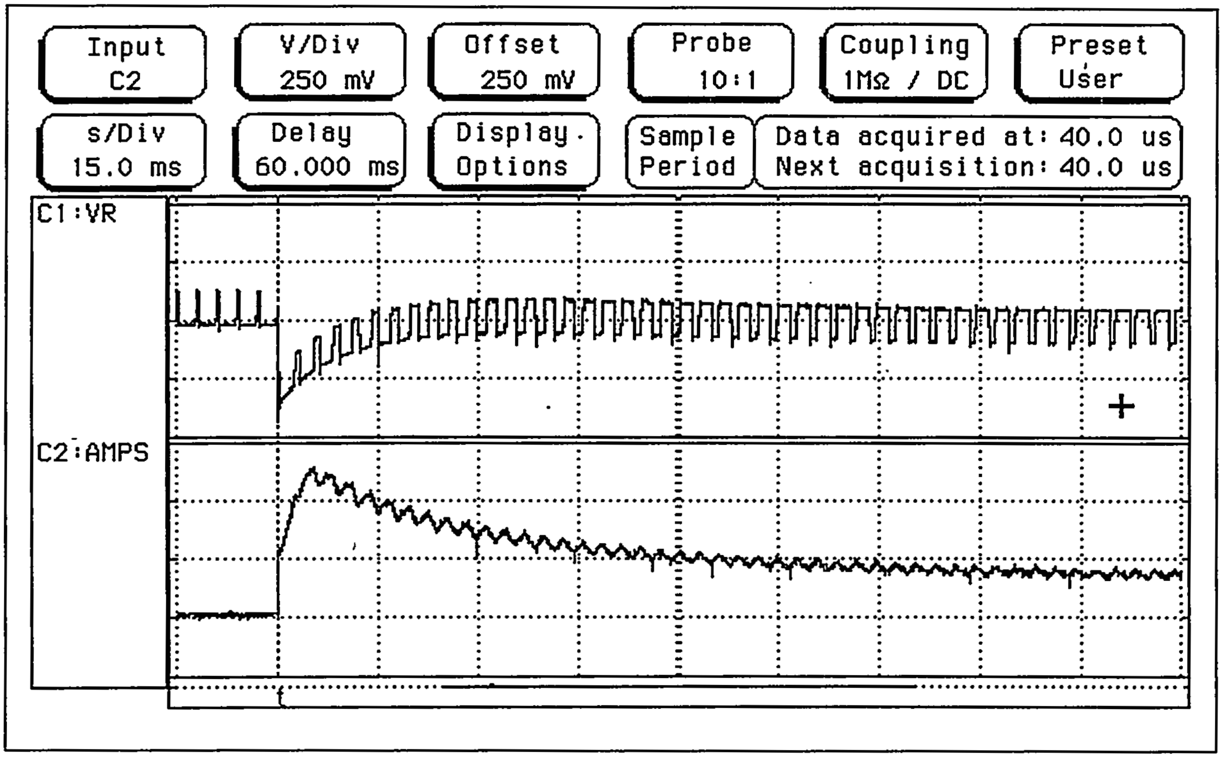


Figure 10. PWM Response and Stability.

BATTERY LIFE GOAL #4: BATTERY TYPE SELECT

As noted above, optimal recharging falls within a fairly tight Vr window. However, there are also fundamental differences between "sealed" (valve regulated lead-acid and gel batteries) and "flooded" classes of batteries that must be considered.

Both battery types must be fully recharged, but the sealed batteries suffer from excessive heating and outgassing if Vr is exceeded, while the flooded batteries must be gassed and overcharged to some degree to avoid electrolyte stratification. Overcharging sealed batteries must be limited to prevent rapid failure, and undercharging flooded batteries can produce stratification that will dramatically reduce capacity and shorten the life.

Extensive PV battery charging data has been developed by Sandia and Florida Solar Energy Center (FSEC). This data, plus input from consultants and battery manufacturers, indicates a consensus for optimum constant voltage charging for a 12-volt PV system as follows:

- Sealed batteries 14.1 volts (2.35 v/c)
- Flooded batteries 14.4 volts (2.40 v/c)

In sealed batteries, most of the oxygen is recombined under 14.1 volts. Above 14.1 volts, most of the overcharge energy goes into gassing and heating. The flooded battery typically starts to gas at 13.8 volts, and at 14.4 volts the gassing rate for a 200 Ah 12 V battery is typically 25 to 45 mL/min. However, above 14.4 volts the gassing increases sharply.

All small PV controllers attempt to split this difference with a single Vr setpoint at about 14.25 volts. However, the average setpoint accuracy of nine leading small controller manufacturers is ±156 mV. Adding this to other circuit tolerances, and most small controllers will regulate at ±200 mV or worse.

This means that sealed batteries can be charging at 14.45 volts and flooded batteries under 14.05 volts. The sealed battery will increase in temperature by 15°C in an hour and vent. The flooded battery will sulfate and the electrolyte will stratify. These single setpoints and circuit tolerances should be considered unacceptable for PV systems.

The SunSaver was designed to include a field-selectable feature for a sealed or flooded battery type. The controller is shipped with a jumper installed in the terminal block, and this is the sealed setting (14.1V). If the jumper is removed, the controller becomes configured for flooded batteries (14.4V). This is easily done with no training, and can be reversed later if the battery type is changed.

BATTERY LIFE GOAL #5: TEMPERATURE COMPENSATION

Temperature affects the rate of chemical reactions in batteries, as well as the rate of diffusion and the resistivity of the electrolyte.[19] Therefore, the charging characteristics of the battery will vary with temperature. This is nearly linear, and the voltage coefficient of the temperature change can vary from -3 mV/°C/cell at 50°C to -5 mV/°C/cell at -10°C.[20]

Regulation setpoints are specified at 25°C. Battery temperatures often vary 15°C from the 25°C reference in PV systems, and the regulation voltage for a 12-volt sealed battery must then be adjusted as follows:

BATTERY TEMP	VR	
40°C	13.8 V	
25°C	14.1 V	Reference
10°C	14.5 V	

If not adjusted for temperature effects, the warmer battery will begin to heat and outgas at 13.8 volts, and will continue to overcharge until the non-compensated Vr is reached (14.1V - or 14.25V with a "single sealed/flooded" setpoint). In cooler temperatures, the 10°C battery will begin to regulate at a state-of-charge about 30% lower than desired if the Vr is not adjusted to the higher voltage. This will cause severe undercharging.

Market research shows that few small PV controllers are purchased with temperature compensation. If a small controller offers temperature compensation, it is typically an option that costs over $20 (average of four leading controllers ≐ $22) at list price. This is nearly half the cost of the controller, and this price is considered by the market to be unaffordable for most small PV systems.

However, Sandia and experienced PV system engineers recognize the critical importance of temperature compensation for battery life, so Morningstar decided that this capability would be added to the SunSaver as a standard feature. This removes the difficult cost decision for dealers and users.

The SunSaver design utilizes a silicon temperature sensor that protrudes through the cover to measure surrounding ambient temperature. It is accurate to within ±2°C from -40°C to +150°C. It has a fast time constant of 8 seconds in air. The SunSaver circuit makes a linear correction for temperature over the full temperature range with a coefficient of -3.3 mV/°C/cell.

This coefficient was selected to favor the correction for high temperature conditions. This is because the majority of PV systems are in hot climates. A cold battery at 10°C will be corrected to within 0.12 volts of the "ideal" Vr with this coefficient.

It should be noted that recent Sandia testing indicates that a larger high temperature correction may be desired for PV systems, and the -3.3 mV coefficient will be increased slightly based on Sandia tests.

The temperature sensor will be affected to a minor degree by the self-heating of the controller. Therefore, the sense circuit is offset from the reference 25°C by 4°C, so the effect on Vr is as follows:

% RATED CURRENT	SELF-HEATING	SENSOR OFFSET	NET EFFECT ON VR
100%	8°C	4°C	-0.08 volts
75%	6°C	2°C	-0.04 volts
50%	3°C	-1°C	+0.02 volts
finish	1°C	-3°C	+0.06 volts

Most SunSaver systems will begin to regulate at about 40 mV to 60 mV below the specified Vr. As the current tapers under constant voltage charging, the finish charge will be about 60 mV above the specified Vr. However, at this point the current level into the battery will generally be less than one amp and heating/gassing will be minimal.

This design enables every SunSaver to include temperature compensation at no added cost to the user. This allows the charging to be temperature corrected to within mV of the needs of the battery, and this feature alone will significantly extend the operating life of the majority of PV batteries in small systems.

BATTERY LIFE GOAL #6: LOW-VOLTAGE LOAD DISCONNECT

An automatic low-voltage load disconnect (LVD) and reconnect feature is common in PV controllers to protect the battery from deep discharges. Given the variable nature of the solar resource in PV systems, there is a high probability for deep discharges of the PV battery.

