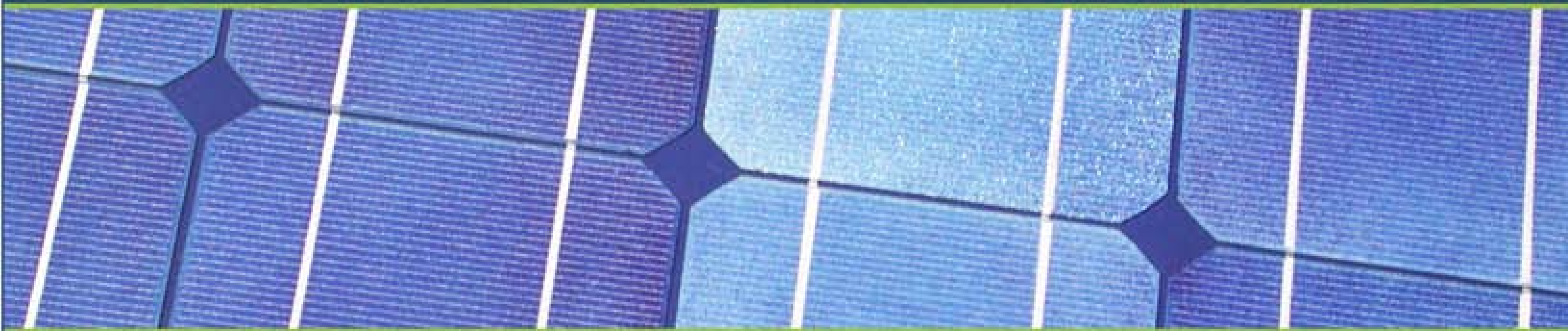

SOLAR ENERGY TECHNOLOGIES PROGRAM

Accelerated Aging Testing and Reliability in Photovoltaics Workshop II Summary Report
April 1st and 2nd 2008

Sponsored by:

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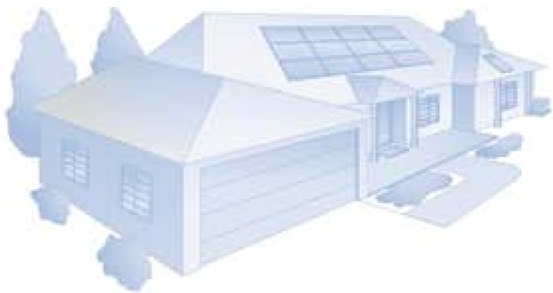

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Executive Summary

The objective of this workshop was to reassess the photovoltaic (PV) industry's needs, priorities and recommendations on accelerated aging and reliability research in light of recent growth and changes in both the PV industry and the DOE Solar Energy Technologies Program. Conversations with industry and observations by U.S. Department of Energy (DOE) and National Laboratory staff led to the decision to schedule a follow-up to the 2006 meeting and to expand the scope of the meeting to include reliability. New issues and changes in priority were obviously occurring as new capital, talent and demand transformed the PV market, at the same time the Solar America Initiative (SAI) transformed the Solar Energy Technologies Program. New talent -- some fresh from college, others recruited from the semiconductor, power engineering and project development industry -- were ready to be introduced to the current practices and issues facing the PV industry and offer insight and ideas gained from their experience in other industries. PV industry and laboratory veterans were ready to revisit issues raised in 2006 and work together to refine challenges, priorities and next steps. As a result, a technical meeting was held in Lakewood, CO on April 1st and 2nd 2008 to discuss the current state of accelerated aging testing and reliability testing and provide new input to DOE's research planning and prioritization by:

- Discussing criteria for success, to help define reliability requirements and what should be expected from accelerated aging testing and reliability research.
- Revisiting or defining for the first time failure modes related to technologies (thin films and emerging technologies, silicon, and concentrator PV [CPV]) and important aspects of PV development (packaging, manufacturing, system design, field and product returns, test protocols, and reliability predictions) to see whether priorities have changed or new failure modes have emerged.
- Discussing needs and priorities for action based on the failure modes, and how DOE and the National Laboratories can address industry needs.

Explicitly addressing reliability as well as accelerated aging in the workshop had a noticeable impact on the group's discussion of systems. Because systems are built from multiple components and there is limited standardization at this stage of PV industry development it was difficult for participants to prescribe how accelerated aging alone could be applied to systems. The tendency was to fall back to discussing accelerated aging for components and how that may or may not be a good indicator of how they will work together in a system. But when reliability became the topic, the discussion of failure modes, tests, and opportunities for improving system performance became very productive. Systems are where the implications of reliability for performance, market share, finance, warranty and actual life are manifested. While collecting and analyzing data on performance of fielded systems was a strong recommendation in 2006, it was emphasized even more in 2008. There are far more systems in the field and growing concern with how their performance could impact the PV industry's reputation – a big concern that has only become more pronounced as the number of installed systems grows.

Early field exposure of developmental products was seen as critical to understanding and mitigating failure modes. The phenomenal growth that preceded the last workshop has only accelerated in the last two years. There are even more new manufacturers (some with new PV technologies) seeking entry into the marketplace and existing manufacturers are aggressively expanding their manufacturing lines to try and keep pace with domestic and world demand. U.S. markets have expanded into new states and into applications -- especially large-scale commercial and utility systems -- that have intensified challenges related to siting systems in different climates involving different configurations and different end-users with expectations that stretch the definition of reliability and aging.

Major Themes

Five major themes emerged from the discussions:

- There is no single definition of failure or of reliability, and definitions vary with application and customer (residential, commercial, utility), industry segment (integrators, manufacturers, financiers, etc.) and PV types.
- Industry needs data on reliability of fielded systems and failure mechanisms so it can be analyzed – as long as the data can be protected from disclosure and potential misuse that could harm individual companies.
- Industry needs analyses of fielded systems, reliability and accelerated aging test results to create predictive models that can be relied upon to produce reasonable correlations between test results and the field life of components and systems.
- Arcing and other safety-related failures are a high priority because of the rapidly expanding number of installed systems and the potential damage to the industry's reputation if failures result in injury or death to installers, operators or customers.
- Industry needs and desires improvements in existing tests, more information on best practices for reliability and accelerated aging tests, and improved and expanded applications of the information derived from reliability and accelerated aging tests and analysis to improve PV products and systems.

Table 1 highlights and consolidates some of the input from the breakout groups related to the themes. It also shows where concerns are specific to a technology and where they cut across all PV technologies. For example, CPV representatives face some unique challenges, including: lens degradation, the need for better machine vision for precision alignment in manufacturing to reduce losses from poor optical focus, and the problem that CPV cells are by definition already under highly concentrated insolation so accelerated testing using even more highly concentrated insolation is not practical.

National Laboratory Role

Support for maintaining or expanding the National Laboratory role in key areas remains high. The labs were suggested as an honest broker in collecting and analyzing field failure data, and in protecting it from misuse. They were also seen as a logical focus for translating best practices into procedures for ALT, procedures for performance monitoring and data acquisition to be used in evaluating field performance, and for testing of product returns and fielded modules. The interest was in the laboratories' technical expertise and in their role as objective sources of information. The laboratories were also seen as the logical place to work on better understanding and models of the physics of failure, particularly in thin-films and emerging technologies. The national labs' expertise and ability to broadly understand and represent PV concerns is valuable in developing and revising IEEE and IEC standards.

Table 1: Summary and Consolidation of Breakout Group Results

	Thin Films/Emerging	*C-Si*	*CPV*	*Inverters*
Theme 1: No Single Definition of Failure or Reliability				
Reliability should be based on expectations between manufacturers and customers - a utility has different expectations than a homeowner, the life expectation for an organic PV product can be different from a thin-film or crystalline silicon product.				
Applications like BIPV introduce new reliability and failure definitions - blemishes or discoloration or inability to perform to a standard as a building component.				
Predictability can be more important than defining level of reliability - if power production and cost are predictable a customer may accept shorter lifetimes.				
Reliability and failure are increasingly influenced by contractual requirements like power purchase agreements that specify minimum power delivery requirements.				
Theme 2: Need for Data and Analysis of Reliability of Fielded Systems				
A database (or data warehouse) of field data for analyzing and understanding failure modes , including field testing in a variety of locations/environments/applications for different PV designs, particularly combined effects failures.				
Reporting mechanisms to collect performance and failure data that include protection for company intellectual property and business reputation while still supporting research into failure modes and reliability.				
Reliability Concerns to Investigate				
Reliability issues associated with specific markets or applications: BIPV will have to start defining PV as part of the building, which results in other requirements - if it is a roof, it has to meet roof requirements.				
Moisture related failure mechanisms and reliability issues.				
Delamination associated with different material interfaces, thermo-mechanical as well as chemical properties that induce different loading at interfaces.				
Crack formation in thinner cells.				
Cell degradation mechanisms -- an understanding of whether corrosion of contacts, degradation of AR coat, or other cell degradation is occurring.				
Degradation of optics (abrasion, corrosion of mirrors, yellowing, soiling, etc.				
Tracker mechanical breakdown and tracker pointing errors.				
Exactness of manufacturing equipment - cell, optics, position, correct temperature.				
Manual solder bonds where even a small % failure is a big problem - industry is going way beyond six sigma - for example at the J box.				
Quick connector reliability - all different aspects. Industry doesn't know if connectors have a long life - they have only been in field about 10 years. Europe is developing standards with little U.S. input.				
By-pass diode and fuse failures.				
Understanding power degradation involved in 25-year life - still worth looking at old modules to understand mechanisms, even if they were manufactured differently.				
Them 3: Correlations Between Test Results and Field Performance to Improve Prediction				
Accelerated Life Tests need to be developed to provide accurate information that adequately portrays field induced degradation and failures.				
Identification of the failure mechanisms associated with failures observed in the field.				
Need higher accuracy predictive tools, believable predictive tools.				
Common failure mode database broken down by technologies, locations/climates.				

Table 2: Summary and Consolidation of Breakout Group Results (continued)

	Thin Films/Emerging	C-Si	CPV	Inverters
Theme 4: Safety Issues Related to Reliability				
More study on arcing, how to test to prevent it. Integrators concerned - any connection that is loose or fails will cause an arc, impacting both safety and reliability.	X	X	X	X
BIPV issues with safety, wiring etc., special handling - tests as a roof or building component and a module, developing architectural design specifications.	X	X	X	X
Grounding failure, identifying/diagnosing ground fault problems -- communication protocols to transmit the information.	X	X	X	X
Improvements in NEC to address ground faults.	X	X	X	X
Theme 5: Test Applications, Best Practices and Improvements				
Manufacturers and system integrators need specifications to use throughout the supply chain to influence reliability from the conceptualization of a system to its design/installation and finally operation and maintenance.	X	X	X	X
Guidance on which tests are appropriate for which materials and packages, ways to adapt to specific products, new failure mechanisms need new protocols.	X	X	X	X
Manufacturing processes that are idiot proof, self-extinguishing, rugged and robust, particularly in eliminating catastrophic failures like arcing or fires.	X	X		
Use information on causes of failures to simplify packages for modules and inverters, reduce inverter parts counts and improve thermal management.	X	X	X	X
Other diagnostic tests:				
Develop tool that give an image of the cure quickly, compared to current 48 hour process. What can thin film industry use besides cobalt chloride?	X	X		
Expand "instant" measurement to other indicators/measures, efficiency, uniformity of resistance across cells, series resistance, shunt resistance, soldering uniformity	X	X		
Need to consider differences between framed, glass modules and flexible structures. The latter may need new solutions and testing. This has gone up in priority as more products use foil and other flexible materials.	X			
Application/customer should determine testing due to different requirements. Roofing-flexible products may require modified tests, e.g., higher temperatures, flex tests.	X	X	X	
Solar simulators could use more uniformity and flexibility - three different machines will give three different readings on a module.	X	X	X	
Labs or third parties to provide access to expensive test equipment and procedures that small companies can't afford, access to equipment used infrequently that make purchase difficult, e.g., diagnostics for partial discharge, surge/impulse voltage.	X	X	X	X
Tests that facilitate substitution of alternative, low-cost materials and new supplier qualification. Cost performance tradeoffs considering some applications may justify higher costs. Reduce cycle time for qualifying suppliers.	X	X	X	
Reducing variations from crystal to crystal in raw materials. Understanding why some cells work in one package but not another. Industry can no longer evaluate each cell with IR camera to screen hot spots. Tool for silicon segregation could help industry.		X		
Highly accelerated tests to reduce the time to test new designs.			X	
Identify key stresses (aerosols, salt content, etc. as basis for qualification tests).			X	
Large-scale solar array simulator.				X
Need standard communication protocols - IEEE, IEC 3 and 6, electronics group.				X
Efficiency standards are needed, recommend task group.				X
Inverter on-board diagnostics to address thermal issues.				X

The laboratories and third-party testing organizations were both suggested for owning and operating expensive equipment or complex analytical tools like a PV array simulator for inverter development. The smaller companies can't afford major testing or modeling efforts on their own and even the larger companies have difficulty justifying investments for equipment that may be essential, but used on a very limited basis. The laboratories were also suggested for developing best practices and methods for industry to get the most from equipment and testing, for enhancing equipment performance for devices like solar simulators for module exposure, and helping improve calibration for reference cells and other services offered by third parties. The following sections and appendices provide more detail on the results of the meeting.

I. Introduction

A technical meeting was held in Lakewood, CO on April 1st and 2nd 2008 to reassess the photovoltaic (PV) industry's needs, priorities and recommendations on accelerated aging and reliability research in light of recent growth and changes in both the PV industry and the DOE Solar Energy Technologies Program. Participants provided new input to DOE's research planning and prioritization by:

- Discussing criteria for success, to help define reliability requirements and what should be expected from accelerated aging testing and reliability research.
- Revisiting or defining for the first time failure modes related to technologies (thin films and emerging technologies, silicon, and concentrator PV [CPV]) and important aspects of PV development (packaging, manufacturing, system design, field and product returns, test protocols, and reliability predictions) to see whether priorities have changed or new failure modes have emerged.
- Discussing needs and priorities for action based on the failure modes, and how DOE and the National Laboratories can address industry needs.

Participants

One hundred and fifteen of the nation's leading module manufacturers, systems integrators, equipment manufacturers, end-users and PV researchers actively participated in the meeting. Many of the 70 participants from the first meeting in 2006 returned, supplemented by a cohort of new participants that in many cases represented talented people who were new to photovoltaics, but who brought strong backgrounds in reliability testing and quality control from other industries. Technology pathway partners and incubator companies funded by the DOE Solar Energy Technologies Program to develop the next generation of PV products were well-represented. When polled during one of the technical presentations, roughly one-third of the audience identified themselves as new to reliability testing and engineering, another third identified themselves as practitioners interested in learning more, and fully one-third identified themselves as experts.