The LVD feature is typically an option to the controller. However, even though the need for this protection is well understood, many controllers are sold without LVD for the following reasons:

- the LVD option cost can add $20 to $30, or about 50%, to the controller cost
- mechanical relays are commonly used, but they can be very unreliable
- the LVD often consumes too much current, which defeats the purpose of protecting the battery

Given the critical role of the LVD, the SunSaver was designed to remedy these problems, as follows:

- the retail cost of an LVD option is $12 for the SunSaver-6, and $16 for the SunSaver-10
- FETs are used for the load disconnect, and these are protected and switched in the same manner as the PWM FETs
- the load FETs do not require any additional current (the red LED indicator pulls only about 1 mA when in LVD)

This approach appears to be highly successful. Over 87% of initial orders for the SunSaver controller include the LVD. This is expected to increase even higher as the market tests the performance of the SunSaver LVD.

BATTERY LIFE GOAL #7: FINISH CHARGING

All batteries require some overcharge to reverse normal sulfation and reach full charge. The finishing charge is of critical importance to enable recharging to 100% SOC, while avoiding excessive heating and gassing.

A great deal of effort was expended to make the SunSaver a series controller, in addition to the constant voltage PWM design. In terms of finish charging, there are significant advantages to the PWM series design vs. an ON/OFF shunt design. These include:

- Self-regulating

  The constant voltage current will decay per the equation $I = Ae^{-t}$, where
  I = charging current
  A = amp-hours discharged
  t = time

  After a number of hours, the charging current tapers and becomes asymptotic according to the SOC and charging needs of the battery. The ON/OFF controller, however, will continue to put 100% of the PV array current into the battery with each "ON" cycle, regardless of the SOC of the battery. This is much more current than the battery can accept at a high SOC, and the result is a very inefficient finish charge.

- Low voltage drops

  As the current tapers in finish charging, the voltage drop between the controller and battery will reduce as well. However, the ON/OFF design will continue to suffer full voltage drops with each cycle which lowers the regulation voltage.

  To illustrate, a system with a 9 amp PV array and 10 feet of AWG #12 wire to the battery will have a voltage drop in the wire of 0.31 volts, but the PWM charger will only see 0.02 volts (at 0.6 amps finish charge). This means the ON/OFF controller, with a Vr of 14.4 volts, will switch off charging at an actual battery voltage of only 14.09 V at every ON cycle. In contrast, the PWM battery is finish charging at a healthy voltage of 14.38 V.

- Less heating

  When the shunt design is in finish charging, the duty cycle of the FET will be over 90% on (i.e., short-circuiting the PV array). In contrast, the series design is over 90% off (FET is open with no current flow). The controller heating measured in shunt designs can be over 10 times greater than the series design in finish charging.

  In the SunSaver PWM series design, the controller will begin to cool at a duty cycle below 84%. This cooling can be seen in Figures 7 and 8, which show the SunSaver case temperatures declining after going into PWM. Thus, any adverse effects from controller self-heating are minimized in finish charging with the series design.

- Aging

  Due to poor charging, PV batteries will age rapidly. Battery aging strongly affects the performance of ON/OFF controllers, but aging does not affect PWM constant voltage charging. With PWM, the only effect of age is that gassing will begin earlier.

In summary, all these factors enable the SunSaver PWM constant voltage series design to effectively reverse sulfation and achieve full battery charge in a predictable, consistent and effective manner.

2.3 THIRD OBJECTIVE: AUTOMATED PRODUCTION

It was necessary to decide early in the development program whether the SunSaver would be manually assembled or built with automated methods. Automation provides unit cost advantages and quality benefits, but this process requires a large initial investment.

A thorough evaluation was done to quantify the relative costs and benefits of each approach. The decision was taken to fully automate the production process for reasons discussed below, and five manufacturing goals were established to ensure the success of this approach.

The competitive prices for 6 and 10 amp PV controllers drove the decision to automate. There are three factors that firmly establish the market pricing for these small PV controllers within a very tight window. These factors are as follows:

- Small regulators were developed in the late 1970's when most PV systems were very small. The designs were typically simple ON/OFF shunt devices that "regulated" excess PV energy to avoid overcharging a battery. Most controllers under 10 amps sold today are only modifications of designs that are 20 years old.
- There are some 85 PV controller manufacturers worldwide,[21] and most are producing only small regulators. These suppliers are typically local companies making very simple devices.
- Small PV systems are generally easy to design and build, so the price pressure for these small systems is intense. Many suppliers have the capability to build these simple systems, and price is often the only competitive advantage.

Given the simple technology, the diverse supply base, and the intense price pressures with small PV systems, a higher quality controller selling at a modest price premium would probably never acquire a sustainable market share.

Most small PV controllers fall within the supply infrastructure described above. Therefore, to be successful with a new high-quality controller, a prerequisite is a competitive price. For models rated 5 to 10 amps, controller list (retail) prices range from $45 to $60, and adding LVD capability increases prices to $65 to $80.

As discussed below in Goal #2, a surface-mount design with automated production will significantly reduce the variable product costs to the levels required to be competitive. In addition, this manufacturing approach ensures consistent high quality levels and superior electrical performance (see Goals #3 and #4).

It was clear that the opportunity to provide a superior product at a competitive price was available through technology. Although over 80% of electronic components sold in the United States today are surface-mount technology (SMT),[22] no PV controllers use SMT. In addition, virtually all small controllers today are hand-made; one exception being a semi-automated process in Germany that uses through-hole parts.

A number of studies were conducted by Morningstar for a period of one year to define the market, competitive pricing, and the manufacturing cost tradeoffs required to remain within the allowable budget. Given the substantial investments in manufacturing and QA testing that would be required for success, five production goals were established to ensure the yields and manufacturing cost targets would be achieved.

MANUFACTURING GOAL #1: WORLD CLASS ASSEMBLY FACILITY

To accomplish the SunSaver's design goals, the board assemblies require between 72 and 93 components. Between 35 to 37 components (depending on model type) are not found on competitive controllers and were added for the sole purpose of improving reliability and battery charging. (note that the photos in the SunSaver brochure show fewer parts, and these were taken with earlier prototypes for competitive reasons)

The higher parts count increases both the material and labor costs. To meet the project's overall cost goals, this product requires assembly in a world class manufacturing facility that has the following characteristics:

- interest and commitment to this product
- state-of-the-art equipment
- highly effective and efficient management
- high productivity
- large plant size for economies of scale
- effective total quality programs

Morningstar surveyed quality contract manufacturers throughout the United States and selected 44 to contact. Of these, 21 proposals were solicited and evaluated. Negotiations and plant audits were conducted with a short list of four companies.

A contract manufacturer in New York, the MATCO Electronics Group, was selected. Both Morningstar and MATCO desired a long-term partnership, since it was necessary for both companies to invest heavily in the start-up of this product.

MATCO is a $250 million company that consists of a printed circuit board fabrication facility, various specialized contract manufacturing locations, and an engineering group to help optimize designs for production. With nearly 750,000 square feet of floor space for manufacturing and electronic assembly, MATCO has a full range of capabilities and state-of-the-art equipment to dedicate to the SunSaver production.

MANUFACTURING GOAL #2: COST REDUCTION

Using advanced technology to reduce costs will also generally produce corresponding improvements in quality. Holding high quality was a mandatory requirement for the SunSaver, and the synergistic relationship between cost reduction and quality will be noted in the following goals.

Two basic technological strategies were used to reduce cost:

- Surface-mount technology - see Goal #3 below
- Automated assembly and test - see Goal #4 below

It was determined early in the SunSaver development that the manufacturing process had to be automated. In the initial design phase, an analysis was done of an automated through-hole technology (THT) assembly. The THT circuit board was 2.5 times larger than the SMT design. This drove the total assembled product cost up by 35% over an optimized surface-mount design. So, the decision was made early to use SMT.

The design of the product also had to accommodate high-speed machine assembly and automated testing. In addition to the circuit board assembly, other components were also designed for high-speed and low-cost assembly. For example, the case is a set of custom extrusions that eliminates many assembly steps. The case fits together without hardware, it positions the board assembly, and it is designed for semi-automated encapsulation. The only screws in the product are used for attaching the label.

Building the SunSaver on high-speed machines with automated testing provides uniform quality, high yields, and the required cost structure. However, there are also constraints with this approach that include:

- High non-recurring investment costs
  Morningstar has the long-term strategy and capital base to make the necessary investments. In addition, about 20% of these costs were supported by the USDOE's Balance-of-System Development Program.
- High-volume production runs
  With expensive set-up for each production run, an automated process is only cost effective for a minimum of 2,000 units per run. Machine assembly requires 60-day lead-times before scheduling production, high inventory levels of parts and finished controllers, and a minimum number of different models to assemble.
- Reduced flexibility
  Given the international distribution channels, the reduced number of models is an advantage for distributors. However, this places additional constraints on the product design. For example, some features such as temperature compensation and battery select must be included as standard with every controller. Morningstar is presently developing certain specialty

SunSaver models to provide for specific application requirements. Eventually, technology will allow these features to also be folded into standard models.

Overall, the high initial investment and production constraints are justified by the reduction in unit costs.

MANUFACTURING GOAL #3: SURFACE-MOUNT TECHNOLOGY

The cornerstone of the SunSaver's manufacturing strategy is surface-mount technology (SMT). This opportunity exists because no other PV controller, of any size, is made today with SMT.

The surface-mount components are soldered directly to pads on the surface of the circuit board, instead of in plated holes through the board. Recent SMT developments have provided a dramatic increase in circuit density and electrical performance while improving cost and quality.[23]

Some of the SMT benefits that apply to the SunSaver include:

- Reduced component size and increased density
  - components are attached on both sides of the circuit board
  - higher pin count allows more functionality for each component
  - the functionality of a single SMT board will be equivalent to several THT boards
  - dimensional stability is improved, especially with thermal cycling
- Improved electrical performance
  - smaller trace widths, smaller vias, decreased trace lengths
  - shorter propagation delays
  - lower impedance
  - better FET stability and load sharing
- Reduced cost
  - smaller circuit board
  - smaller component packaging and often lower cost components
  - better availability of components
  - higher speed automated assembly
- Higher Quality
  - automated assembly required by the small body size and lead pitch of the SMT components
  - very high placement accuracy yields higher quality and more consistent product

- computer-driven assembly equipment reduces errors
- defect rates often below 50 parts per million as measured by solder joints[24]

The trend in SMT is to put more circuitry on a silicon IC. Integrated semiconductor technology advances will offer higher speeds, higher performance, and greater functionality.

Morningstar is presently working on multichip modules (MCM) and application-specific integrated circuits (ASIC's). These more specialized SMT components can expand the benefits from the automated assembly process. These advanced components can also achieve six sigma soldering and further improve thermal performance.

MANUFACTURING GOAL #4: AUTOMATED PRODUCTION

Having achieved significant component cost reductions through SMT, the decision was taken to automate the manufacturing process to the greatest extent possible. In addition to labor cost reductions, this level of automation provides a high degree of repeatability, reliability and efficiency. This leads to increased yields in production and fewer warranty returns from the field.

The following key steps form the manufacturing and quality assurance cycle:

a) **Bare board inspection**
- ATG Universal - bare board tester

Every printed circuit board receives a double-sided universal grid electrical test before going to assembly. A custom clamshell fixture is required to test both sides of the board.

b) **Incoming component inspection**

All components are inspected against specifications, drawings, and acceptance criteria before release to the assembly floor.

c) **Board assembly**

- Universal Instruments, Model 4790 HSP - high speed placer
- Universal Instruments, Model 4681A - fine pitch placer
- Universal Instruments, Model 4713D - adhesive dispenser
- Universal Instruments, Model 5362D - handling conveyors
- Vitronics, Model SMR 1200N - nitrogen convection reflow

Arrays of 10 SunSaver boards are assembled on multi-million dollar SMT lines. All steps are programmed using computer-aided design (CAD) for precise alignment. Vision-assisted board registration using fiducial marks accurately aligns each array at each step. Vision-assisted placement ensures the precise location of each component on the circuit boards.

The Universal 4790 "chip shooter" installs the common SMT devices at rates up to 7 parts per second. The parts can be placed with an accuracy better than 0.0006 inch. The Universal 4681 is a flexible placement machine with high magnification optical features for even greater placement accuracy.

The final assembly step uses a forced-air convection reflow oven to form the electrical and mechanical connections to the printed circuit board (PCB). There are four critical steps in the process to ensure a reliable and durable solder connection: preheat; soak; reflow; and cool down. A computer profile is established for each individual SunSaver model to optimize and control each critical process step.

d) **Electrical test**

- GENRAD, Model 2283 - computer-based test system

After the completed assemblies are visually inspected in QC, each assembly receives a 100% electrical test on a GENRAD tester. Automated testing removes operator error and reduces test time.

Moving from a Morningstar functional test fixture to the GENRAD computer proved to be much more difficult than expected. For example:

- a custom bed-of-nails test fixture is required, and initially only individual boards will be tested on the GENRAD vs. an array of 10 that can be tested with the Morningstar fixture
- the GENRAD analog to digital converter is so fast that only parts of the oscillator periods were being captured, so it was necessary to average 25,000 data samples for an accurate Vbat calibration
- the hysterisis in the PWM control loop had to be carefully filtered to produce the required level of accuracy
- it was necessary to calibrate the GENRAD system to compensate for contact and wiring losses, plus some temperature offset effects

Twenty "golden boards" were carefully hand calibrated on actual PV systems to serve as the reference to calibrate the GENRAD. It required about a month to calibrate the GENRAD to the required tolerances. As experience is gained in production, the GENRAD testing is expected to become faster.

e) **Final assembly / potting**

- DTI, Model MIX 750 - bulk meter mix dispensing system

A custom epoxy potting material was formulated to encapsulate the SunSaver board assembly. This material's special properties include high thermal conductivity, long-term stability to extreme environmental conditions, a coefficient of thermal expansion that matches closely to the board assembly, and a Shore A hardness under 90 to minimize thermal cycle stress on the components.

The initial material viscosity was 70,000 cps which proved to be unsuitable for volume production. After 3 months of testing and modifications, the viscosity was reduced to 28,000 cps. This material is then heated for production to 110°F so that the viscosity is further reduced to 8,000 cps.

A special room was constructed by MATCO to semi-automate the potting and final assembly. The potting material is stored in 750 mL cartridges at 40°F, then preheated, and finally dispensed in a fixed-ratio, positive displacement meter mix dispensing system. The 2-part epoxy is combined in a special mixing nozzle at a 1:1 ratio. The final curing is done in a room heated to 150°F.

To meet the cost and reliability requirements of the SunSaver project, the potting material, dispensing system, and assembly facility had to be specially designed.

MANUFACTURING GOAL #5: TOTAL QUALITY PROGRAM

No amount of investment, technology or automation will prove to be cost effective unless there also exists strong management and effective quality programs. Both Morningstar and MATCO have a full commitment to total quality programs to ensure the manufacturing process will produce high-quality controllers every time.

All the MATCO facilities are ISO 9002 certified.

MATCO has established a comprehensive Total Quality Management (TQM) process and a Continuous Quality Improvement (CQI) program. These quality assurance programs follow the requirements of the ISO 9000 / Q90 series Quality Management Standards.

2.4 FOURTH OBJECTIVE: DESIGN VERIFICATION TESTING

The final objective of this development project was to validate the technology and the design. This last step is especially critical since the product starts shipping at rates of 2,000 units per month, and the majority of the controllers are shipped overseas.

Tests were conducted throughout the development process so that preproduction testing covered a period of about 15 months. The first simple breadboard was tested to confirm stability of the analog PWM control. Each incremental change or new prototype was then fully tested. By the end of the design phase when the final prototypes were tested, a great deal of data and experience with the circuit had been acquired.

Most of the ongoing testing over the 15-month development period was done on the bench at the component or subassembly level. The behavior of the circuit and the schematic values were constantly being measured to move the design forward. This level of testing on the circuit itself is beyond the scope of this report.

Of more interest for this report are the functional and performance tests that prove the operating characteristics of the circuit in PV systems. These tests also include EMI and reliability testing to ensure that the design goals were achieved. This test data also provide the foundation for future improvements to the design.

This validation testing of the final design is described in the following categories:

A) Morningstar test facility

B) Functional test matrix

C) Lab certification tests

D) Environmental chamber tests

E) Ongoing and future tests

A) MORNINGSTAR TEST FACILITY

Most of the in-house testing was done by Dan Welsh, Vice President of Engineering, at Morningstar's Solana Beach, CA facility. Equipment and test bays dedicated to the SunSaver functional testing includes:

- 600-Wp PV array in five subarrays
- 400-Ah battery storage
- 60V, 30A dc power supply
- 16 channels of 12-bit data acquisition @ 1 Hz

- 8 channels of 8-bit data acquisition @ 10kHz
- 16 thermocouple channels
- environmental chamber (-40°C to 100°C)
- test loads including incandescent, fluorescent, motor, radio, inverter, and relay loads

The facility is presently being expanded to add four identical long-term test stations. Each includes a 240-Wp PV array, 200-Ah battery, 12 channels of data acquisition, matched loads, and fully instrumented controller stands.

B) FUNCTIONAL TEST MATRIX (See Appendix)

An initial functional test plan was written in May 1995. As the design evolved into working prototypes, a test matrix and written test procedures were completed 19 July 95. As the SunSaver design progressed closer to its final configuration, the test matrix was modified to REV 2 dated 8 Nov 95.