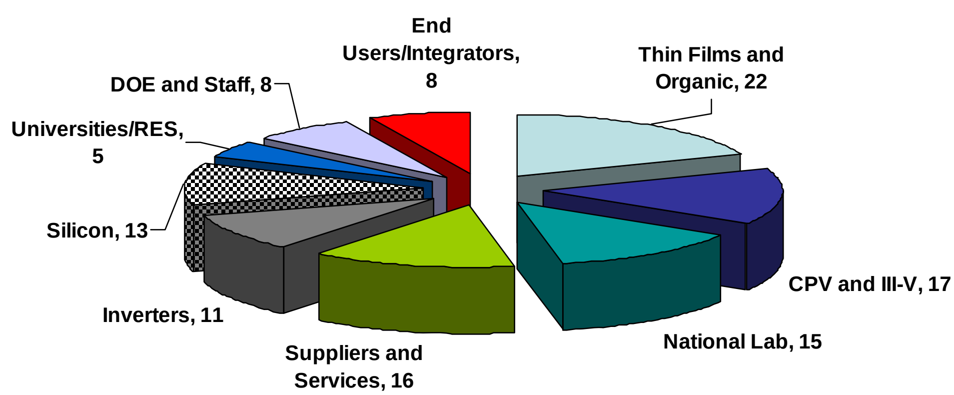

Figure 1: Participant Affiliations

As shown in Figure 1, all the major PV materials were represented including thin-films and organic PV and crystalline silicon. Concentrator PV and companies working with III-V materials were strongly represented at the workshop. There was substantial representation from companies that supply materials and parts, including encapsulant manufacturers, 3rd party PV test facilities, and 3rd party engineering firms that are playing an increasing role in external reviews of large-scale systems for investors. End users/system integrators were also well-represented and active in the discussions. The location of the meeting in Denver facilitated participation from both Sandia National Laboratories and the National Renewable Energy Laboratory. The Residential Experiment Stations (RES) at the Florida Solar Energy Center and the Southwest Technology Development Institute sent representatives, as well as the Institute for Energy Conversion at the University of Delaware.

Highlights

The industry representatives described the types of decisions that can and cannot be made today based on the current testing protocols. This information can help focus the R&D performed in the DOE Solar Energy Technologies program on the industry's highest priority needs. Expanding the subject of the workshop to include both accelerated aging tests and reliability was very successful – the discussions were lively and flowed easily from accelerated testing to reliability. This led to much more emphasis on systems where the implications of reliability for performance, market share, finance, warranty and actual life are manifested. The discussions of failure modes, tests, packaging, manufacturing, and opportunities for improving system performance were very productive. Since there were many attendees who were new to the PV industry, and many who were relatively new to reliability and accelerated testing, the guidance for best practices and incorporating reliability engineering in all stages of product development were very well-received.

Five principal themes or emphases resulted from the workshop.

- There is no single definition of failure or of reliability, and definitions vary with application and customer (residential, commercial, utility), industry segment (integrators, manufacturers, financiers, etc.) and PV types.
- Industry needs data on reliability of fielded systems and failure mechanisms so it can be analyzed – as long as the data can be protected from disclosure and potential misuse that could harm individual companies.
- Industry needs analyses of fielded systems, reliability and accelerated aging test results to create predictive models that can be relied upon to produce reasonable correlations between test results and the field life of components and systems.
- Arcing and other safety-related failures are a high priority because of the rapidly expanding number of installed systems and the potential damage to the industry's reputation if failures result in injury or death to installers, operators or customers.
- Industry needs and desires improvements in existing tests, more information on best practices for reliability and accelerated aging tests, and improved and expanded applications of the information derived from reliability and accelerated aging tests and analysis to improve PV products.

The themes are all strongly interrelated: the growing number of stakeholders and applications that impact the definition of reliability are increasing the pressure to improve understanding of failure mechanisms and apply new knowledge to improve lifetime predictions and enhance safety. Participants were very clear that reliability in the context of a power purchase with a utility or commercial customer, an architectural installation on a large building, or a system on a homeowner's roof can be very different. There are more entities demanding and examining reliability and life expectancy information, including third party engineering firms hired by banks and financiers to affirm manufacturer and integrator long-term performance predictions.

One of the strongest appeals was expressed in the second theme, for means to share and analyze failure-related information from fielded systems in order to establish clearer correlations between accelerated life testing and actual system life. Industry expressed a strong desire for partnering between industry and labs in collecting this sensitive information and using it to evaluate the long term performance of fielded systems. There was specific mention of a database or databases. As the breakout summaries show, what might go into a data collection and how to use and protect it from misuse generated many ideas. Considering the workshop as a whole, the discussion of databases results in a broader description of a data warehouse given the diversity of sources and types of information that might be collected, and the different levels of user access and control involved.

What the group wanted from the field data analysis is better correlations between accelerated tests and lifetime performance prediction, the third broad theme. Early field exposure of developmental products was seen as critical to understanding and mitigating failure modes. The phenomenal growth that preceded the last workshop has only accelerated in the last two years. There are even more new manufacturers (some with new PV technologies) seeking entry into the marketplace and existing manufacturers are aggressively expanding their manufacturing lines to try and keep pace with domestic and world demand. U.S. markets have expanded into new states and into applications, especially large-scale commercial and utility systems, that have intensified challenges related to siting systems in different climates, different configurations and different end-users with expectations that stretch the boundaries of reliability and aging. All these changes heighten interest in more effective prediction based on field experience.

Safety issues were affirmed as an integral and very important part of reliability. When it comes to failure modes that impact safety, industry wants procedures and tests that can predict reliability and provide confidence at levels beyond six sigma. Arcing, emerging safety issues associated with building-integration, and changes to the National Electrical Code and industry practices to address ground faults were all high priority items related to safety.

Finally, participants identified a broad range of specific improvements in tests, their application, and best practices for conducting tests that apply to problems they are experiencing. Specific packaging reliability issues and manufacturing diagnostics were concerns, especially for emerging thin film and CPV products. Desired improvements or extensions of test protocols were identified, especially those related to reducing testing costs while at the same time providing timely qualification/certification of new products. In-line diagnostics discussion started as plea for a quick, in-line test to characterize the EVA cure and quickly expanded to the value of quick, non-destructive tests/diagnostics for improving manufacturing control and product uniformity.

Changes in processes and production rates, evaluating materials from new suppliers, and bringing new plants on line create challenges to product quality. Engineers in every plant are concerned with assuring the quality and reliability of their products, but in many cases on a much larger scale than they were coping with just two years ago. It is understandable that the desire for high quality, validated testing techniques hasn't diminished. Other pressures that have not changed:

- Production and test engineers want to be assured (as rapidly and inexpensively as possible) that their products will last for a long time (often 30 year lifetime is desired for photovoltaic systems).
- Manufacturers seek data to assure that changes in production processes and materials have not negatively impacted the longevity and reliability of the products.
- The need for high quality test procedures, protocols, and data that can assess reliability and long term performance has never been greater.
- Expanded understanding of accelerated aging testing technology and its role in reliability will be pivotal in furthering the credibility of this growing industry.

While collecting and analyzing data on performance of fielded systems was a strong recommendation in the first workshop, it was emphasized even more in this meeting because of the greater focus on systems issues. It was also a product of many more systems in the field, and the concern with how their performance could impact the PV industry's reputation – a big concern in the first meeting that has only become more pronounced.

Since the first workshop DOE has also undergone two years of extensive changes to the Solar Energy Technologies program. When the first workshop was held in 2006 the Solar America Initiative had just significantly enhanced efforts with more structured reliability R&D efforts. Now the SAI is fully operational and it has changed the magnitude and direction of the resources the program is investing in both research and development and market transformation. Results include the major Failure Modes and Effects Analysis (FMEA) Study, a new coring technique to evaluate interface toughness/outdoor weathering, completion of a report on Test to Failure (TTF), itemization of the failure mechanisms for different PV technologies, expansion of the program's capability to test small systems, new equipment including added chamber capability, and convening this second accelerated aging workshop.

Failure modes have not changed dramatically, but some have grown more urgent, such as moisture ingress and arcing, fuse failures, and problems with packaging, particularly in flexible modules and other packages that may not fit into old models and test procedures.

Report Structure

The following sections document the results of the meeting in more detail. Section II summarizes the technical presentations and the questions asked of the presenters. Section III summarizes the key findings from the breakout groups. Detailed appendices document the participants (A), the agenda (B), the presentations (C), terms and acronyms (D) and the handout on reliability issues provided to the breakout groups A, B, C and F (E).

Summary

The meeting reaffirmed the conclusion drawn from the first meeting: the results from current accelerated aging tests and reliability research continue to be much more than a research curiosity, they are in daily use throughout the industry as a decision-making tool, and are integral to achieving the reliability the industry needs to continue expanding markets. With new technologies and larger-scale manufacturing processes continually being deployed, substantial expansion and extension of accelerated aging techniques and tools for predicting and improving reliability are needed now to assure even better, more reliable PV energy systems.

II. Technical Presentation Summary

The technical meeting began with welcoming remarks and introductions from Dan Ton, the Solar Energy Technology Program's Team Leader for Building/Grid Integration who explained DOE's interest in the topic. This was followed by nine presentations from leading PV experts who were asked to explain their experience and perspective on reliability and accelerated aging testing in the PV industry, and their thoughts on key issues. Each presentation title is hyperlinked to the relevant page in Appendix C.

- **Welcome and Overview of DOE Program**
  Dan Ton
  U.S. Department of Energy Solar Energy Technologies Program, Building/Grid Integration Team Lead
- **Reliability Vision and Program**
  Michael Quintana
  Member Technical Staff, Sandia National Laboratories
- **Large-Scale Systems Integrator – Reliability Needs**
  Laks Sampath
  Executive Director of Technology, SPG Solar Inc.
- **Perspectives on Thin Film PV Reliability and Initial Product Introduction**
  Kurt L. Barth
  VP Product Development and Co-Founder, AVA Solar
- **CPV Reliability – Reliability in an Expanding Technology**
  Robert McConnell
  Director of Government Affairs and Contracts
  Amonix, Inc.
- **Modules: Remaining Reliability Challenges**
  Akira Terao
  Principal Reliability Engineer, SunPower
- **PV Safety Issues: Key to a Reliable, Viable Industry**
  Tim Townsend
  Sr. Mechanical Engineer, PE, BEW Engineering
- **Initial Reliability Considerations for Design of Commercial PV Systems**
  Mike Fife
  Director of Reliability, PV Powered
- **System Availability: A Must for Profitable Large-Scale Systems**
  Steve Voss
  Director of Applied Engineering, SunEdison
- **Progress Since First Workshop: What's New and What's Needed**
  Tom McMahon
  Technical Staff Member, National Renewable Energy Laboratory
- **Best Practice for Achieving High Reliability with PV Systems**
  Carl Carlson
  Reliability Consultant
- **Field Observations and Product Returns – What Can We Learn?**
  John Wohlgemuth
  Senior Scientist, BP Solar International

The technical presentations and panel discussions were structured to prepare the participants for the breakout sessions that followed. All of the presentations are reproduced in Appendix C. Questions and discussions were encouraged either during the presentations or at the end of a group of presentations. The morning technical presentations on day one covered the solar program's reliability research efforts, observations from a large-scale integrator, the perspective from a company manufacturing thin-film products, and a presentation from a concentrator PV (CPV) manufacturer/integrator which added a new dimension that the first workshop did not include. These presentations gave the participants ideas and information that naturally complemented the sessions on thin-films, silicon, and CPV that followed.

On the afternoon of day one a panel of presenters covered the broad topic of how to build a reliable system, including presentations that examined module reliability challenges, PV safety issues and their relationship to reliability, design of commercial PV systems from the perspective of an inverter manufacturing, and the views of a large-scale developer/integrator on large-scale systems and the importance of availability. These presentations were immediately followed by question and answer sessions, and then breakout groups discussed packaging and design, manufacturing, and system design.

Finally, on day two a panel of presentations set the stage for the final breakout groups with information on progress made since the last workshop and issues the Solar Program is encountering in reliability research, best practices for achieving high reliability, and field observations and product returns. The breakout groups then delved into field and product return insights, test protocols, and reliability predictions.

All the attendees participated in the presentation portion of the agenda then attended one of the three concurrent breakout sessions that followed. Participants chose which breakout they wanted to attend when they registered for the meeting. The approach to facilitating the breakout sessions is explained in the next section of the report. The full agenda is available in Appendix B.

Day One Morning Presentations

Welcome and Overview, Dan Ton

Reliability is important for several reasons. They include meeting SAI goals and enhanced confidence in performance. Reliability is essential for the PV industry to be able to support current and projected growth. Based on industry input, the DOE has requested and received additional funding for these activities and initiated a reliability program to support the PV industry. DOE is aggressively supporting companies and universities along the entire research pipeline from basic research through applied research and market transformation through the laboratories and multiple solicitations in the Solar America Initiative.

Reliability is important throughout the entire technology pipeline, from materials through the final product. The technology pipeline and Solar Program activities in each area are highlighted in the figure below. Reliability needs to be considered at all steps, and needs to be integrated into the production sequence.

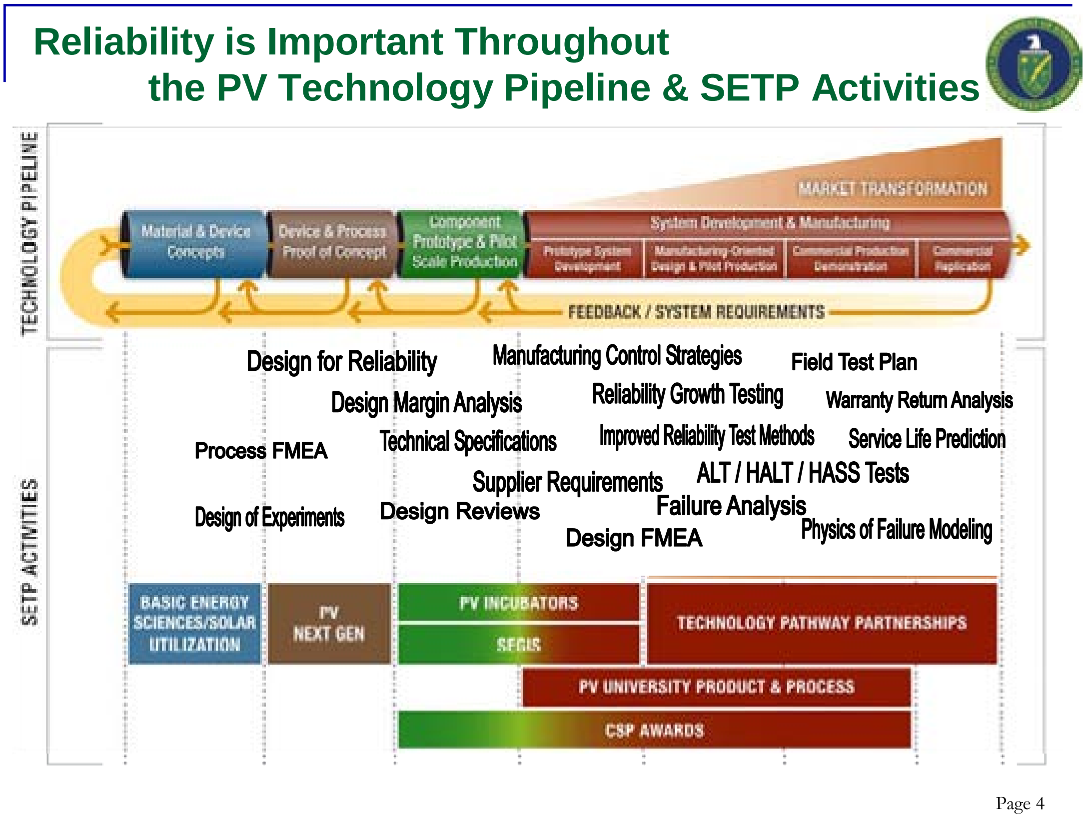

Figure 2: PV Technology Pipeline

DOE's vision of reliability involves working through national labs and establishing partnerships with industry. The goal is to have industry adopt and apply these practices to produce more reliable, cost-competitive products.