REV 2, titled "SS-Design Verification Tests," served as the record for final verification testing. A copy of the results of some of the final testing, covering the period 11 April 96 to 20 April 96, is included in the Appendix.

This test matrix documents the functional performance testing for all five SunSaver models. It is a series of 93 system oriented tests to document and verify the operation and performance of the controllers to the design specifications. It is important to note that this set of functional tests was developed by PV system engineers who have over 10 years of experience with international PV systems.

The matrix of verification tests is divided into 10 categories. These are described below with some comments on the test results.

1. SPECIFICATIONS

These tests cover some general specifications that are not found elsewhere in the test matrix. Although the tare losses are equal to the initial SunSaver specifications, note that these losses are 1.5 to 2 mA above the target specifications that were derived from earlier prototypes. This increase resulted from final changes to the circuit to make it more robust, and there are a number of ways being considered to reduce self-consumption by 1-2 mA.

One significant improvement over the original design specifications was in the area of voltage drops. A low voltage drop in the controller gives the PV module more voltage headroom to operate in the peak battery charging area of the I-V curve. Since most small PV controllers are shunt designs, the SunSaver spec goal was to drop less voltage than the Schottky diodes used in shunt models. The specified and measured voltage drops are summarized as follows:

specification at 75% rated current	= 0.4 V	PV-Battery
	= 0.3 V	Battery-Load
test result at 100% rated current	= 0.3 V	PV-Battery
	= 0.15 V	Battery-Load
test result at 50% rated current	= 0.14 V	PV-Battery
	= 0.08 V	Battery-Load

2. BATTERY CHARGING

One purpose of this section is to test the stability of the PWM and the duty cycle under extreme system conditions. The results indicate that the SunSaver's analog version of the PWM is extremely stable under any operating condition that might occur in PV systems.

All five models were first tested on PV systems with relatively stable conditions (e.g., light clouds). The absolute max and min Vr (voltage regulation setpoint) values in PWM were at most 0.009 volts apart. This was confirmed by other stability tests, and indicates the constant voltage Vr will generally vary only about ±0.03% from its setpoint during PWM.

When tested under sharply changing conditions, the Vr remained very stable, and the results were consistently reproducible. To test the full range of the circuit's response to changing conditions, many of these stability tests were repeated on unpotted units with the temp comp defeated.

With some other "PWM constant voltage" PV controllers, it has been observed that the battery voltage can rise to dangerous levels after the battery reaches full charge. The SunSaver tests for stable operation at 0% and 100% duty cycles confirmed that this problem cannot occur with the SunSaver design.

In addition to the stability tests, many battery charge curves were recorded on the bench and in actual PV systems. Two curves are included as Figures 7 and 8. The nature of the constant voltage algorithm and the SunSaver's stability under variable conditions can be clearly seen.

3. FET'S

The ability to operate the FET's is critical to the reliability and operating life of PV controllers. Subtle design flaws can produce poor battery charging, controller overheating, and reliability problems. While most FET testing was done at the board level, the functional tests serve as a macro check of the FET operation in systems.

Based on experience from the ProStar development, there was an early concern over the potential for some form of capacitive coupling between the aluminum case and the board assembly that could effect the FET operation. Careful gate drive design and board layout eliminated this potential problem. Testing of the final assembled and potted units could not measure any such capacitive effects.

4. TEMPERATURE COMPENSATION

The design for temperature correction has been discussed earlier. One original design goal shown in this test matrix was that a failure in the temperature correction circuit would cause the controller to default to 25°C operation. This proved to be too costly to implement, and thus the test note indicates "fails."

Given this cost constraint, the temperature compensation circuit was then significantly strengthened to protect against surges and transients. It was tested successfully at a licensed lab for ±8 kV electrostatic discharge pulses. The air discharges were applied all over the controller, and also included were ±4 kV pulses in direct contact with the temperature sensor. In addition, Morningstar has not been able to fail this part of the circuit in destructive testing.

The test data for the temperature sensor (MTS - marked #6) records measured temperatures that range between 1°C and 10°C above ambient. Given the 4°C offset built into the circuit, this means the sensor can measure up to 6°C over ambient worst-case (Vr is 0.12 volts lower than the setpoint) and eventually will correct to 3°C below ambient (Vr is 0.06 volts higher than the setpoint) in finishing charge at low current levels (see Battery Life Goal #5).

At full charge before regulation begins, the data indicates the sensor will typically read 1°C above ambient (5°C minus 4°C offset) so that PWM will begin about 0.02 volts below the setpoint.

5. LVD

The low voltage load disconnect was originally specified to be 11.3 volts, but this was subsequently changed to 11.5 volts.

The original specification also included a 2-second delay to prevent nuisance load disconnects due to transient conditions. It was determined later that 0.5 seconds was an optimal value for the circuit design. So, the LVD was rigorously tested with harsh loads, with noisy loads and high inrush currents at low battery voltages just above the LVD. It was concluded that there is no difference in stability between 2 seconds and 0.5 seconds of delay.

The testing confirmed that the LVD function is very stable and is not affected by abnormal system conditions.

6. THERMAL TESTING

High-temperature equilibrium under worst-case conditions was a major design issue, as discussed earlier (Reliability Goal #3). These functional tests are system level tests to ensure the thermal model is accurate for the full range of PV system conditions found in the field.

Numerous prototype units had thermocouples epoxy bonded to the FETs, areas of the board assembly, and to the case. Testing was done with and without potting over three evolutions of the design. This allowed calibration of the thermal model so that the thermal impact of design or material changes could be accurately predicted.

The temperatures measured during testing were converted into a temperature gradient profile to confirm the heat transfer from the FET junctions to the case. This is illustrated in Figure 11.

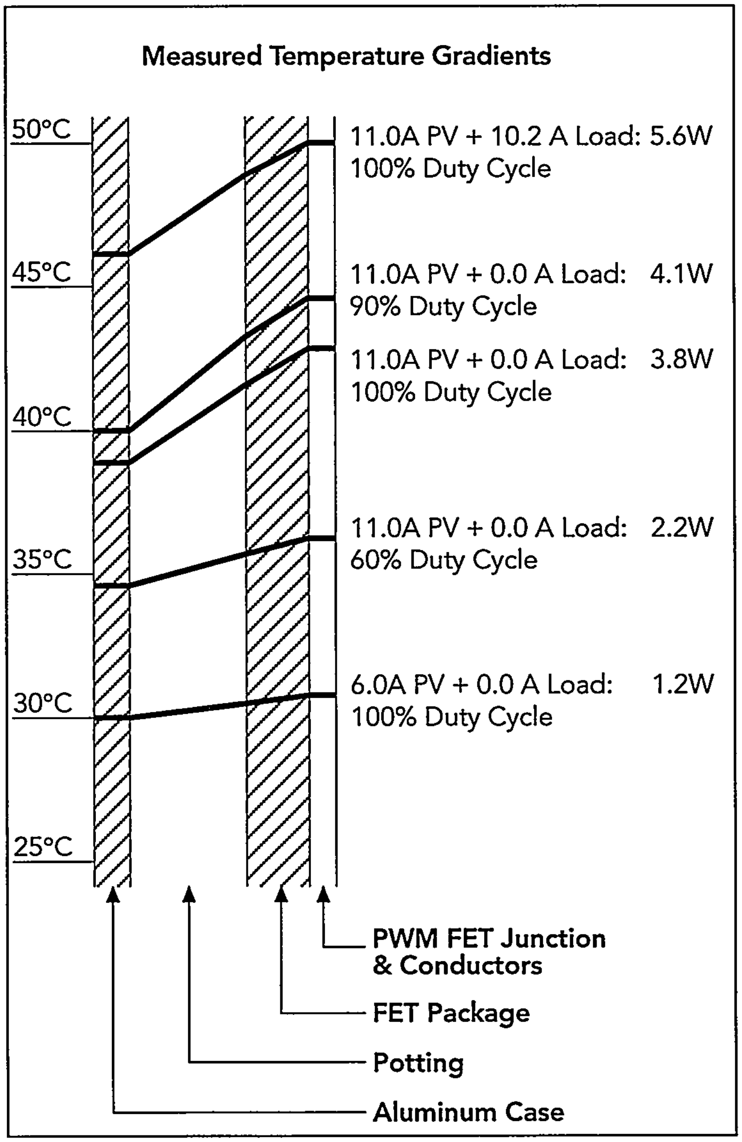


Figure 11. SunSaver Temperature Gradients.

The test matrix captures just a small amount of the thermal data recorded. The overall thermal testing has proven the design model to be extremely accurate and conservative, and the final FET junction temperatures are slightly lower than predicted by the model.

Enclosure thermal profiles will be completed over the summer. The worst-case heating test for horizontal mounting was done in January and not repeated in these tests. The potting stress testing is presently ongoing for 800 cycles in an environmental chamber for thermal cycles from -30°C to +85°C. After most of these thermal stress cycles have been completed, there have been no failures.

7. EMI / NOISE

This part of the circuit copies the ProStar, which has proven to be very effective with EMI and noise. Rigorous EMI testing of the SunSaver for CE certification was completed in June.

These functional tests confirm that noise in the PV system cannot affect the operation of the SunSaver, and noise from the controller will not affect loads.

8. LOADS

Given the diverse types of loads a PV controller will operate, functional testing must include a complete set of the loads that typically cause the most problems. This is only a partial list of the loads that were tested. Note the inrush loads tested to 125 amps peak.

Again, this part of the circuit emulates the ProStar, and the behavior was accurately predicted from 2 years of load testing with the ProStar.

9. CONNECTIONS

Users and installers demonstrate remarkable creativity in the methods by which they connect and operate a PV controller. These tests cover some of the more stressful interactions between controller and user to detect sensitive or weak areas.

10. PROTECTION / OPERATION

These last tests are to verify certain critical protection and operating features. The design allows the battery to be removed during daytime charging (as often occurs in the field), and the controller will continue to operate powered by the PV array. This ensures that the loads will not be damaged by sudden open-circuit voltage spikes from the PV array.

A variety of loads were tested with the battery removed to confirm that none could be damaged. When the array is connected, the voltage typically rises to 15-16 volts. The array is then disconnected in PWM, and the capacitors in the controller power the load while the voltage drops to about 10 volts. With large loads, the unit sometimes goes into LVD.

The controllers parallel with no problems. Also, any reversed connection cannot harm the controller. In theory, multiple reversed polarity connections could possibly cause damage. However, many of these combined reverse polarity tests were done, and no damage was ever suffered by any of the test controllers. It is unlikely there will be any damage in the field from multiple reversed connections.

In the last evolution of the design, testing of the day-night circuit (which opens the PV FETs at night to prevent reverse current leakage) indicated a potential problem. A harsh transient that is present at sunrise damaged a protective component in one test unit, so this part of the circuit had to be reconfigured. It was necessary to isolate this part of the circuit from the rest of the power control circuits to fully protect it. These changes added about 8 weeks to the schedule, but this test provided the opportunity to eliminate any chance of a failure in the field.

C) LAB CERTIFICATION TESTS

Photovoltaic controllers shipped into Europe must comply with the European Directive for EMC and be certified for the CE mark. Certification requires passing a series of very rigorous EMI tests. This testing also forms a significant part of Morningstar's verification test plan for the SunSaver.

The SunSaver was tested by MET Laboratories, Inc. MET Labs is a nationally licensed testing lab which has been approved by three European Competent Bodies for testing to the European EMC Directive.

The SunSaver successfully passed this testing in June 1996, and the CE mark is being added to the label. The tests include the following:

- EN 61000-4-2 Electrostatic Discharge
  Electrostatic air discharges of ±8 kV and contact discharges of ±4 kV are applied over 10 times each at all locations on the controller while it is operating.
- ENV 50140 Radiated Electromagnetic Field
  The controller is operated for 24 specific tests in a radiated electromagnetic field of 3 V/m in the frequency band of 80 MHz to 1000 MHz.
- EN 61000-4-4 Electrical Fast Transient/Burst
  The controller is operated with positive and negative transients applied to the power cables. Eight specific tests are done to different cable configurations, with 15 msec burst durations as shown in Figure 12.
- EN 50081-1 Radiated Emissions
  This tests for emissions from the controller. No radiated emissions were detectable. This test also passes U.S. FCC requirements.

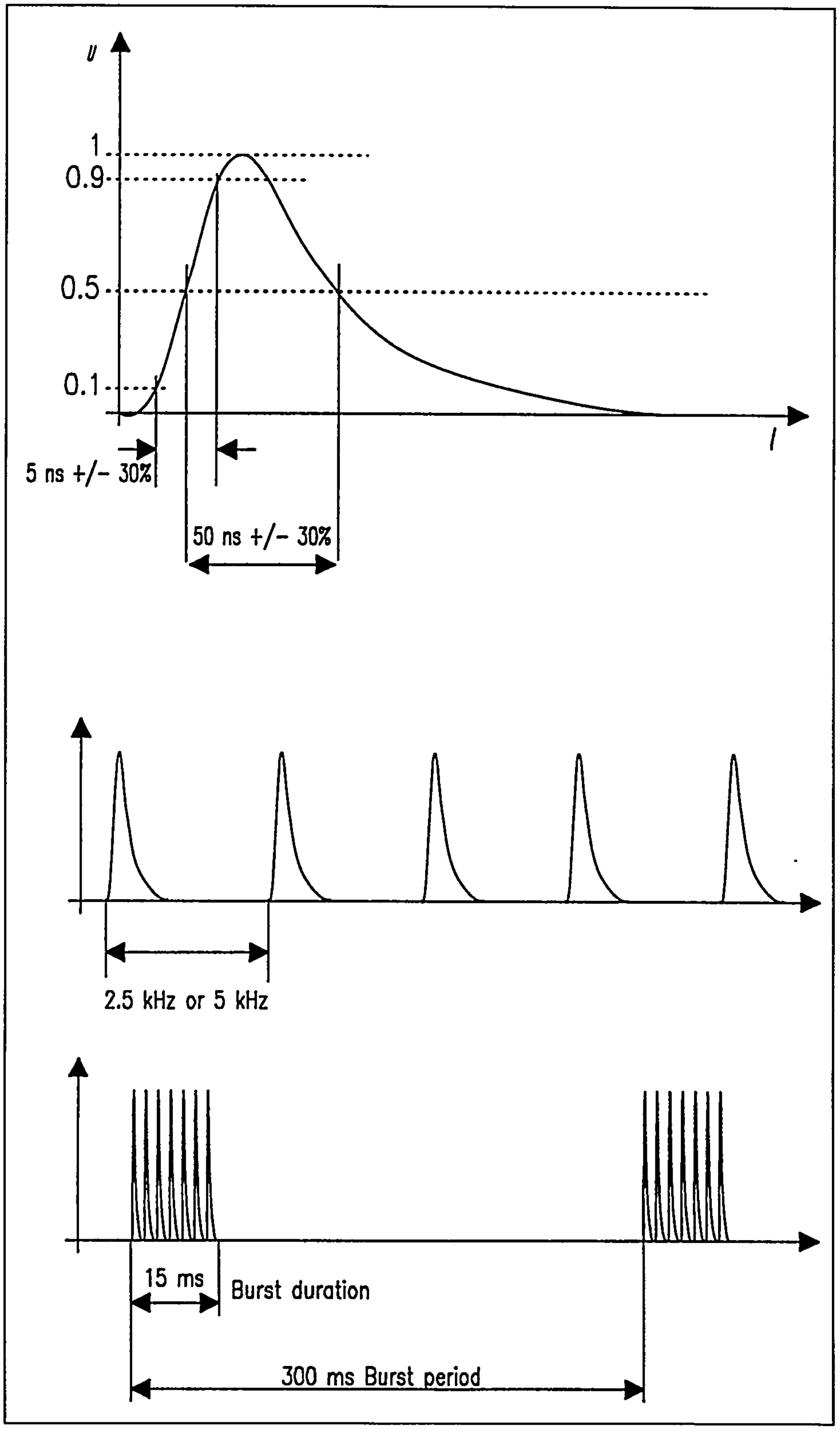


Figure 12. Fast Transient/Burst Test Waveform.

D) ENVIRONMENTAL CHAMBER TESTS

Temperature extremes will often cause circuits that operate perfectly at room temperature to fail. Because PV controllers are exposed to temperature extremes more than most electronic devices, Morningstar does long-term environmental testing in-house for all controllers.

Before releasing the SunSaver to production, it was performance tested over a wide temperature range and stress tested for failures. Specific tests included:

- operate at elevated temperatures to thermally stress the circuit
- test for potting stress from -30°C to +85°C
- temperature stability of the circuit from -20°C to +60°C
- behavior of the temperature compensation circuit in operating controllers from -10°C to +50°C
- unit start-up at -30°C
- verify the thermal model design for 25°C, -40°C, and +60°C cycles

Typically, five test units (one of each model type) are placed in the temperature chamber. The units are connected to a PV array, battery and loads. The battery may be inside or outside the chamber, depending on the type of test.

After specs and performance were tested at temperature extremes, long-term stress testing was started. An 800-cycle test that thermally stresses the circuit has been mostly completed, and this also confirms that the board design will not be damaged by potting stresses.

Since the controller is exposed to very large thermal cycles, it is critical to confirm that the potting encapsulation will not damage components on the board during these cycles. Early testing was done with very hard 85 Shore D material, and the final production units have been tested with the softer Shore A material. The long-term thermal test cycles use controllers with both the hard and soft potting material. There have been no failures after months of testing.

E) ONGOING AND FUTURE TESTS

In addition to long-term temperature cycling, other tests are planned for the SunSaver. Most of these tests are to further characterize the behavior of the design for future improvements.