DOE needs to hear this group's input related to testing, data evaluations, and predictive analyses. DOE also needs feedback on how to best support the PV industry.

Reliability Vision and Program, Michael Quintana

The new DOE reliability project is a team effort between Sandia & NREL.

The first issue is how to define reliability. The definition of reliability depends on who is asked. System owners, integrators, module manufacturers, inverter manufacturers, and BOS manufacturers have different views. A dynamic market with equally dynamic expectations is driving reliability needs.

Work done by Alex Mikonowicz showed that the industry does not have an end of life test and does not have the resources or time to create one. The industry also lacks suggested tests of life affected performance, tests for EVA, back sheets, and other components.

Given the current state of the industry and reliability testing, what can the national laboratories do for manufacturers? Some suggestions include developing procedures (but not setting standards) for accelerated tests that can be correlated to life expectancy of modules; and operating long-term site installations to measure performance over time in representative environments.

DOE focuses on three major elements of reliability linked across the entire PV program – prediction, detection, and mitigation. Right now the emphasis is on prediction and detection. The mitigation effort does not have significant funding this year, but it is planned. When problems become a priority DOE should invest in mitigation.

The leading project objective is to accelerate development and adoption of methodologies that increase the reliability of PV components/systems, including: screening protocols, predictive models, accelerated tests / standards, system availability functions, design-for-maintainability, identifying barriers and solution-oriented R&D, and assisting the Solar America Initiative participants to meet their stage-gate requirements.

The scope of the program for fiscal year 2008 (FY08) includes Failure Modes and Effects Analysis (FMEA), fault tree analysis (FTA), long term exposure, system studies, accelerated tests, screening protocols, and predictive models. In many of these areas DOE is seeking commercial partners. Reliability research is driven by data, and targeting high-value and easily accessible data is a priority to get the best payoff for resources invested.

The Solar Program is developing a tool called XFMEA to aid analysis – some of its key parameters are highlighted in the screenshots in Figure 3. Failure Modes and Effects Analysis is a bottom up approach to identify dominant failure mechanisms, develop theoretical models

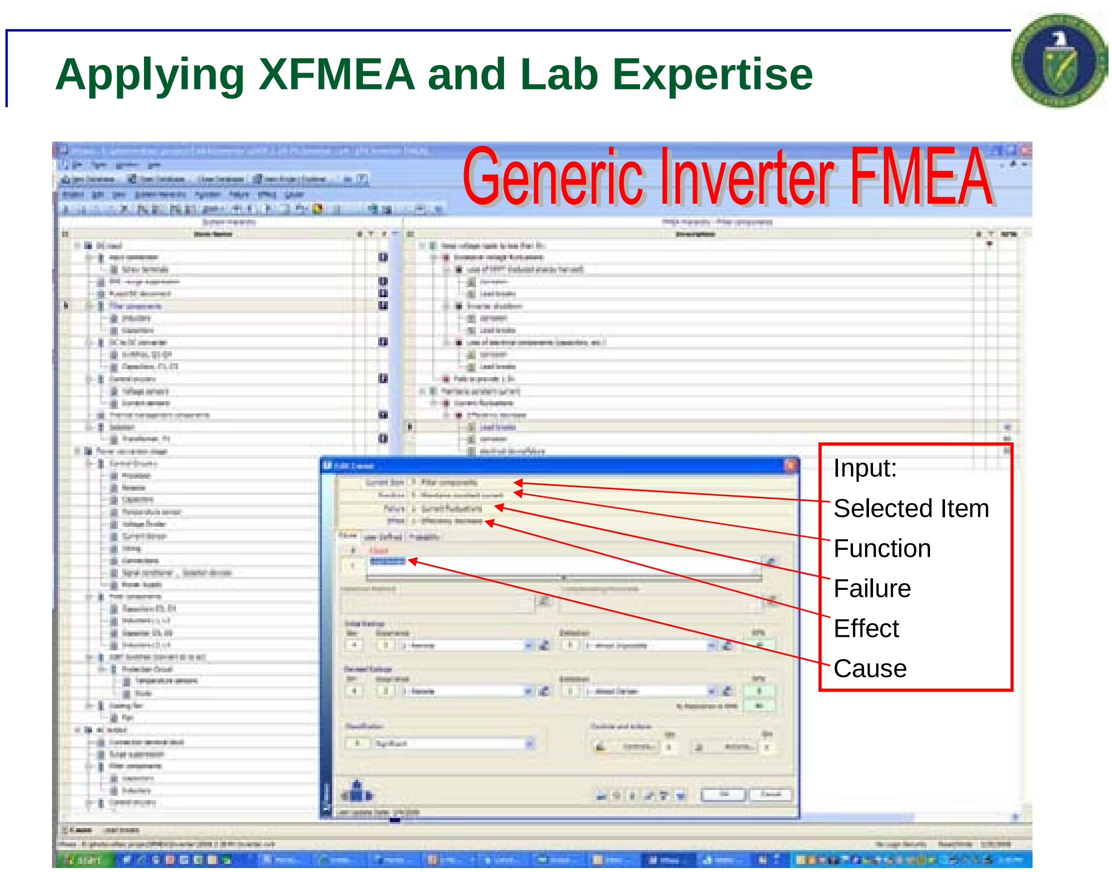

Figure 3: XFMEA Screen Shots

to predict failure, and identify candidate items for accelerated life tests including cost and action elements.. The FMEA includes all system components. with inputs for function, failure, effect, and cause. This framework allows users to identify and address high priority areas where mitigation efforts can focus.

In system reliability modeling the goal is to apply block diagrams and Fault Tree Analysis to predict the time for degradation of system to a specified level of unreliability. The Reliability Block Diagram (RBD) is the "heart" of the predictive system model. Figure 4 shows illustrates some early RBD work,and how parts fit into the RBD. Fault Tree Analysis is a system-to-components top down approach – an example is provided in Figure 5.

Both industry and DOE are very interested in accelerated tests. The objective is to apply lab-based tests to shorten test time and effectively estimate long term performance. The tests will be based on FMEA, field data, and test data (not acceptance testing). An important outcome of accelerated testing is to identify failure mechanisms and associated stresses. Combined effects are important. Users need to apply short and mid term tests and make correlations with long term exposure/performance.

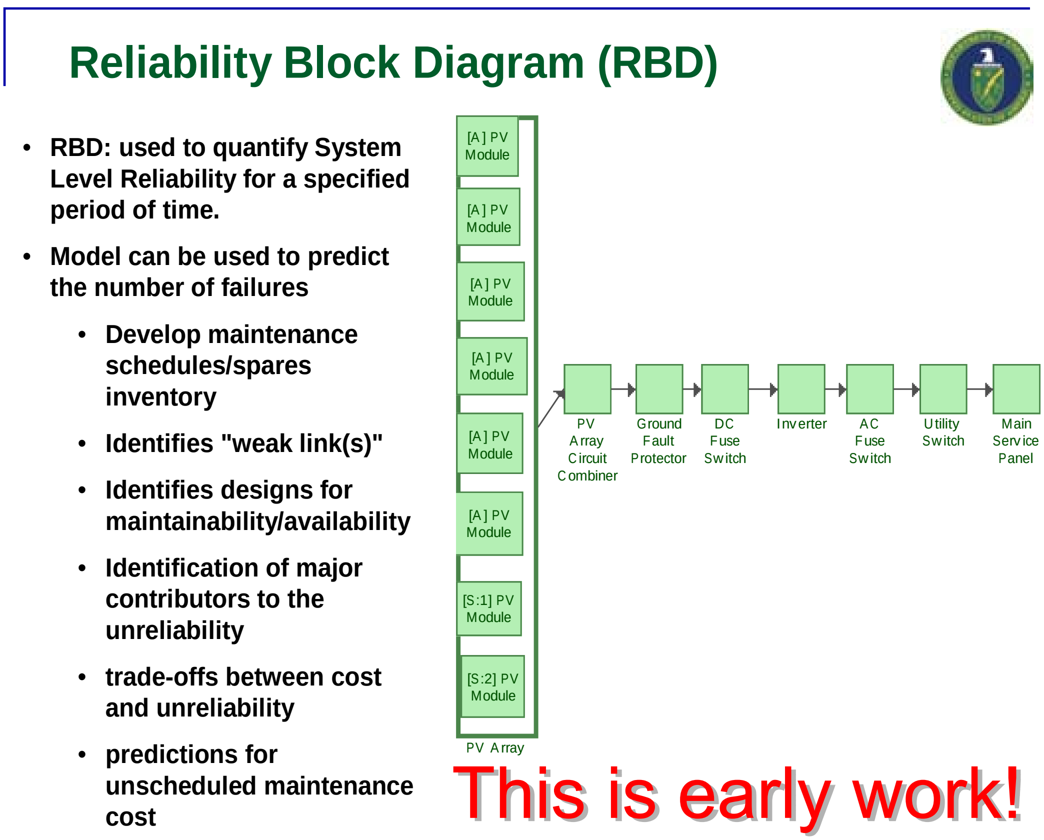

Figure 4: Reliability Block Diagram

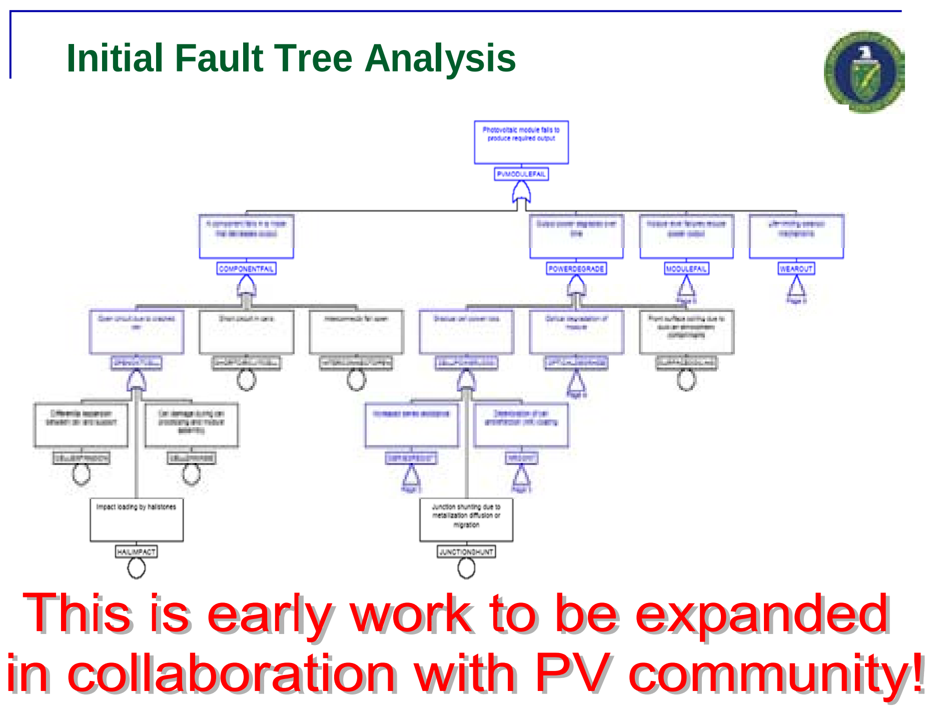

Figure 5: Initial Fault Tree Analysis

Field based surveillance studies are important! Industry needs to be involved for return data, system evaluation, and coupons. Validation tests as well as short and intermediate outdoor exposure tests (both labs) are needed. In summary:

- Industry is evolving rapidly.
- Reliability is a key element.
- DOE labs are invested in robust reliability methodologies.

Large-Scale Systems Integrator – Reliability Needs, Laks Sampath

SPG Solar is a turnkey solar PV system developer/integrator with over 1000 installations and multi MW individual projects. Therefore their perspective comes from the far end of the food chain – turnkey providers. SPG Solar brings experience with large systems, including 1MW on single-axis tracking. SPG recently passed the 20 MW installation mark. Some of the services they provide include:

- Feasibility studies
- Analysis and system design
- Real-time online performance monitoring

SPG has learned from experience that customers just want to know how much their system will produce. Power purchase agreements (PPAs) always focus on performance. As incentives move from capacity to performance based metrics, system monitoring and ultimately performance will be of utmost importance.

Figure 6 shows SPG's main areas of concern. Uptime means a reliable system that will deliver power as expected and operate at least to the projected warranty term. SPG is also concerned about their ability to respond to field failures of inverters/modules, and the implications for customer care.

As seen in Figure 7, components that have failed involve the entire system: modules, inverters, combiner boxes, AC disconnects, fuses, foundation in ground mounts, and roof penetration leaks. Roof leaks continue to be a particularly troublesome issue.

Module failures include tab failures, poor soldering, and junction box failures. One of the interesting tab failures SPG encountered was a system problem in the manufacturing, which led to a common, widespread failure in modules from that production run. Vandalism (breakage and theft) is also a problem. As modules fail the replacements are hard to find. For example, in some cases months after a failure there are still no replacements available of comparable modules. That causes reconfiguring systems to minimize the loss of production.