Near-term tests that are planned include:

- battery charging
- heat rise in various enclosure types
- UL and Factory Mutual certification

In summary, the SunSaver has passed all the verification tests. Over 4,000 units have been shipped at the time of writing this report. The results of the extensive testing clearly demonstrate that this design significantly exceeds the original performance and reliability specifications.

3.0 CONCLUSION

The research done under Phase 2 of the BOS Development Program resulted in significantly advancing the technology for small PV system controllers in a number of areas.

Extensive testing confirms a robust design with excellent lightning and overvoltage protection, the ability to operate in worst-case environments, and very low operating temperatures that provide the margin needed to exceed 15-year lifetimes. In addition, the testing indicates improved battery charging efficiency. The advanced charging algorithm is capable of recharging a PV battery quickly to full charge, yet minimizes harmful heating and gassing.

Finally, to remain cost competitive and commercially viable, much of the development effort was devoted to the manufacturing of the controller. The latest surface-mount devices and automated production technologies are used to increase quality and reduce costs. The first pass yield for the initial production run was 98%, and this has improved to over 99% on the second run.

The resulting commercial product, the SunSaver, elevates the technology, value and performance of small controllers up to the level of the PV modules. The product started shipping in May 1996, at a rate of 2,000 units per month. Over 75% of the new controllers are shipping directly to international markets, and part of the balance is going overseas via U.S. distributors. The market reaction to this new controller has been very positive.

A number of new controller models are presently being designed based on the circuit developed under this BOS Development project. Since the reliability and performance of the circuit has proven to be so strong, new models will focus design resources on additional features for special applications and continued cost reductions.

REFERENCES

1. *The National Photovoltaics Program Plan for 1996 - 2000*, U.S. Department of Energy, Washington, DC, January 1996, 25.

2. Ibid., 25.

3. Crosetti, Michael, "Household Photovoltaic Systems in Developing Countries: Experience, Issues and Outlook," The World Bank, Washington, DC, presented at 10th European PV Conference, 1991, 1349.

4. Posorski, R., "From Aid Projects to the Market Introduction of PV Systems," GTZ, Energy Division, Germany, presented at 10th European PV Conference, 1991, 1354.

5. Dr. Wiesner, "Photovoltaic-powered Television Relay Station," TUV Rheinland, Germany, presented at 10th European PV Conference, 1991, 1167.

6. Transient Voltage Suppressor, Semitek Ishizuka Electronics Corp., Catalog No. 67A.

7. Metal Oxide Varistor, Semitek Ishizuka Electronics Corp., Catalog No. 82B.

8. Transient Voltage Suppression Products, Semtech Corp., 1994 Catalog, 48.

9. Transient Voltage Suppression Products, Semtech Corp., 1994 Catalog, 42.

10. Transient Voltage Suppression Products, Semtech Corp., 1994 Catalog, 46.

11. Transient Voltage Suppression Products, Semtech Corp., 1994 Catalog, 49.

12. ADMA-OPCO, United Arab Emirates, Test data provided during meeting with author in Abu Dhabi, 1991.

13. *The National Photovoltaics Program Plan for 1996 - 2000*, U.S. Department of Energy, Washington, DC, January 1996.

14. Hammond, Robert, "Photovoltaic Industry Battery Survey," Southwest Technology Development Institute, Las Cruces, NM, April 1993.

15. Woodworth, Joseph, "Evaluation of the Batteries and Charge Controllers in Small Stand-Alone Photovoltaic Systems," Sandia National Labs, Presented at WCPEC, Hawaii, December 1994, 8.

16. Ibid., 2.

17. "Pulse Charging of Lead-Acid Batteries," Private consultant for Morningstar Corporation, May 1994.

18. Mulcahy, Joe, "Gassing Characteristics of GNB Absolyte II Sealed Cells," GNB Industrial Battery Co., 1990.

McKinney, Bryan, "The Comparison of Flooded, Gelled and Immobilized Lead-Acid Batteries," Johnson Controls, Inc., 1984.

Gerner, Scott, "Thermal Management of Valve Regulated Lead-Acid Batteries," Johnson Controls, Inc.

Alminauskas, V., "Performance Evaluation of Lead Acid Batteries for Use with Solar Panels," Crane Division, Naval Surface Warfare Center.

Harrington, Steve, "Balance-of-System Workshop," Sandia National Laboratories, Soltech 1992.

Dunlop, J., "Evaluation of Batteries for Photovoltaic Systems," Florida Solar Energy Center, July 1994.

Dunlop, J., "Battery Charge Controllers for PV Systems," Florida Solar Energy Center, FSEC Test Results - Phase 2.

Stevens, John, "Field Investigation of the Relationship Between Battery Size and PV System Performance," Sandia National Laboratories.

19. Vinal, George, *Storage Batteries*, John Wiley & Sons, Fourth Edition, 1955, 240.

20. Technical Marketing Staff, *Rechargeable Batteries Applications Handbook*, Butterworth-Heinemann, Gates Energy Products, 1992.

21. McCarthy, S., "Developments in Battery Storage for PV," Hyperion Energy Systems, Ltd., Cork Ireland, 1991.

22. Hobson, Ronald, "Tiny Components Evolve Rapidly for SMT Assembly," *Electronic Business Buyer*, June 1995, 511

23. Coombs, Clyde, *Printed Circuits Handbook*, McGraw-Hill, Fourth Edition, 1996, 5.1-5.47.

24. Ibid., 5.3.

APPENDIX

This is a copy of design verification test results for the SunSaver covering the period from April 11 to April 20, 1996.

A review and discussion of these test results can be found in Section 2.4-B of this report (Functional Test Matrix) beginning on page 46.

Final Testing
4/11/96 - 4/20/96

SS - Design Verification Tests

	REV 2 11-8-95	SS6	SS6-LVD (6-6L)	SS10	SS10-LVD	~~SS10-L20~~ SS6-10L	Notes
	SPECS						
	• 30 volts at PV input	Pass	Pass	Pass	Pass	Pass	Applied 10 times, maintained 30 minutes
	• Temp comp = -20 mV/°C	-19.4	-20.9	-19.7	-19.5	-20.1	+50°C to -10°C Nominal
1	• Voltage drops						25, 50, 75, 100% of rated current
	• Parasitic losses						SS-6 and SS-10
	Night	4.98	4.97	4.99	5.01	4.97	
	Charging	5.02	5.03	5.02	5.04	5.01	Green Led draws 1.5mA off array
	LVD	—	6.48	—	6.53	6.49	
	• Reverse current leakage	<10μA	<10μA	<10μA	<10μA	<10μA	Ambient temp = 24°C
	• Minimum voltage to operate	Pass	Pass	Pass	Pass	Pass	Test @ 6V battery
	• LED's bright enough? green	✓	✓	✓	✓	✓	Visual
	red	—	✓	—	✓	✓	
	CHARGING						
	• PWM frequency	342 Hz	351 Hz	347 Hz	334 Hz	339 Hz	
	• PWM duty cycle (0-100%)	Pass	Pass	Pass	Pass	Pass	Stable at 0 and 100%
2	• PWM voltage variation						± volts around Vr (vary PV & loads)
3	• Vr stability, repeatability						Temp, load, PV variations
4	• Vr accuracy (± error)						at 1A and 10A PV
	• Temp stability of reference	± 1.1mV	± 0.9mV	± 1.0mV	± 0.8mV	± 0.9mV	+60°C to -20°C Nominal
	• Sealed / flooded	Pass	Pass	Pass	Pass	Pass	Change repeatedly
5	• Sudden loss of PV	Stable	Stable	Stable	Stable	Stable	PWM charge pump

SS - Design Verification Tests

	REV 2 11-8-95	SS6	SS6-LVD	SS10	SS10-LVD	SS10-L20	Notes
	• Highly variable PV	No	No	No	No	No	PWM charge pump become unstable?
	• PWM too fast? 0-10% Duty Cycle	Stable	Stable	Stable	Stable	Stable	Conditions too fast to fully enhance?
	• Highest voltage above Vr	—	—	—	—	—	Extreme conditions force Vr higher
	• Can Vbatt creep up > Vr	No	No	No	No	No	Batt voltage creeps up over time?
	FET's						
	• Case capacitance	Not Measurable	—	—	—	—	Raise drive current too high?
Same	• Min width of PWM pulse	180 μsec	210 μsec	195 μsec	220 μsec	200 μsec	Minimum ON time
	• Risetime (PWM & ~~LVD~~)	30 μsec	32 μsec	43 μsec	40 μsec	31 μsec	Compare to ProStar Similar to PS-12 + PS-20
	• Time integration via ~~C8~~ C12	—	—	—	—	—	Ensure FET fully enhanced
59	• Parallel FETs	—	—	No	No	NO	Any oscillation or resonant condition?
	• LVD reconnect time	< 200 μsec	< 200 μsec	< 200 μsec	< 200 μsec	< 200 μsec	Conditions that can cause oscillation?
	TEMP COMP						
6	• Temp rise at MTS						25, 50, 75, 100% of rated current
	• Accuracy of TC	± 1mV/°C	± 1mV/°C	± 1mV/°C	± 1mV/°C	± 1mV/°C	Over operating temp range
	• Consequence of MTS failure	Unit Fails	Units Fails*	Unit Fails*	Unit Fails*	Unit Fails*	MTS SHORT Vr ↓ to about 9V-
			~~[illegible]~~				MTS OPEN Vr ↑ to 25V - battery
	LVD						
	• Setpoints	N/A	D / N	N/A	D / N	D / N	
	LVD	|	11.42 / 11.51	|	11.44 / 11.47	11.37 / 11.51	Both nite and charging
	LVDr	|	12.43 / 12.44	|	12.40 / 12.39	12.46 / 12.45	Both nite and charging
			L / NL		L / NL	L / NL	

SS - Design Verification Tests

REV 2 11-8-95	SS6	SS6-LVD	SS10	SS10-LVD	SS10-L20 (SS-6-102)	Notes
• Accuracy (± error)	~~±—~~	± 50mV	—	± 50mV	± 50mV	Average Value is too high though
• Sealed / flooded	~~Yes~~	Yes	~~Yes~~	Yes	Yes	LVD remains same?
• LED on/off	│	No	│	NO	NO	Is LED "ON" during 2 second delay?
• Time delay (2 sec)	│	0.5 sec	│	0.6sec	0.4 sec	
• Sensitivity to temp (±)	│	None	│	None	None	
• Verify not temp comp.	│	11.51	│	11.49	11.53	+ 50 °C
• Rapid voltage changes	│	O.K.	│	O.K.	O.K.	roughly ± 0.1 volt around LVD & LVDr
• Large new load at 11.4 V	│	O.K.	│	O.K.	O.K.	apply about 1 to 1.5 sec - disconnect?
• Start loads "ON" with LVDr	│	O.K.	│	O.K.	O.K.	motor & harsh loads, overstress FET?
THERMAL						
• Confirm all current ratings				23-25 °C		Max heat rise to equilibrium 10A Array 18A load
During full charging				10-12°C		10A Array 13A Load
In PWM				12°C-15°C		90% duty 10A Array 3A Load
• Confirm 5 minute overload				O.K.		25% overload ratings, stable temp
• Verify optional load ratings				NO		Can 20 amp load rating be increased?
• Max FET junction temps				+40-45°C		Calculate from data (degrees above ambient)
• Thermal profile				Q1-Q3 Top		Identify hot spots & heat delta
• Confirm thermal model				O.K. so far		Tune the assumptions of model
• Environmental:						
Direct sun						Heat rise enough to burn user?
Inside small enclosure						Additional heat rise during charging

SS - Design Verification Tests

REV 2 11-8-95	SS6	SS6-LVD	SS10	SS10-LVD	SS10-L20	Notes
Water entry				Spray O.K.		Operation with water entry via rain
Start-up at low temp	Pass	Pass	Pass	Pass	Pass	Can SS start at -40°C temps? (Tested @
• Confirm operation +85°C	Pass	Pass	Pass	Pass	Pass	Ambient + heat rise = 85°C
• Worst-case mounting						Added heat rise - horizontal mount
• Max PCB trace temp (CALC)				24°C / 45°C		10A Load / 20A Load
• Potting stress testing		2 units		3 units	1 unit	Rapid extreme temp cycles {Misc. potting 2.1 + 2.2 versions
Cycles A / B (OFF)		50 / 750		50 / 750	50 / 750	A = -30°C ↔ +50°C B = +30°C ↔ 85°C
EMI / NOISE						
• Noise input at batt terminals				Vr Varies		Interfere with PWM, operation?
• Noise input at load terminals				Vr Varies		
• Noise input at PV terminals				Not Noticeable		
• Radiated noise into SS				No Effect		Interfere with SS operation?
• Measure SS noise to loads						Interfere with loads? Not integrated to Semiclass to PS.
LOADS						
• Confirm 10X inrush rating	OK			OK 125A peak	OK 125A peak	Use Cold 10A incandescent
• Inductive loads	OK			OK	OK	Charging & PWM (starter)
• Capacitive loads	OK			OK	OK	Charging & PWM (motor w/ starter cap)
• Very noisy loads (Inverter)	OK			OK	OK	Charging & PWM (12W flourescent)
• Loads > 25 ft away	OK			OK	OK	Using 100' Cord
• ~~Inverter at SS and battery~~ Switching Supply	OK			OK	OK	

SS - Design Verification Tests

REV 2 11-8-95	SS6	SS6-LVD	SS10	SS10-LVD	SS10-L20	Notes
CONNECTIONS						[User & system issues]
• Disconnect / reconnect	OK			OK		All 6 connections, rapidly
At nite with load & no load	OK			OK.		
At full charging	OK			OK		
In PWM	OK			OK		
• Above tests, but jiggle wire	OK			OK		Rapidly jiggle loose wire in terminals
• Switch loads on/off rapidly	OK			OK		At nite; full charging; PWM
• Connect wire to terminal #7	OK			OK		PV, Battery, Load (both + & -)
• Reverse load polarity	OK			OK		Both sealed/flooded - any effect?
PROTECTION / OPERATION						
• Remove battery						Charging & PWM
Max voltage to the load						
Max time to shut-off						
Disconnect during powerup	OK	OK	OK	OK	OK	
• Parallel						
At night, under load	OK	OK	OK	OK	OK	
Charging with load	OK	OK	OK	OK	OK	10% & 100% PV rating .5A, 3A, 5A
PWM with load	OK	OK	OK	OK	OK	Different loads .5A, 3A Loads
Rapidly switch 1 load	OK			OK		Turn load on & off rapidly

SS - Design Verification Tests

REV 2 11-8-95	SS6	SS6-LVD	SS10	SS10-LVD	SS10-L20	Notes
• Day-nite selection						Stable & consistent selection
During full charge	0-43s	0-44s	0-47s	0-41s	0-45s	Remove array
During PWM	<100ms	<100ms	<100ms	<100ms	<100ms	Remove array
OFF cycle 1 minute	43s	44s	47s	41s	45s	± variation, any drift?
Low light conditions	No	No	No	No	No	Can nite selection become unstable?
• Reverse polarity	OK			OK		PV, Battery, Load - high currents, > 1 hr
Any sequence of connection	OK			OK		Note any LED indications
Multiple reversed connect.	OK			OK		Array + Battery Reversed

See additional data for items marked 1-8

Dave Katz
Alternative Energy Engineering
P. O. Box 339
Redway CA 95560

Jack Knowles
Ananda Power Technologies
14618 Tyler Foote Road
Nevada City CA 95959

Timothy Ball
Applied Power Corporation
1210 Homann Drive S.E.
Lacey WA 98503

R. Hobbs
Arizona Public Service
P. O. Box 5399
Phoenix AZ 85072

Herb Hayden
Arizona Public Service
MS-8931, P. O. Box 53999
Phoenix AZ 85072-3999

Bob Hammond
Arizona State University
CERS/CEAS
Tempe AZ 85287-5806

Miles Russell
Ascension Technology
P. O. Box 314
Lincoln Center MA 01773

Bruce Wilson
Atlantic Solar Products
P. O. Box 70060
Baltimore MD 21702

Steve Willey
Backwoods Solar Electric Systems
8530 Rapid Lightning Creek Road
Sandpoint ID 83864

Joe Bobler
BP Solar, Inc.
2300 N. Watney Way
Fairfield CA 94533

Larry S. Meisner
C & D Powercom
P. O. Box 3053
Blue Bell PA 91422-0858

Ed Mahoney
Concorde Battery Corporation
2009 San Bernadino Road
West Covina CA 91790

Russell Newnham
CSIRO Div. of Mineral Products
P. O. Box 124
Port Melbourne Victoria 3207 Australia

Cedric Currin
Currin Corporation
P. O. Box 1191
Midland MI 48641-1191

Mark Boram
Delco/Delphi Energy
P. O. Box 2439
Anderson IN 46018

Jeffrey J. Randall
Direct Power & Water
3455-A Princeton N.E.
Albuquerque NM 87107-

Gene Cook
Douglas Battery Company
P. O. Box 91
Furlong PA 18925

Gene Hitney
E V Solar Products
2655 N. Highway #89
Chino Valley AZ 86323

Renwick Santangelo
East Penn Manufacturing Co., Inc.
Deka Road
Lyon Station PA 19536

R. Schainker
Electric Power Research Institute
P. O. Box 10412
Palo Alto CA 94303-0813

Abtahi Amir
GeoSolar Energy Systems, Inc.
3401 N. Federal Highway
Boca Raton FL 33431-