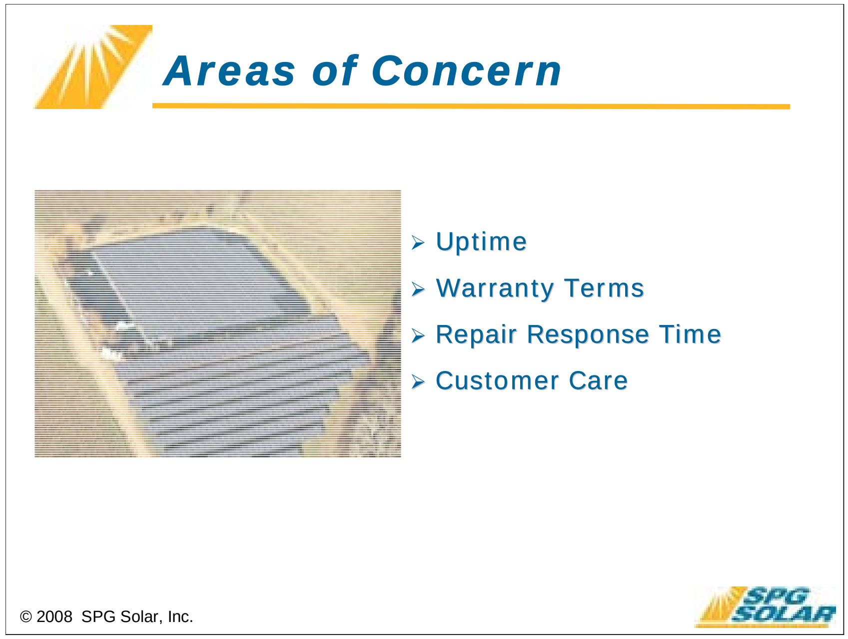

Figure 6: Areas of Concern

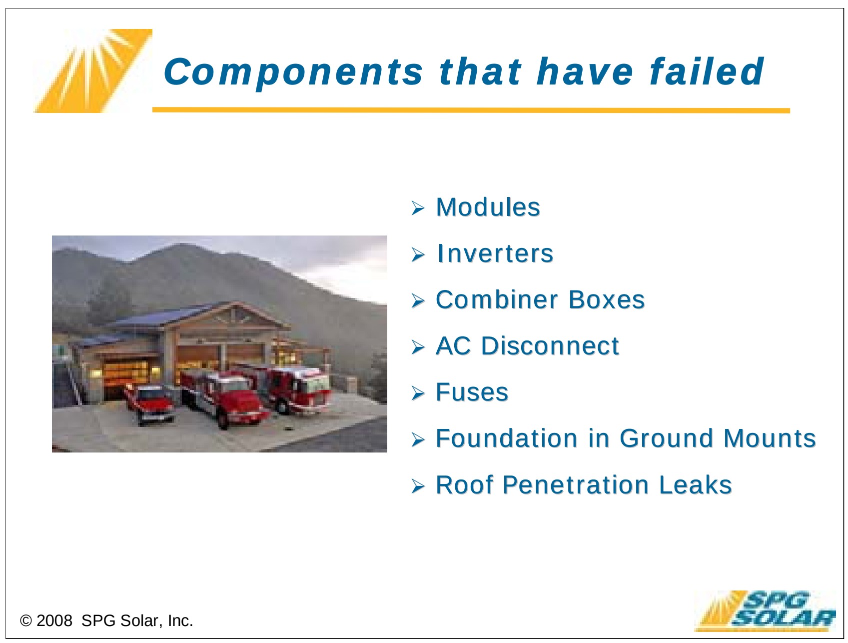

Figure 7: Components that Have Failed

Failures need to be considered from a system impact perspective. Junction Box failures start as a little burn through, leading to complete short out, burn marks, and eventually a shattered panel. One system where this happened involved 5000 panels. Out of the 5000 panels, 119 panels had this problem, only about 2%, but it occurred in 25% of the arrays. So the customer lost 25% of their production. SPG first saw the problem in November, now it is April, and SPG still cannot find replacement panels. Even if SPG could find replacements, they would probably be higher wattage. Therefore SPG has to swap out modules at added expense.

Inverter failures strand all of the PV associated with that inverter. High quality control is essential for proper operation of systems. Under these conditions it is vital to have replacements and sufficient technical support readily available.

Voltage windows are important for inverters because SPG operates in a grid-connected market. SPG wants training from inverter manufacturers so they can be part of the first line of response to fix problems, then rely on the manufacturers only when a problem must be escalated. Because inverters are UL listed and there are issues involved with that certification, manufacturers insist on doing maintenance work, but SPG believes it is important for their staff to be trained and certified to some extent because they can be more responsive.

One of the examples displayed in a photograph showed holes in a 500 kW inverter caused by an arc. The penetrations were the size of bullet holes in a metal cabinet. This failure happened just the previous week. It was caused by the bus bars, which had bolts inserted the wrong way. The arc was triggered when SPG turned on the inverter. Better QA/QC and design by the manufacturer could have helped avoid this failure.

Combiner Boxes/Junction Boxes are another problem area in large systems where it is hard to identify a non-functioning string. The types of systems SPG installs have a real need for string monitoring capability. Fuses are also an issue in combiner boxes. Each box has 10 strings with 2 to 2.5 kW on each fuse. On a big system failures are hardly noticeable. An alert to identify blown fuses on 2 kW strings would help. The fuses need to let the operator know the failure has happened instead of just failing. Some customers check and replace fuses, but others want the integrator to take care of that, which can involve hundreds of miles of travel and the associated time and expense. If it is a remote system, how can it be maintained at all if fuses regularly fail?

Monitoring is a solution to some of these problems. Figure 8 shows some of the key attributes a monitoring system should include. Monitoring can also be a source of failure. For example, revenue grade meters have malfunctioned. Loss of communications can lead to loss of production monitoring. Industry needs an economical way to monitor each of the strings associated with a large-scale PV system; provide potential diagnostics for ill-performing systems; and O&M scheduling.

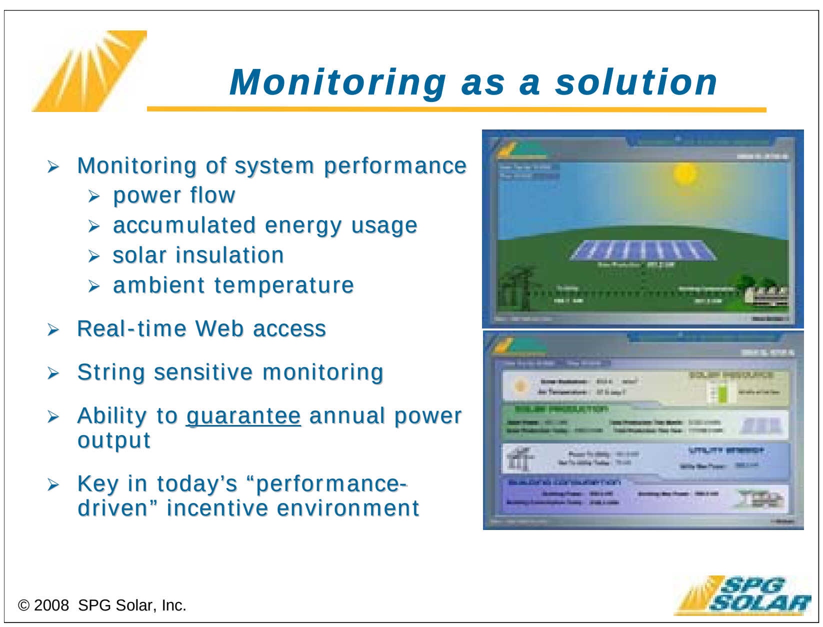

Figure 8: Monitoring as a Solution

In conclusion, systems must produce power. Integrators need meantime between failure (MTBF) numbers from manufacturers, and accelerated aging testing of modules and inverters because they are essential to production. Reliability is key to continued acceptance of PV systems, which means greater demands on suppliers to deliver components that are tested and will be reliable when integrated into systems.

Perspectives on Thin Film PV Reliability and Initial Product Introduction, Kurt L. Barth

AVA Solar Inc. is a new thin-film photovoltaic module company (began in early 2007) located in Fort Collins, CO. They produce CdTe products based on 15 years development experience at Colorado State University. Their product are ~10% efficient 120x60 cm modules with a market focus on utility and commercial scale applications. Their mission is to produce solar energy at costs competitive with conventional electricity. AVA has an aggressive production volume expansion plan and a rapid product introduction plan. Product reliability and qualification testing is critical in this rapid growth environment.

AVA targets grid-tied applications, and they focus on their customers' needs to help drive reliability requirements. Utility and commercial PV customers' expectations are dominated by cost of energy produced, closely followed by the need for predictable, stable energy production for economic analysis. Other considerations driving the need for a reliable product include the reputation and cost to a new company, and the importance of reliability to their investors. A reliable product is necessary to gain access to capital.

AVA has an in-house approach to reliability that includes the semiconductor and the package. Their highly accelerated stress testing uses both temperature and electrical bias and compares their results to long term outdoor testing. The comparison shows significant differences between the two. The accelerated stress tests over-predict degradation as compared with outdoor testing. However, AVA has determined a relationship between unstressed device performance and long-term stability. Figure 9 and 10 on the next page highlight AVA's major tests and provides an example of the results

The bottom line for AVA: a start-up company needs to have a reliable product to enter the marketplace, gain the acceptance of their customers, create a positive reputation, and maintain their investors. The key challenges in measuring the reliability of their product include developing accelerated tests that accurately predict lifetime in field conditions and the time required for stress testing, which can be a barrier to rapid product insertion into the market. HALT is not enough; new products need very long-term exposure testing. AVA outlined three opportunities for advances:

- understanding effects of moisture on the semiconductor materials and electrodes;
- materials development, specifically with regard to encapsulation; and
- streamlining certification and standards.

These are areas in which the national labs could play a role.

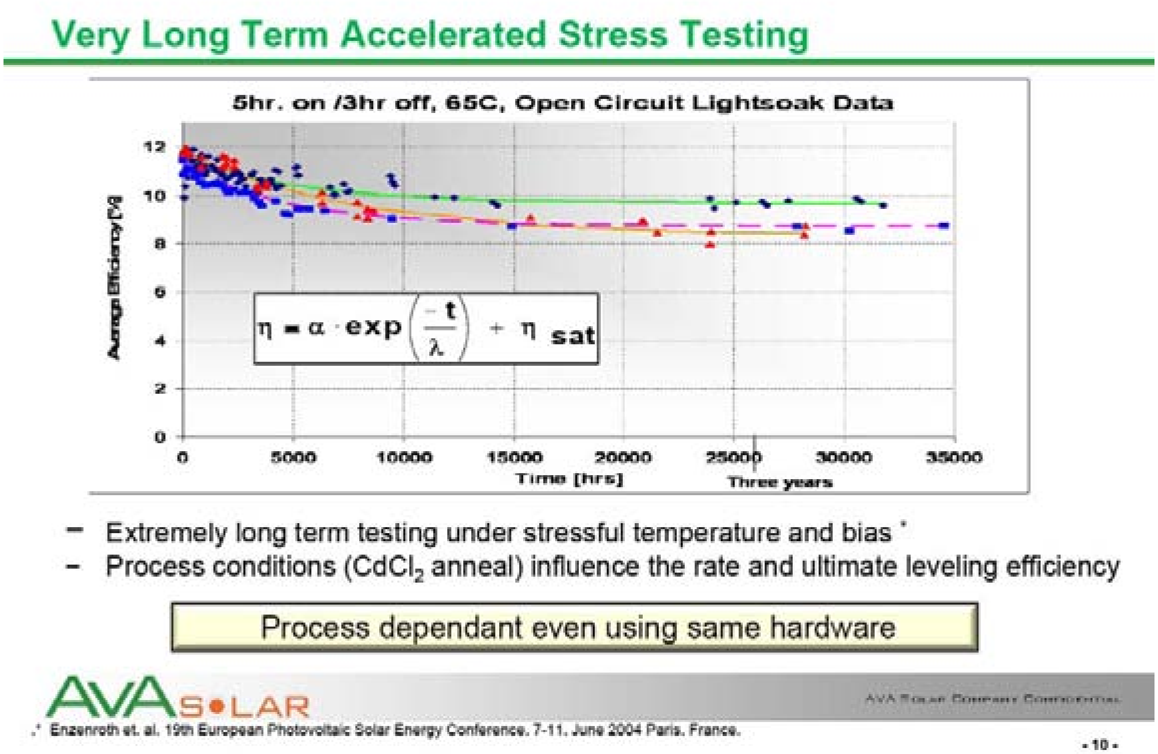

Figure 9: Very Long Term Stress Testing

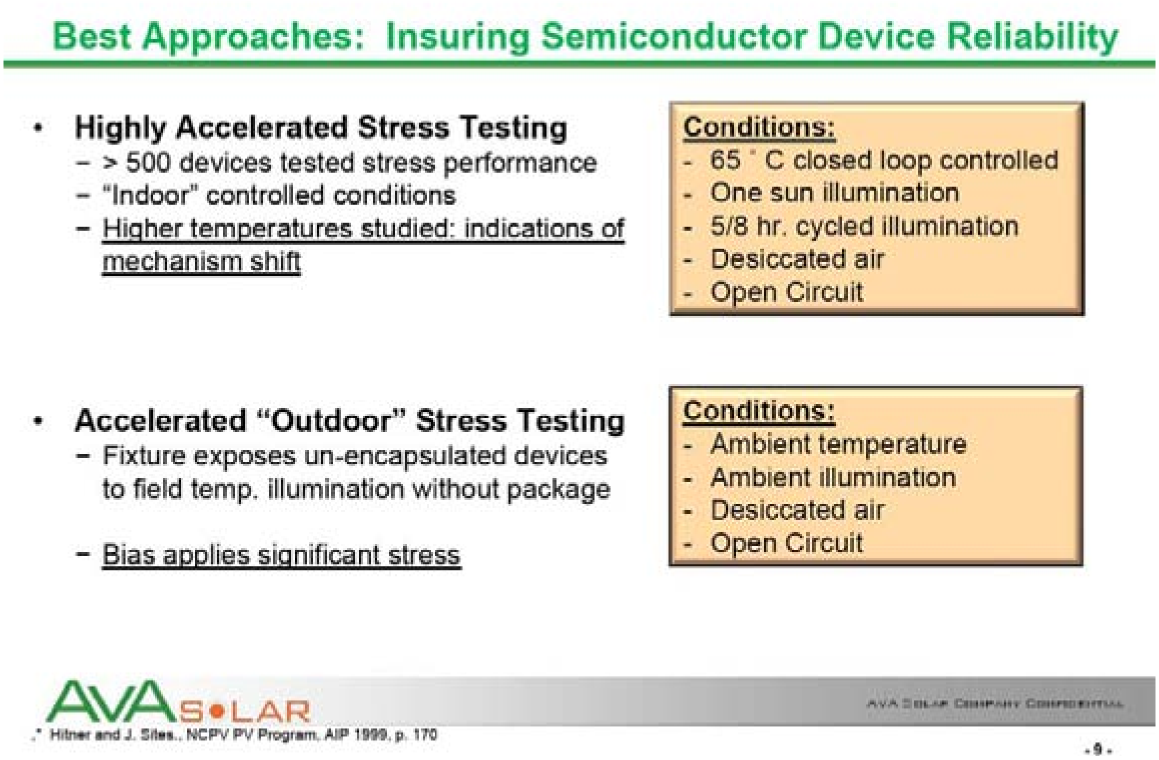

Figure 10: Best Approaches to Insuring Semiconductor Device Stability

CPV Reliability – Reliability in an Expanding Technology, Robert McConnell

Figure 11: Early CPV Example WIthout Qualification Standard

Robert McConnell addressed challenges related to concentrating photovoltaic (CPV) reliability and to the development of suitable qualification standards and testing protocols. Qualifications standards (e.g. IEC 62108) are important in developing technologies because the failure of one company's product can have an impact on all companies. This is what happened in the 80's when some large PV installations failed prematurely due to encapsulant failure. An example of an early system failure associated with deployment without qualification standards is shown in Figure 11. Additionally, safety standards are necessary to prevent accidents that could harm the reputation of the industry.

One of the challenges to standards development is to get a balanced group of manufacturers, customers and testing labs on the committees. A healthy tension on the standards committee is needed because manufacturers may want cheap tests and solutions and labs may want impractically high confidence in performance. The purpose of standards is not to produce accelerated aging or accelerated lifetime tests but to produce minimum standards for performance and safety, and to minimize the risk of short term field failure.

CPV system qualification and testing presents a unique set of challenges. CPV systems can be so large and so expensive that they can only be tested under fielded conditions. As a result CPV qualification tests use representative samples instead. Another challenge is the fact that the physical configurations are highly variable between different manufacturers making it difficult to obtain tests that are fair to all technologies. Because most CPV systems cannot be exposed in a flash simulator, a side-by-side IV test is conducted using a reference sample.

The current CPV qualification test contains many components that were adapted from qualification tests for crystalline silicon. As this is a new standard there are still many changes and improvements to be made.

Day One Morning Joint Question and Answer Session

The morning session included an opportunity for the audience to address questions to all four morning presenters.

In response to a question about sources of failures, the panel noted that many failures are due to arcing. It is a potential area for collaborative work between SNL and system integrators. Sandia is getting field data on arcing to help solve problems.

When asked about key opportunities for improving reliability, panelists replied there is not a good understanding of moisture and CdS/CdTe films. The materials for thin film encapsulation are also a problem. Asked about some of the extremes in data collected from accelerated testing on new thin film products, panelists noted that most were clearly associated with higher temperatures.

To distinguish reliability testing from qualification testing the panel explained that reliability is manufacturing-driven and related to warranties. Qualification testing is a necessary minimum to enter the market, but not sufficient to back warranties. Reliability takes a lot longer to establish. Reliability is a function of market and application experience, to a point where ALT allows a manufacturer to offer a warranty. For automobiles the perception of reliability is based on knowledge that a system has worked for others. National laboratory research is looking at complete system reliability. Labs are now getting the field information that is key to system reliability and taking the analysis down to component levels.

In response to concerns about glass supply, panelists noted that manufacturers are integrating their entire process and developing partnerships with suppliers to ensure access to materials. The partnerships are often proprietary. If companies don't have their materials and supply chain commitments, they won't have materials. Photon International is predicting the next shortage in PV may involve glass.

The panel acknowledged that there has been a backlog in certification and testing labs in the U.S., but didn't directly address the need for more facilities. A representative from UL noted that UL just announced a new lab in the San Francisco Bay Area, and has invested several million dollars in expanding its capabilities. Arizona State University also noted that they have expanded their capabilities and reduced their backlog.

Concerning single and dual axis tracker reliability, the panel noted that from their experience single axis trackers are structurally sound. Most had less experience with dual axis trackers and so had no comments. Trackers could be improved with temperature sensors to compensate for sleet and icing, citing an example where a system had stowed itself as planned during a storm, but then when it tried to restart the freezing rain caused it to fail and damage the tracking system. In that case it would have been better to have temperature sensors to alert the system to move the tracker occasionally to prevent ice buildup and binding. At the Tenerife CPV project the energy production suffered because of modules, but the trackers worked just fine. The CPV Working group has a draft standard for two-axis trackers that is in final qualification. The flat plate and CPV groups could work together on a standard. The National Laboratories will be looking at complete systems, so tracker reliability and failure modes will be analyzed.

Concerning mechanisms for reporting or collecting information on field failures, a UL representative explained that UL has a group that collects that type of information for appliances, which might be a model for PV. Today there is no formal reporting mechanism for PV field failures. That kind of data is usually gathered by the manufacturers and kept internally. Integrators haven't been reporting failures but do collect the information for their own use.

There is a lot of discussion about UV tests right now, and some of the tests try to lower the level of exposure testing. If there was more evidence of UV problems it might help discussion on new UV testing. In response, panelists noted that as far as UV is concerned, there are all kinds of codes, but when something goes into service is where susceptibility to UV finally plays out and sometimes all the codes and requirements still don't prevent failures. In CPV the biggest concern is with plastic lenses. The MTBF and degradation on Fresnel lenses is unknown. Manufacturers need to address those problems.

Concerning HALT testing and how to get accelerated aging from a five hours on vs. 3 hours off test the panel replied that the bias itself introduces stress even in cycle. Turn-on creates heat stress as well. Some companies are testing at 65^{o}C for the duration of the tests. For reference, in the desert SW modules may only cross 70^{o}C once or twice a year, where HALT testing may expose them to 65^{o}C for the duration of a test.

The emphasis on production, production, production, raises questions about how that plays into parts choice, and whether there has been Pareto analysis of the failure profile for components. Cost and reliability go hand in hand. A manufacturer or integrator pays more for reliability, but can get more production. It should be analyzed from the point of view of what power density higher reliability will provide. The California Energy Commission (CEC) has a listing for nameplate and expected output, derating at roughly 88%. Integrators focus on just how many kWH a system will produce, and how many square meters need to be installed.

Regarding failure sources, it is impossible to speak to percentages for failures. Generally inverters suffer infant mortality. Modules experience long term degradation and failure over roughly 5 years – even with 20 year warranties integrators are seeing some failures at 5 years. Other BOS elements fail over even longer periods, for example NEMA 4 boxes may start leaking after many years.

Day One Afternoon Presentations

The afternoon presentations on Day One addressed how to build a reliable system from different perspectives. It was designed to provide information and instigate fresh thought on important aspects of building reliability systems, starting with module challenges then moving through safety during installation (as well as its implications for design), inverter issues, and finally an integrator/owner's concerns with system reliability.

Modules: Remaining Reliability Challenges, Akira Terao

SunPower has been in the photovoltaic business for more than 20 years, producing crystalline silicon modules. Even in this "mature" technology, there are still many "remaining" reliability challenges. These include:

- 25 year warranty: This is still a barrier. How does a company prove a 25 year life?
- Ill-defined field conditions: The same warranty must apply for all conditions for the same modules
- Harsh and varied outdoor conditions
- Materials used near their limits: How to accelerate the effects on a material already being used near its limit? E.g. EVA softens at 85°C, and operating conditions are very near this limit
- Limited acceleration factors – there are few available – mean industry has to rely on long tests instead. Long test time can be a hindrance to rapid market introduction
- Large samples, small sample size: Difficult to attain adequate statistical sampling
- Subtle polymer chemistry: A slight change in the process can strongly affect reliability and performance of the product
- Cumulative effects, positive feedback loops: Challenging to determine and test for all interactions in the field
- New materials, new structures: Reliability testing is an on-going process

The best approaches to reliability engineering include using the standard Weibull "bathtub" curve to determine both reliability and lifetime, illustrated in Figure 12. In addition, analysts need to determine the physics of failure for each failure mode. Although the theory is straight-forward, the implementation is challenging. The advantages to using the physics of failure models include:

- Each failure mode can be studied separately
- Smaller samples can be used, allowing for larger sample sizes and increased statistics
- Each failure mode can be fully accelerated
- Different field conditions can be simulated
- Degradations can be measured even before they affect performance at the module or system level

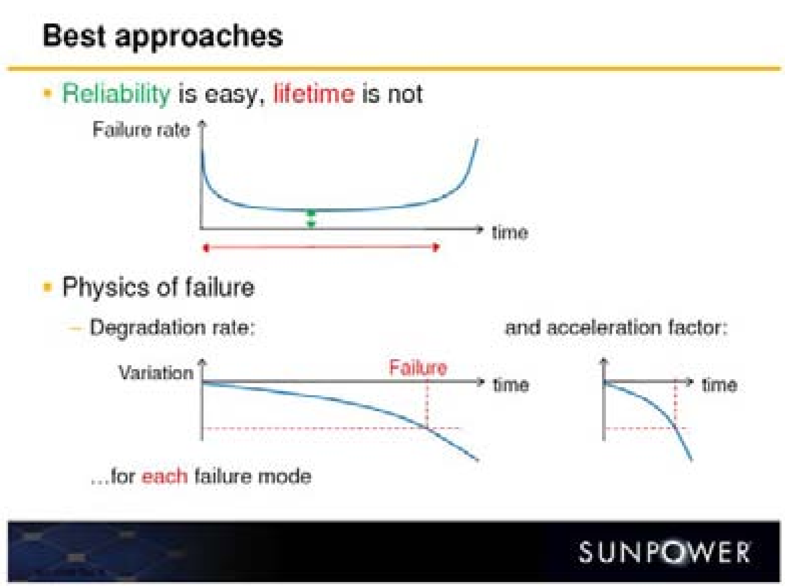

Figure 5: Bathtub Curve, Reliability and Lifetime

Necessary advancements and areas where the national labs could help include:

- Determining acceleration factors, and/or standardized definition of field conditions
- Help in determining the correct certification tests based on new designs, range of applications, harshness of environmental conditions.

Bottom line: There are still many challenges to determining reliability that will require diligence by both companies and labs.

PV Safety Issues: Key to a Reliable, Viable Industry, Tim Townsend

Tim Townsend, BEW Engineering, Inc., spoke about the important overlapping issue of PV safety as it is tied to reliability and availability. Operating Reliability Factor (ORF) and Performance Index (PI) are related to safety, but safety is difficult to measure on its own. It is easier to quantify the lack of safety in incidents of extended shutdowns, worker/consumer accidents, and the effective direct and indirect economic consequences.

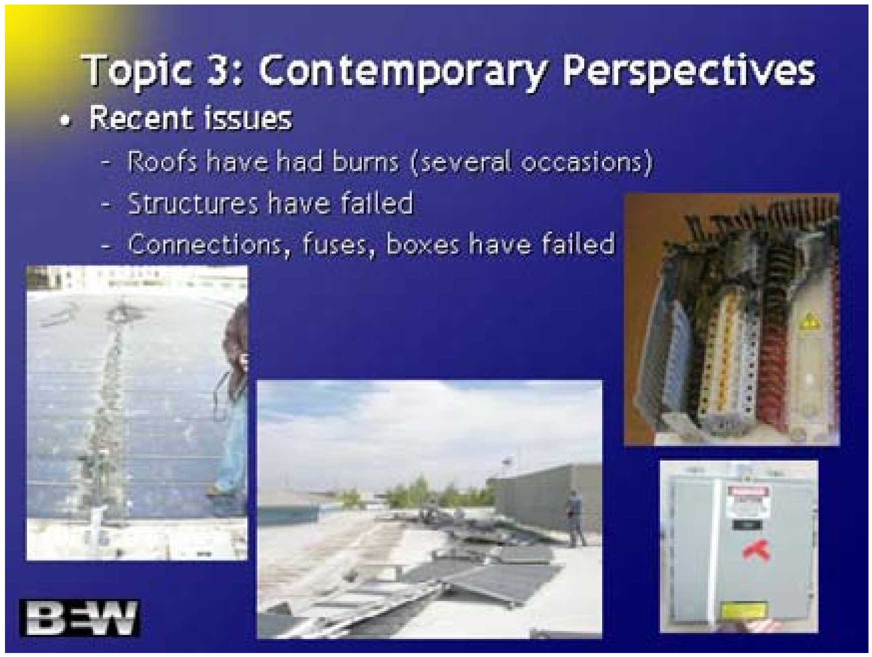

Figure 13: Contemporary Perspectives on Safety Issues

The history of PV safety has been quite good but it only takes a few bad incidents to significantly affect the industry. UL 1703 and 1741 have improved safety and PVUSA's experience helped prompt closer attention to safety issues.

Equally important is a reliably manufactured and safe product design and correct installation of PV systems. Recent safety issues include burns on rooftops; failed structures; and connections, fuses, and box failures. Incidents have occurred because licensed electricians/installers have sometimes been unwilling to use proper torque wrenches, have mistaken 600 Vac/300 Vdc fuses in 600 Vdc locations, have treated grounding as overkill, and have been reluctant to conform to the National Electrical Code (NEC) wire color coding. Some laborers are not trained properly to handle glass and heavy equipment. Shorted panels can cause fire hazards by arcing onto metal and even non-metal roofs. Other electrical safety issues can be caused by water combined with high-voltage systems. Lastly, theft and vandalism can cause hazards with visible wires and some mounting designs. A few examples are provided in Figure 13. Key safety fundamentals are summarized below, and in Figure 14.

- *Education* – IBEW training, CPR training / refresher courses, reviewing publications such as SNL's "Working Safely with PV".

- *Codes and Standards,including: OSHA: 29 CFR, Parts 1910, 1926, subs e.g. LOTO 1910.147; NFPA70 (NEC): especially Sec 690; IEEE, IEC, ANSI, ASTM, NESC, UL (& NRTLs), NEMA*
- *Electrical Safety* – shock / burn / blast susceptibility
- *Non-electrical Safety* – installer / system exposure to temperature extremes, wide-range of weather conditions including high winds, heights, etc.