Stephen L. Vechy
GNB Industrial Battery Co.
829 Parkview Blvd.
Lombard IL 60148-3249

Dan Gilman
GSE Solar Systems
17451 Racoon Ave., #12
Adelanto CA 92301

Mark J. Heinz
Heinz Solar
16575 Via Corto East
Desert Hot Spgs. CA 92240-

Sam Dawson
Heliotrope General
3733 Kenora Drive
Spring Valley CA 91977

J. Cole
ILZRO
P. O. Box 12036
Research Triangle Park NC 27709

P. Moseley
ILZRO
P. O. Box 12036
Research Triangle Park NC 27709

C. Parker
ILZRO
P. O. Box 12036
Research Triangle Park NC 27709

Bill Holmquist
Industrial Battery Engineering, Inc.
9121 DeGarmo Avenue
Sun Valley CA 91352

Paul Garvison
Integrated Power Corporation
7618 Hayward Road
Frederick MD 21702-3006

Thomas Ruhlmann
Johnson Controls, Inc.
P. O. Box 591
Milwaukee WI 53201

Mike Sagrillo
Lake Michigan Wind & Sun
3971 Bluebird Road
Forestville WI 54213

Ken Gerken
Morningstar Corporation
3414 Morningwood Dr., Ste. 200B
Olney MD 20832

Richard DeBlasio
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden CO 80401

Larry Flowers
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden CO 80401

S. Hock
National Renewable Energy Laborator
1617 Cole Blvd.
Golden CO 80401

J. Green
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden CO 80401

Ron McConnell
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden CO 80401

Pat Lauzon
Northern Arizona Wind & Sun
2725 E. Lakin Drive #2
Flagstaff AZ 86004

Clint Coleman
Northern Power Systems
P. O. Box 999
Waitsfield VT 05673-0999

Robert Spotts
Photocomm, Inc.
7681 East Grey Road
Scottsdale AZ 85260-4670

William Kaszeta
Photovoltaic Resources International
1902 N. Country Club, Ste. 6
Mesa AZ 85202

Laurence Jennings
Photron Inc.
P. O. Box 578
Willits CA 95490-0578

Arthur D. Sams
Polar Products
2908 Oregon Court, Bldg.K-4
Torrance CA 90503

Daniel Shugar
PowerLight Corporation
2954 San Pablo Avenue
Berkeley CA 94710

Len Loomans
Remote Power, Inc.
12301 North Grant, #230
Denver CO 80241-3130

John Allen Gunn
Scientific Analysis Inc.
6012 E. Shirley Lane
Montgomery AL 36117

Scott Sklar
SEIA
122 C Street N.W.
Washington DC 20001-2109

Clay Aldrich
SEIA
122 C Street N.W.
Washington DC 20001-2109

Al Simpler
Simpler Solar Systems, Inc.
3118 West Tharpe
Tallahassee FL 32303

Steve R. Robbins
Solar Electric Power Company
P. O. Box 2165
Palm City FL 34990-

James Padula
Solar Electric Specialties Company
P. O. Box 537
Willits CA 95490

Michael Collins
Solar Electric, Inc.
5555 Santa Fe Street, #J
San Diego CA 92109

Alan Hurst
Solar Outdoor Lighting, Inc.
3131 S. E. Waaler Street
Stuart FL 34997-

Gerald W. Braun
Solarex Corporation
630 Solarex Court
Frederick MD 21701

Marshall Blalock, Jr.
Southwest Photovoltaic Systems, Inc.
212 E. Main Street
Tomball TX 77375

Terry Staler
Specialty Concepts, Inc.
8954 Mason Avenue
Chatsworth CA 91311

Joe Wise
SunAmp Power
1902 N. Country Club Drive, #8
Mesa AZ 85201

Dan Brandborg
Sunelco Inc.
P. O. Box 1499-C
Hamilton MT 59840

David Kulik
SunWize Energy Systems, Inc.
1151 Flatbush Road
Kingston NY 12401

Sam Vanderhoof
Trace Engineering
5916 195th N.E.
Arlington WA 98223

Jim Drizos
Trojan Battery Company
12380 Clark Street
Santa Fe Springs CA 90670

Don Wallace
U. S. Battery
1675 Sampson Avenue
Corona CA 91719

Daniel F. Ancona
U.S. Department of Energy
FORS/EE-11

Dan A. Sanchez
U.S. Department of Energy
DOE/AL, ETDD Mod 18

Frank M. Stewart
U.S. Department of Energy
Golden Field Off/1617 Cole Blvd.
Golden CO 80401

Robert L. San Martin
U.S. Department of Energy
FORS/EE-1

Richard King
U.S. Department of Energy
FORS/EE-11

Thomas Hall
U.S. Department of Energy
FORS/EE-11

Alec Bulawka
U.S. Department of Energy
FORS/EE-11

Mark Ginsberg
U.S. Department of Energy
FORS/EE-90

Christine Ervin
U.S. Department of Energy
FORS/EE-1

Mark Burger
U.S. Department of Energy
9800 Smith Cass Avenue
Argonne IL 60439

Ronald W. Bowes
U.S. Department of Energy
FORS/EE-14

James Rannels
U.S. Department of Energy
FORS/EE-11

Allan Hoffman
U.S. Department of Energy
FORS/EE-10

Hugh Saussy, Jr.
U.S. Department of Energy
Supp Off, One Congress St.,Ste 1101
Boston MA 02114-1035

James Spaeth
U.S. Department of Energy
1617 Cole Blvd.
Golden CO 80401

Clare Giesen
U.S. Department of Energy
FORS/EE-1

Andre Van Rest
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585

Tex Wilkins
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585

U.S. Department of Energy
P. O. Box 50168
Honolulu HI 96850

Buddy Jackson
U.S. Department of Energy
Atlanta Support,730 Peachtree NE
Atlanta GA 30309-

Rufus Shivers
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585

Gary Stein
U.S. Department of Energy
1420 W.Mockingbird, Ste. 400
Dallas TX 75247-

Joe Galdo
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585-

Robert Becker
U.S. Department of Energy
1617 Cole Blvd.
Golden CO 80401-

Robert Hassett
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585-

Paul Carrier
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585-

Michael Brown
U.S. Department of Energy
FORS/EE-90 FEMP

Wilson Reynolds
U.S. Department of Energy
1312 N. Arcadia Street
Colorado Springs CO 80903

Robert Annan
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585-

Dan Ton
U.S. Department of Energy
FORS/EE-11

Philip N. Overholt
U.S. Department of Energy
FORS/EE-11

Jeff Mazer
U.S. Department of Energy
FORS/EE-11

Tatiana S. Muessel
U.S. Department of Energy
FORS/EE-90

Wendy Butler
U.S. Department of Energy
FORS/EE-70

James Kern
U.S. Department of Energy
FORS/EE-13

Thomas Rueckert
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585

John Archibald
U.S. Department of Energy
FORS/EE-90

Anne Crawley
U.S. Department of Energy
FORS/EE-90

Earl W. Hodge
U.S. Department of Energy
P. O. Box 98518
Las Vegas NV 89193-8518

Gary Burch
U.S. Department of Energy
1000 Independence S.W.
Washington DC 20585

Robert Martin
U.S. Department of Energy
1617 Cole Blvd.
Golden CO 80401

Richard Michaud
U.S. Department of Energy
1 Congress Street
Boston MA 02204

Christopher Powers
U.S. Department of Energy
1617 Cole Blvd.
Golden CO 80401

Peter Goldman
U.S. Department of Energy
FORS/EE-11

Lawrence Slominski
United Solar Systems Corp.
5278 Eastgate Mall
San Diego CA 92121-2814

MS-0513	R. Eagan (1000)
MS-0613	P. Butler (1525)
MS-0613	G. Corey (1525)
MS-0614	R. Jungst (1522)
MS-0702	D. E. Arvizu (6200)
MS-0702	A. Van Arsdall (6200)
MS-0704	C. Hanley (6201)
MS-0704	P. Klimas (6201)
MS-0704	E. Richards (6201)
MS-0752	M. Tatro (6219)
MS-0753	C. P. Cameron (6218)
MS-0753	R. Bonn (6218)
MS-0753	W. Bower (6218)
MS-0753	R. Chapman (6218)
MS-0753	J. Ginn (6218)
MS-0753	R. Hill (6218)
MS-0753	T. Hund (6218) [50]
MS-0753	A. Maish (6218)
MS-0753	H. Post (6218)
MS-0753	M. Ralph (6218)
MS-0753	J. Stevens (6218)
MS-0753	M. Thomas (6218)
MS-0753	PVSAC Library (6218) [5]
MS-0953	W. Alzheimer (1500)
MS-0619	Review and Approval for DOE/OSTI (12690) [2]
MS-0899	Technical Library (4414) [5]
MS-9018	Central Technical Files (8940-2)