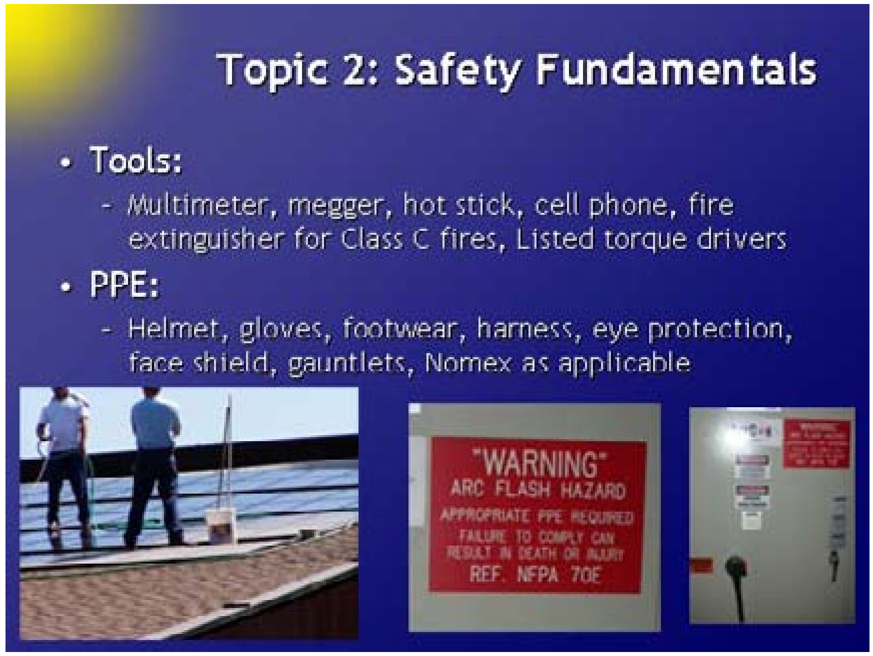

Figure 6: Safety Fundamentals

Safety also involves design issues, where there are no guidelines. Codes and Standards describe safety minimums. Constructability and serviceability need attention. For example NEC does not require rooftop dc disconnects. Installation safety issues involve the vigilance and commitment needed to maintain safety, especially with new installers who are unfamiliar with PV systems and under pressure to work fast to increase the bottom-line. For service industry needs code-compliant, permanent labeling; accurate as-built systems documentation; and requirements that crews use buddy systems and follow proper safety procedures. Safety also depends on proper use of tools and personal protective equipment (PPE), including multimeter, megger, hot stick, cell phone, Class C fire extinguishers, listed torque drivers, helmets, gloves, footwear, harnesses, eye protection, face shields, gauntlets, and Nomex as applicable.

Industry viability is dependent on safety – in design, installation, and maintenance. And it will take vigilant commitments from management and field staff, with proper training and oversight, to maintain high levels of safety as the industry continues to grow.

Initial Reliability Considerations for Design of Commercial PV Systems, Mike Fife

Since 2004 PVPowered (PVP) has developed and marketed over 16 different residential grid-tie inverter models ranging from 1.1 to 5.2 kW, as well as two 30 kW commercial models. All the company's inverters offer remote web-based data monitoring options.

PVP uses a low component count approach and simplicity as an advantage. PVP's large scale inverter is a 100kW unit targeting a 20-yr service life.

PVP's inverter reliability plan, illustrated in Figures 15 and 16, emphasizes design for reliability, qualification testing (HALT), production quality control and assurance (HASS), test design to meet safety standards and making sure the inverter does what it is specified to do, including field monitoring. In designing for reliability, field data is golden, and 95% of reliability can come from a few steps:

- Fully analyze worst-case product
- Perform computational modeling in time dependent manner
- Design thermal management (this is essential for good reliability)
- Collect thermal data from extreme testing
- Redesign subsystems showing low reliability predictions (this is a must because subsystems have different susceptibilities and failure rates)

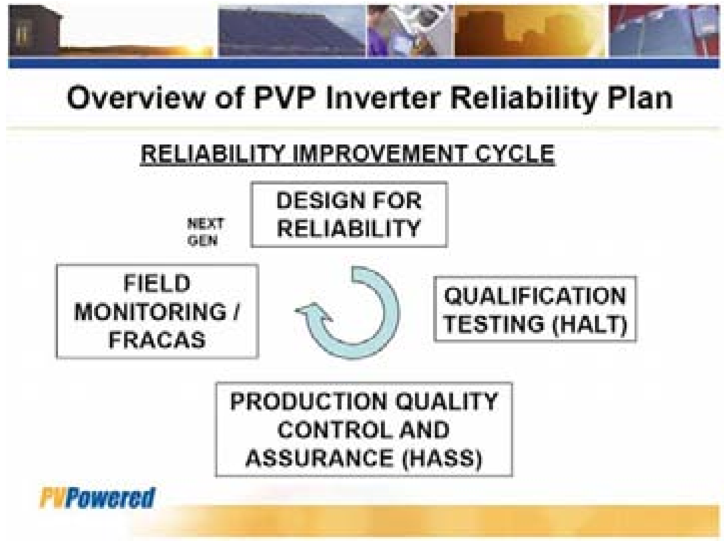

Figure 8: Diagram of PVP Inverter Reliability Plan

Figure 8: Features of PVP Inverter Reliability Plan

Validating predictions with HALT requires using a predictive reliability model to calculate stress and potential. Manufacturers should not not be afraid to break prototypes. They should assure quality manufacturing using well-known practices (HASS), and they should perform field verification of performance and reliability using data monitoring.

It is important to maintain proper documentation and proper testing procedures to validate the inverter under development. The industry needs a PV array simulator that has the capability to characterize the inverter's performance, power quality, and array utilization capabilities – a potential role for the laboratories. The reliability testing process is not simple, and it can take years to build an effective system.

System Availability: A Must for Profitable Large-Scale Systems, Steve Voss

SunEdison was founded in 2003 to make solar photovoltaics a meaningful worldwide energy source, delivering electricity at or below existing retail prices. SunEdison provides solar energy as a "turnkey" service, with no capital outlays required, no impact on existing services, and no ongoing customer maintenance costs. SunEdison is "simplifying solar" by providing on-site engineering evaluation; comprehensive engineering design; complete system provisioning and total installation management; performance validation; utility connection and commissioning; and a full service, operations and maintenance program.

SunEdison currently manages 38 MW of 100% renewable electricity in North America. As such, they are in a good position as an integrator to evaluate the reliability of systems using different PV arrays and different inverters. Integrators are most concerned about the project rate of return, and system availability is key. In 2007, SunEdison observed:

- Fleet energy production was as expected
- Fleet availability exceeded 97.5%
- Inverter faults were the most frequently observed events
- Grid related outages were the second most frequently observed downtime events
- <5% of all events caused more than 50% of lost energy production
- Real time monitoring and service are essential to minimizing the impact of minor events -- for example, cleaning modules regularly, but at the right time of the year in a given location, can improve energy production
- Annual degradation rate is another major driver of IRR (Internal rate of Return)

Bottom line: From an integrator's point of view, reliable system components are essential to keep energy production and IRR high. Inverters are a primary area for improvement. Annual degradation rate impacts IRR, and therefore it is important for manufacturers to be able to accurately predict degradation. Maintenance schedules tailored to the point of use can improve energy production.

Day One Afternoon Joint Question and Answer Session

In bringing new products to market there is tension between the desire to launch products quickly and ensuring reliability. The integrators on the panel noted that they are not as familiar with product introduction issues because they do not have many projects with emerging technologies. For heritage inverter designs product launch can take 3-4 months. Brand new designs take 6 months to get to qualification testing, using an aggressive schedule.

After installing many MW of capacity and several years of operating experience, it would be interesting to know if there are notable differences between technologies. Some integrators have used ASi, and there are plans to use CdTe. Integrators do have enough data to look at differences between manufacturers and what different products deliver versus what is expected.

The panel suggested that a document on preventive maintenance for inverters would be useful: what to torque, other preventive measures. At least some manufacturers are specifying preventive maintenance for their commercial products.

Integrators tend to under-predict output – why? Third party engineering firms are responsible for many of the predictions because banks require third party verification of systems. Many favor PV Assist for modeling. The ability to choose all the right factors in a model is a problem. Some models are not as effective for time of use and time of day analysis, or are weak in dealing with shading and other items. Different models deal with the nuances of predicting PV output more or less effectively. Models in general do need more sophistication. Once a prediction is complete, companies generally do not go back and make adjustments, so the predictions are not weather adjusted. The sun tends to vary more than the prediction. It is better to under-predict than over-predict in those situations – at least then the integrator or developer can deliver what it promised. Integrators also do their own internal analyses for performance indexing, to identify systems that need service.

Concerning the residential market, how does a homeowner know their system is working, much less working well? When an inverter has a 5-year life should a homeowner plan on replacing it when it fails, or should they replace before it fails catastrophically? How should they deal with variable lives of components? Some of the large integrators noted that these are some of the reasons they are not involved with residential developments. However residential is where a lot of the publicity and growth is going. Anecdotally, some suppliers have said that even if half the inverters from a batch might fail, the manufacturer will just wait to find out which ones failed. That is a public relations issue. Panelists noted that the first question is really about data monitoring. The industry needs a simple way to display information so customers know their systems are working. Some companies are moving to a web-page that displays information for their customers, including indicators on the screen that show generation. On the second question, it is not clear what the best policy is for inverter replacement. There is a big difference between warranty and expected life. There is not a lot of data showing FMEA catastrophic failure on inverters. The PV industry is not that different from the auto industry in this respect. With cars, consumers only know the miles per gallon and speed. Most people don’t know what is going on inside their auto, just as they don’t know much about what is going on inside their PV system.

Concerning safety for R&D mode, the panel advised that it is better to experiment in your lab and not in someone’s backyard. A lot of the safety basics are the same for the lab and the field. In PV everything is still sun, volts, amps, etc., so safety procedures are broadly applicable.

Concerning degradation from soiling and from accumulation, the panel replied that their fleet is relatively young, so it is hard to estimate the impact on a cumulative basis. Some integrators contract to clean twice a year. When those cleanings are scheduled is important depending on the local climate – wind-borne dust, peak smog production, and other factors. In California cleaning is done in June and August. Soiling may explain the 2% difference in output prediction versus results, because modeling usually assumes no cleaning and degradation is based PVUSA experience with dust, which approached a 14% to 15% impact in the summer. Cleaning the arrays twice a year is currently not factored into predicting performance.

In response to a general observation about fatalities in the PV industry, a participant noted that there has been one death from PV, in Australia. There has been one smoke inhalation death in wind power. The panel noted that PV has a great safety record, but there is a very small sample size so far. There is concern that the “DC factor” – the perception that DC systems are less dangerous than AC systems -- tends to make people more careless. The systems that are being installed now are high voltage system, so there are significant risk factors. Although the industry safety record is very good, people generally don't know enough about the safety issues with PV – industry can't become complacent.

Day Two Presentations

Progress Since First Workshop, What's New and What's Needed, Tom McMahon

Work and progress that have occurred since the first Accelerated Aging meeting in Baltimore include a much stronger team approach to research between NREL and SNL which has accomplished:

- FMEA study initiated
- Coring technique to evaluate interface toughness/outdoor weathering correlation (to be published in Progress in Photovoltaics April 2008 pp. 1-9)
- TTF report completed
- Failure mechanisms for different PV technologies itemized
- Expanded small systems capability
- Added chamber capability
- Convened this workshop, Accelerated Aging and Reliability II

The NREL/SNL team has added to its test capabilities since the last meeting, including work on standard qualification/safety testing and accelerated versions of the same tests (damp heat, thermal cycling, UV, hail simulation, mechanical loading, light soaking, outdoor exposure, combined effects tests). The Lab team needs to continue real-time outdoor testing to accurately measure array degradation rates, and to capture the data needed for correlating accelerated testing results to what actually happens in the field. The Packaging Team provides diagnostic tools and tests, including WVTR (water vapor transmission rate), adhesion and corrosion of interconnects, thermal imaging to diagnose shunting issues, measurement of module series resistance and shunt resistance, and shear strength measurement at the front cell/EVA interface. Data on array degradation rates from testing is illustrated in Figure 17, and the shear strength measurement test apparatus is illustrated in Figure 18.

Bottom line: NREL and SNL have made progress on analyzing failure modes for various solar cell/module technologies, and that work needs to continue. The team has also expanded their module testing capabilities and diagnostics with regard to accelerated aging testing. The primary take-away from the presentation is the continued universal need for correlations of real-time outdoor testing with accelerated exposure testing.

Array degradation rates:

- Module/array power logged real-time
- Monthly multiple linear regressions to PTC equation
- PTC ratings – 1000 W/m², 20°C ambient, 1 m/s wind speed
- Linear fit gives degradation rate
- Important for true LCOE

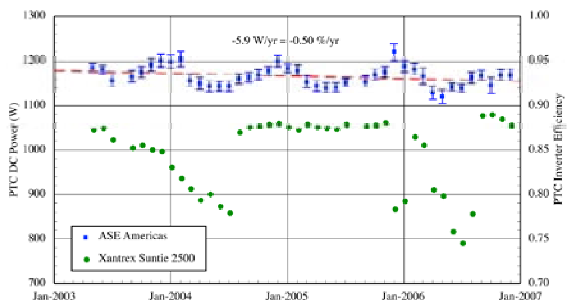

Figure 9: Array Degradation Rates

Shear Strength Measurement at Front Cell/EVA Interface

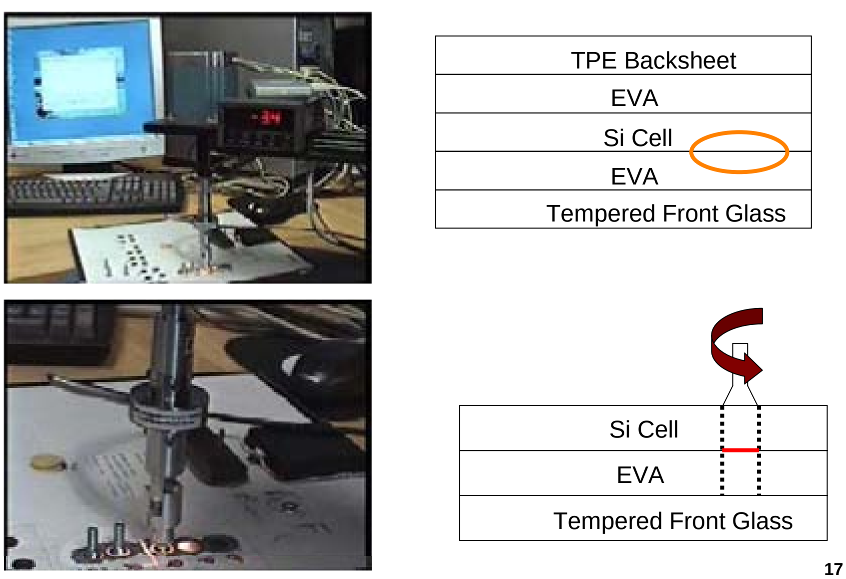

Figure 10: Shear Strength Measurement

Best Practice for Achieving High Reliability with PV Systems, Carl Carlson

There are five overarching questions facing the PV industry regarding reliability:

- How can a maturing industry benefit from applying reliability engineering?
- What are some of the best practices from other industries?
- What are some of the techniques / approaches that will likely be applicable in PV?
- Can reliability engineering be cost-effective?
- Can service life predictions ever be made without enormous amounts of testing?

One of the key points is that achieving high reliability is a business necessity, and it requires FOCUS. While reliability testing and processes can involve extensive detail, even simplified versions can be useful if they cover some of the key points. Users should not be dismayed or discouraged by the complexity and level of detail seen in a well-established program. The most advanced approaches have developed over many years. Companies starting to build a reliability program can choose the steps and measures that are most important and implement them effectively, and gradually expand their programs. An effective reliability program can be built over time, from manageable steps, with FOCUS and documentation.

The first principles for achieving high reliability are:

1. Set Well Written Reliability Requirements
2. Understand the Entire System
3. Design in Reliability to Products and Processes
4. Properly Use Accelerated Life Testing as Part of Overall Test Plan
5. Ensure Supplier Parts are Reliable
6. Ensure Manufacturing Processes are Free of Defects that Impact Reliability
7. Execute All Tasks Through a Best Practice Reliability Program Plan Aligned to Product Development Stages and Staying Within Cost and Timing Requirements

The definition of reliability is the probability that an item will perform its intended function for a designated period of time without “failure” under specified conditions. It is different from quality control or testing in that reliability considers how long a product will work after assembly. The definition implies statistical measures (probability), a definition of function, a time frame, conditions, and a precise definition of failure.

Reliability starts at the concept stage of development. It involves agreeing on best practice reliability requirements and incorporating them into technical specifications, which then flow down to subsystems and components. Specification helps drive the right tasks internally and with suppliers in order to achieve reliability. The vital few tasks that support the concept stage are developing a profile of the conditions the system will be used under,

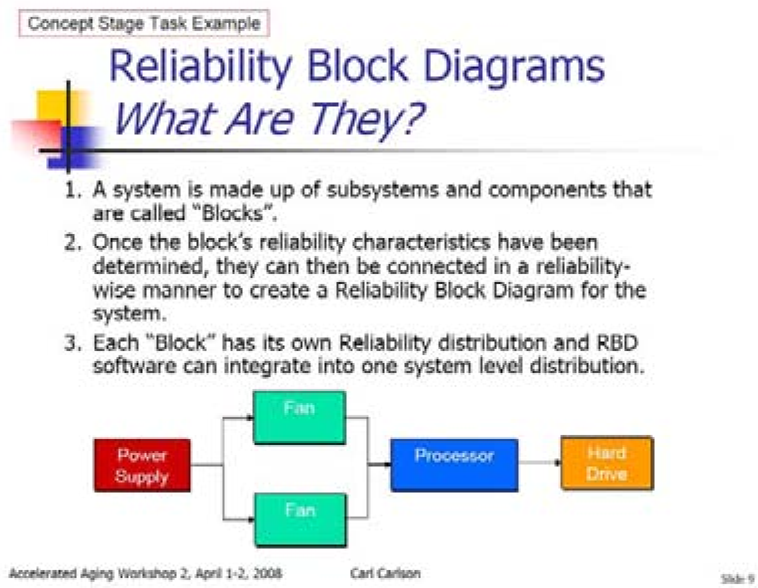

Figure 19: Reliability Block Diagrams

developing system level reliability requirements, then flowing those down to subsystems and components. A reliability block diagram (RBD) documents the flow down from system to components and helps identify "reliability critical" components and subsystems. See Figure 19 for an explanation of RBDs. This lays the groundwork to perform system level failure mode effects analysis (FMEA).

Writing reliability requirements down and documenting them is essential to repeating, refining and applying the process. A good reliability requirement includes probability statements that are measurable by testing, linked to functional product requirements, with a clear statement of time, defined customer usage and operating environment, and a clear definition of product failure.

Reliability during the design stage of product development is important because that is when there are greater opportunities for improving reliability from a cost and feasibility perspective. This is the stage where changes to enhance reliability are still relatively easy to make and implement. The methods and tools applied at this stage are often called Robust Design or Design for Six Sigma. The vital few tasks to perform during design are:

1. Perform Design Margin Analysis
2. Perform Design and Process FMEAs
3. Address Root Cause of Known Reliability Problems
4. Develop and Use Product Design Guides
5. Incorporate Reliability Input Into Design Reviews
6. Identify and Execute Specific Robust Design Tasks, such as Design of Experiments (DOE), Physics of Failure Modeling and Highly Accelerated Life Testing (HALT)

There are lessons to be learned from the design stage. First, waiting for testing to discover design weaknesses leads to problems that result in program delays and cost overruns. Second, FMEA is not just a "check off" – it has to be done properly to reduce risk to an acceptable level.

In the assurance stage reliability ensures that products are launched with the highest possible system reliability. The vital few steps in the assurance stage are:

1. Develop Improved Reliability Testing Methods, including ALT
2. Develop and Get Approved Reliability Test Plan
3. Conduct Reliability Component and Module Level Testing
4. Conduct System Reliability Growth Testing
5. Verify that Suppliers Meet Supplier Reliability Requirements
6. Implement Ongoing Management Reviews to include test failure data

The first lesson to be learned from the assurance stage is that not modifying test procedures based on expected environments, conditions of use, field histories or FMEAs will lead to poor results. Second, doing system testing with parts that have not been reliability tested by suppliers will prevent system testing from discovering interface and integration problems. Finally, life-stress models must be understood before doing ALT.

Well done design for reliability must have manufacturing and field support tasks to ensure that the inherent design reliability is not degraded or unstable. The following are the minimum tasks to support manufacturing reliability:

1. Develop Preventative Maintenance Plan (advanced application would be Reliability Centered Maintenance)
2. Develop Manufacturing Control Strategies
3. Develop Screening & Monitoring Plans
4. Develop and Implement Field Test Plan
5. Verify All Requirements Met Before Launch
6. Document Field Lessons Learned

Finally, all the stages of reliability testing need to be put together in a Reliability Program Plan that applies the "vital few" best practices; addresses high risk areas; closes gaps; strengthens organizational weaknesses; is explicit about what, who, when, where and how; and is approved by management and supported through regular reviews.

Fire fighting is usually rewarded and recognized more than fire prevention. A fire fighter is a hero, but if you do your job and the fire is prevented in the first place, your work is almost invisible. In reliability terms, if you mess something up and then correct it later, you become a hero. The role of management is to create the environment that encourages prevention and supports world-class reliability, rather than world-class responses to problems that could have been avoided.

Field Observations and Product Returns – What Can We Learn, John Wohlgemuth

PV modules are designed to work outdoors, so it is important to observe the performance of fielded modules. But why should industry be interested in determining how and why fielded modules fail, and what can be learned? Second, how can field and return data be used to improve products? Third, how can industry use that same data to develop better accelerated tests to help predict failure in the field and lifetime?

There are three types of field observations. Active observations involve installing a product in various climates and observing performance. Active observations are the most like experiments in the field and are usually designed to produce more data and parameters for analysis. Active observation is also the most expensive. Semi-active involves monitoring fielded system to determine energy production and any long-term decrease in output, and any other environmental or other factors that can be easily monitored. It is not as expensive as active observation, but potentially can be done on more systems. Finally, passive observation involves analyzing product returns. It is the least expensive, but also provides the least contextual data for why something failed – data comes in separated from the system, usually with no environmental data, and sometimes with very limited explanations of why the product has been returned.

Not all returns are failures – sometimes the return is a system failure. For example, the wrong product was shipped or the product was damaged during shipment. Product returns are equated with warranty returns, but in some cases, with good customers, returns are accepted for reasons short of warranty coverage – like discoloration or blemishes in an architectural product. The modules may work fine, they just don't look as good as the customer expects. There is a technology definition of failure and a customer service definition of failure that are different. The decision to accept a warranty claim is primarily a commercial decision.

Failure analysis is a determination of why a module was returned – "the claim." For reliability purposes it is important to determine if it really is a failure – does it still meet the specification and/or warranty conditions? If it is a failure, the next step is to identify the root cause.

When analyzing failures in fielded modules, the first concern is to determine if the sky is falling -- if all the modules the company has manufactured and sold are likely to fail before the warranty expires. Second, companies want to know the root cause of failure to estimate what fraction of fielded modules are likely to suffer the same failure, to help determine what warranty reserves are necessary. Understanding the failure modes also helps identify product changes that might eliminate or reduce some types of failures. The knowledge can also help to develop or improve accelerated tests to screen products for a failure mechanism and avoid the expense of field failure and replacement. If the analysis shows a safety issue, it becomes the trigger for communicating the problem to customers and avoiding bigger problems.

Typical observation and measurement tools are listed in Figure 20. There are four types of mechanisms for failure, plus mechanisms that impact safety: Mechanisms for Power Loss; Mechanisms for Functionality; Mechanisms for Workmanship; Mechanisms for Cosmetics. Typical power loss mechanisms include broken interconnects, bad solder bonds, cracked cells, corrosion on contacts or between thin film layers, inadequate isolation scribe lines, shorted bypass diodes – which have been mentioned frequently during this workshop – cell hot spots, arcing and discoloration.

Functionality mechanisms involve glass breakage, which always raises the question of how and why the glass broke; structural failure of frames, mounting structures and adhesives; and failures in junction boxes and output leads.

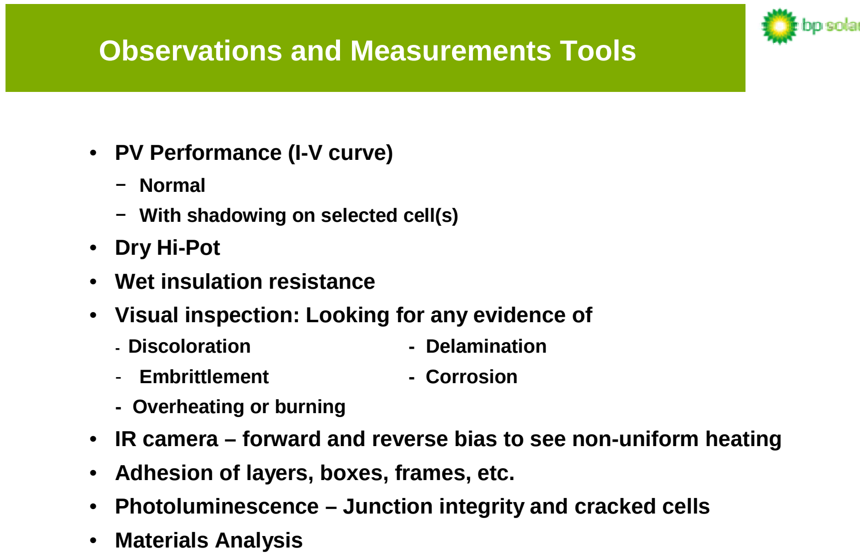

Figure 11: Observations and Measurement Tools

Workmanship issues are associated with delamination of encapsulants, loose frames, loose junction boxes, and any item on the power or functionality list before it reaches a critical level. These are problems waiting to impair power or functionality.

Cosmetics involve discoloration or blemishing of the encapsulant, the backsheet, or cover sheet; foreign items in the module; misalignment of cells in a package or glass frame; and variations in thin film coating thickness – semiconductors within thin film modules, AR coatings on cells or glass. Anything visible that impacts appearance, when PV is in an architectural setting, can become a cosmetic failure. Cosmetic failures have put companies out of business.

Finally there are safety issues. These are the worst, and typically fall into two categories – exposure to high voltage and potential for fire. These also have the potential to put a company out of business.

Determining the root cause of a failure is only the beginning. Next comes determining why and how by looking at sample history, finding out if it is an isolated occurrence or one of many, and whether it is showing up in accelerated stress testing. To understand causation the failure must be duplicated using existing tests, by increasing the cycles on established tests, by combining stresses, or in some cases developing new tests. Once a failure is duplicated it is possible to find out where it originated – in a design flaw, in poor materials, in workmanship, or in a deployment that is just too extreme for the product. Understanding root causes provides information needed to make effective changes in design, process and/or materials to reduce or eliminate the failure. A new cause of failure may also require a new test methodology to assess future changes in products to assure that the failure mechanism doesn't reappear.

Day Two Morning Joint Question and Answer Session

In response to a question concerning recent recalls, a panelist noted that the percentage of failure among all their shipments is .1%. The last recall they experienced was a result of workmanship, so it tends to be clumped in one or two day's worth of production. That problem peaked and declined.

In response to a question the panel commented that the right reliability program can drastically reduce the number of emergency phone calls and crises, but they are not reduced to zero. Unexpected failures will still be there. What can be done is apply some of the principles of reliability and methods very quickly when a new problem arises and get control of it? Root cause analysis and testing must be done very quickly in emergencies, after doing as much prevention as possible. GM rewards people for prevention rather than emergency response through job requirements, performance reviews, and salary increases. But doing that requires a management role. For reliability tools, there are a number of well-written life stress models on Reliasoft's website at www.reliasoft.com.

III. Breakout Sessions Summary

Introduction

The participants were organized into three breakout groups after each set of presentations so that the information from the presentations would be fresh in their minds:

- Day One Morning
  - A: Reliability Challenges in Thin Film and Emerging Technologies,
  - B: Silicon Reliability Issues,
  - C: Concentrator Systems Reliability Questions
- Day One Afternoon
  - D: Packaging Design and Evaluation – Successes and Current Barriers
  - E: Manufacturing – Automation, Continuous Improvement, Diagnostics – Assuring and Improving Reliability
  - F: System Design for Reliability – What Needs to be Improved
- Day Two
  - G: Field and Product Return Insights – Data Gathering Priorities and Best Practices
  - H: Test Protocols – Priority Challenges
  - I: Reliability Predictions – How Better Correlations Can be Achieved

Participants selected their breakout groups when they registered. Each group had a facilitator to help record results and keep the discussion moving forward. Each group also had a National Laboratory expert to help spark discussion, answer questions about DOE/Laboratory research, and capture the technical content of the discussions. Each session also had a scribe to help ensure that all the results were captured. A breakdown of the assignments for each breakout group is included below and in Appendix A, Participants.

On day one in the morning groups A, B, C and F were given a set of handouts that suggested criteria for success and failure modes to help start the discussion and build off the results from the previous workshop in 2006. The handout information is included in Appendix E. Facilitators emphasized that these questions and topics were purely for sparking discussion and the groups would not be limited to these topics or required to respond to each item on the list. Most groups did use the lists as a guide, but set their own priorities for what to discuss and how to organize their results. Each of these four groups was asked to focus first on identifying and prioritizing failure modes and reliability issues, then on suggesting actions for DOE, industry and other organizations to address the issues. The remaining groups discussed important issues and recommendations for action to address key challenges.

Personnel from the National Laboratories and DOE were asked to participate, but to let representatives from other organizations take the lead. DOE and National Laboratory personnel made valuable contributions by providing information and following up with questions, but let the other participants establish what was most important to discuss. Facilitators were instructed to prompt their groups for details and specifics and to make sure the groups kept the discussions moving toward information and results that would meet the goals of the technical meeting and to give everyone a chance to contribute.

Breakout results were reported back to the entire group after a break. This gave the audience the chance to clarify the results and follow up with comments and questions.

Participants, Staffing

Table 2 below shows how the breakout sessions were staffed. Table 4 shows the breakout sessions participants elected during registration, although they were free to change their selections during the meeting.

Table 2: Staffing

Facilitators		
DeGroat	Kevin	McNeil Technologies, A
Kurtz	Sarah	NREL, H
McMahon	Tom	NREL, D
Quintana	Michael	SNL, C, F and I
Tillerson	Joe	SNL, B, E and G
Technical Representatives for Breakouts		
Gonzalez	Sig	SNL, F and H
Kempe	Michael	NREL, D
Kurtz	Sarah	NREL, C and E
McMahon	Tom	NREL, A and G
Osterwald	Carl	NREL, B, E and H
Sorenson	Rob	SNL, B, D and I
Scribes		
Albin	David	NREL, A and D
DeGroat	Kevin	McNeil Technologies, E and G
Kendrick	Lumas	McNeil Technologies, B, F and H
Kurtz	Sarah	NREL, C
Sorenson	Rob	SNL, I

Table 3: Breakout Group Elections

	A	B	C	D	E	F	G	H	I
Adriani, Paul	X			X				X	
Albin, Dave	X			X				X	
Asher, Sally		X			X		X		
Barikmo, Howard	X					X	X		
Barth, Kurt	X					X		X	
Beaupre, Richard A.		X				X			X
Beck, Markus	X			X				X	
Berens, Troy	X				X				X
Birincioglu, Gencer			X	X					X
Bower, Ward	X					X			X
Bury, Scott	X					X			X
Call, Jon	X			X					X
Capps, Phillip			X			X		X	
Cart, Bob			X	X					X
Chang, Rex			X	X					X
Chemelewski, Gary		X				X			X
Chen, Lei	X			X					X
Coleman, John		X			X				X
Coleman, Nate			X			X			X
Covarrubia, Eberth A.		X			X			X	
Coyle, Dennis J.	X			X				X	
Creel, Howard			X		X			X	
Dabeer, Vikas		X			X				X
Dhere, Neelkanth	X			X					X
Dickinson, Joel	X					X	X		
Emery, Keith			X	X				X	
Enzenroth, Al	X				X				X
Fabick, Leon	X			X				X	
Fahrenbruch, Shawn		X				X	X		
Felder, Bethanne	X			X			X		
Ferguson, Bruce	X				X		X		
Ferrigan, Sean	X			X					X
Fife, Mike			X		X		X		
Fischer, Dick	X					X			X
Foy, David		X		X					X
Gaston, Ryan	X			X					X
Gonzalez, Pedro	X			X			X		
Gonzalez, Sigifredo			X			X		X	
Gostein, Michael	X				X			X	
Harwood, Duncan	X				X				X
Haskell, Bert	X			X					X
Hebert, Peter			X		X		X		
Hegedus, Steve	X			X				X	
Herb, John			X			X			X
Hudson, Ray		X				X	X		
James, Ted		X			X				X
Ji, Liang			X			X		X	
Kabade, Raj	X			X			X		
Kanto, Eric	X			X					X
Kilkenny, Matt			X	X				X	
Kukulka, Jerry			X			X			X
Kurtz, Sarah			X	X			X		
Lu, Dingyuan	X			X					X
Lu, Jason			X			X	X		
Luo, Yuhao		X		X					X
McCabe, Joseph	X					X			
McConnell, Bob			X		X				X
McDaniel, E.L. "Mick"	X					X			X
Meisel, Andreas	X				X				
Meydbray, Yevgeny		X			X		X		
Morris, Russell			X			X			X
Mundt, Mike	X					X			X
Nguyen, My	X					X		X	
Pankow, Joel	X			X			X		
Parker, Terence		X				X	X		
Payne, Jim	X					X		X	
Pern, John	X			X					X
Pinarbasi, Mustafa	X			X					X
Reedy, Bob	X					X	X		
Ressler, Stephen		X		X					X
Ring, Brad	X					X			X
Saito, Patricia			X	X				X	
Schiesher, Nathaniel		X				X	X		
Scott, Kurt	X					X		X	
Seymour, Fred H.	X			X			X		
Shah, Shirish		X				X		X	
Sherwood, Larry	X					X		X	
Shisler, William			X			X		X	
Sorenson, Jim	X				X				X
Spencer, Mark			X			X	X		
Stresing, Klaus			X			X			X
Strzegowski, Luke	X			X			X		
Suell, James	X					X	X		
Sun, Lizhong	X				X				X
Surendran, Sandheep			X			X		X	
Tamizh-Mani, Mani		X		X					X
Tornstrom, Eric		X				X			X
Vaidya, Swanand S.	X			X				X	
Voss, Steve		X				X			X
Whitfield, Kent	X			X				X	
Wicks, Steve	X			X					X
Wohlgemuth, John		X			X		X		
Xavier, Grace		X		X					X
Xia, Zhiyong		X		X				X	
Xu, Helen			X	X			X		

A: Reliability Challenges in Thin Film and Emerging Technologies

Criteria for Success

The group discussion was led by Tom McMahon who distributed a handout on criteria for success and key failure modes (see Appendix E). The group agreed there is no single criteria for success, but the statement "…a reliable PV module has a 'high probability' that it will perform its intended purpose adequately for 30 years, under the operating conditions encountered" creates a starting point for refining success criteria specific to applications, products and customers. Similarly, the statement that "A PV module fails to provide service if its power output decreases by more than 30% before 30 years, e.g., require a loss less than 1%/year, in its use environment" can be viewed as a goal, something to direct research and internal improvement processes. Reliability means different things to different stakeholders (bankers, manufacturers, customers, power integrators, different thin film producers). Reliability should be based on expectations between manufacturers and customers. A measurable understanding of reliability for a utility is different from the military, or a residential customer or a commercial customer. Customers ultimately decide what level of reliability is acceptable.

Rather than focus on an ultimate reliability level, it is more important to focus on understanding reliability issues, because predictability may be more important. Integrators want to know how much energy they can expect for a given time, and, if it is predictable, can accept different product lifetimes and performance degradation.

Reliability should also be technology-specific; reliability means different things to different technologies. The organic PV (OPV) business model may support less reliable products, as an example, because they are planning on very low costs. Module failures can be managed by looking at the cost of failure over the lifetime of the module; with this information the manufacturer can decide to either fix the problem or manage the cost.

Failure Modes

Overall the group agreed that the list of failure modes developed by the DOE Laboratory team (Figure 21 and Appendix E) is good for thin films. The first three items in Table 4 were clearly the most important failure modes for the group, while the remaining items are not necessarily in priority order. Many of the failure modes are interrelated.

FMs: Modules Technology Specific

Field returns and anticipated failures

Thin Film:

- **Flexible packaging interconnect failure**
- **Laser scribe interconnect failure**
- **De-adhesion of device layers, inc. CTOs and metal contacts**
- **Busbar adhesion and electrical contact**
- **Weak diode or shunt defects**
- **Decreasing ff (field collection or series resistance issues)**
- **Moisture ingress problems, esp. flexible with CIS**
- **Diffusion, esp. Cu in CdTe**
- **Staebler-Wronski, esp. single junction a-Si**
- **SnO_2 corrosion in superstrate cells**

3

Figure 21: Technology Specific Failure Modes Handout

Table 4: Thin Films Breakout Results	
Success Criteria	• Proposed definitions should be viewed as goals, something to direct research and internal improvement processes. • Reliability based on expectation between mfr. and customer, and customer decide what's acceptable. Reliability differs with products and markets, utility-scale versus residential. • Rather than focus on definitions of reliability, focus on understanding reliability problems to improve predictability, which is critically important. Integrators want to know how much energy they can expect for a given time at a given cost. • Module failures can be managed by looking at the cost of failure over the lifetime of the module; manufacturers can either fix the problem or manage the cost.
Failure Modes	• Moisture ingress problems, especially flexible modules and CIS • Flexible packaging interconnect failure • By-pass diodes • Laser scribe interconnect failure • De-adhesion of device layers including CTOs and metal contacts • Bus bar adhesion and electrical contact • Weak diode or shunt effects • Decreasing ff (field collection or series resistance issues) • Diffusion, especially Cu in CdTe • Staebler-Wronski, especially single junction a-Si • SnO2 corrosion in superstrate cells
Issues/Needs/Priorities	• Correlations between lab Accelerated Life Tests and field test data • Approach to protect company intellectual property while still supporting research into failure modes and reliability • A Sematech approach to tackling general, ubiquitous issues across industry • Understanding moisture ingress – its effects and how to minimize (universal across thin-film materials) • Developing models and understanding the physics of failures • Packaging – corrosion, novel packaging • Guidance on which tests are appropriate for which materials and packages, ways to adapt to specific products • Experimentation and out-of box thinking – thin films don't have to use same materials as Si (for example, and especially, EVA) • Quantifying cost of reliability • Quantifying other benefits/issues associated with thin films – for example, their lower carbon footprint
Actions	• A database (or data warehouse) of field data to analyze and understand failure modes • Approaches to protect intellectual property and confidentiality while still sharing field data and test results for analysis, fostering industry-wide cooperation • More research on moisture and packaging issues and their impact on reliability. • Develop more open-ended, flexible approaches to testing. • Distinguish between human error failures and real product failure mechanisms; both are important but the labs should focus on the latter.

Issues/Needs/Priorities

The top issues/needs/priorities were clearly focused on solving problems in getting and using data on fielded systems to improve prediction, followed by moisture ingress, modeling of the physics of failures, and packaging issues that reflect the top failure modes.

Actions

The actions summarized in the table highlight the interest in a database or data warehouse for analyzing and understanding failure modes in the field. However, the group also emphasized industry concern with disclosing such information. The actions also emphasize continuing concerns with packaging and moisture ingress.

B: Silicon Reliability Issues

Criteria for Success

The silicon group identified multiple success criteria, documented in Table 5. This added substantially to the ideas offered by the handout in Appendix E.

Failure Modes

In the discussion of failure modes the group endorsed the modes included in the handout and then expanded the list, as shown in Figure 22 and Table 5. Clearly crack formation in thin cells is a by-product of improvements in manufacturing to reduce silicon material requirements and lower costs. Solder joints along with open circuits and shunting related to ribbons were also recurring problems. Problems with failures at the J-Box and quick connector reliability were first brought up in this session and were then repeated and emphasized in several other sessions. The growing concern with these problems are related to more installed systems

FMs: Modules Technology Specific

Field returns and anticipated failures

Wafer Si:
- **Crack formation in thinner cells**
- **Solder joint degradation on cells**
- **Ribbon related open circuit or shunting**

Figure 12: Failure Modes for Silicon Handout

Issues/Needs/Priorities

In discussing needs the group focused on what is different in today's environment. Most of the responses reflected changes in the market. First, the customer is changing and growing more sophisticated, involving professional financiers; tougher, performance-based incentives programs; and more utilities. Banks are hiring third-party engineers. As a result industry needs more accurate and believable predictive tools to pass the higher levels of scrutiny. The needs and priorities also reflect challenging applications, particularly building integrated PV (BIPV) and concerns with installation and inspection. The needs also reflect the impact of expanding production – better manufacturing systems, approaches to reduce damage during shipping and handling, reducing parts counts and simplifying packages, and analysis and test procedures that can help identify the most important problems to solve given the growing number of components and systems the industry manufactures and installs.

Installation problems are also emerging from variations in the quality of inspectors, the quality of installation personnel and their adherence to NEC and other standards. There are also problems with testing systems built from parts and that have not been adequately qualified and tested by suppliers. Conversely, system design has to focus on and be tested for reliability – not just the components of systems. As new failure modes emerge, industry needs assistance with FMEAs, analysis and guidance on best practices for applying and conducting tests to stay ahead of problems. Feedback from all the world's labs, including Europe and Japan where many more systems have been installed, would be highly valuable.

Actions

Companies are dealing with smarter customers who know more about what they want. As a result the emphasis is on high-fidelity data and modeling that can produce the information and predictable performance the market demands. There is also more testing, therefore industry needs a framework for which tests to use and how to apply them. Finally, J Box/Combiner Box and quick connector issues received more emphasis. Even though industry has done a lot of work on these failure points, they remain a problem.

Table 5: Silicon Breakout Results

Success Criteria	• Low returns, (6 sigma over warranty period). • Process Control/Qualification, (standards plus internal). • No catastrophic failures – no headlines, >>> 6 sigma. • Inverter warranted beyond 10 years, lifetime. • More modular designs. Design for maintainability. • Uniform module aging within, and module to module, with minimum power loss. • Ability to maintain and replace components (when new products come out). • Ability to substitute alternative, new low-cost materials. • Qualified installers • Low Cost – parity in < 10 years.
Failure Modes	• Crack formation in thinner cells. • Solder joint degradation on cells, and other solder issues including lead, outgassing, new tests on cell cracking. • Ribbon related open circuit or shunting. • J Box/Combiner Box failures. • Quick connector reliability – all different aspects.
Issues/Needs/Priorities	• BIPV issues with safety, wiring etc., special handling – tests as a roof or building component and a module, developing architectural design specifications. Need consensus on threshold for design input – when to go back to redesign? • Reliability issues with new component and material supplier qualification. • Manufacturing processes that are idiot proof, self-extinguishing, rugged and robust. • Installers not following NEC leads to failures, inspectors are missing problems • Systems testing with parts that have not been tested by suppliers. • FMEA that can drive new testing and screening, process/product design FMEAs. • Need higher accuracy predictive tools, believable predictive tools. • Ability to do more reliability testing in-line with manufacturing. • Priorities and guidance – new failure mechanisms need new protocols. • Need feedback from all world's labs. • Simplify module and inverter packages, cut parts counts, thermal management. • Designing modules to reduce failures from damage in shipping and handling. • Design systems not just the components. • Framed modules don't cover everything – other types need attention.
Actions	• Specifications to deal with smarter customers, who want high-fidelity data and modeling of output and performance over time. • Framework to help organize the greater volume of testing. • More emphasis on J Box/Combiner Box and quick connector issues – the jury is still out whether these connectors will last 35 years.

C: Concentrator Systems Reliability

Criteria for Success

For CPV, it is more appropriate to define failure or reliability of a *system* rather than of a *module*. System availability is different from system reliability. Both are important. A number of people expressed the opinion that it would be inappropriate to try to communicate a single definition of failure. Usually, a Power Purchase Agreement (PPA) defines reliability for that agreement. The definition included in the PPA may not be stated in the language of a reliability engineer. Establishing a warranty is a business decision. A number of people questioned the implication that a 30-year lifetime is an appropriate goal, suggesting that 20 years is a better target because most power purchase agreements (PPAs) and warranties are closer to 20 years. Ultimately, the thing that matters is Levelized Cost of Energy (LCOE). If a system functions fine but the system availability is decreased because of shading from a new building, then this affects the LCOE. If preventative maintenance is costly, then the number of years to total failure may be less important. The reliability metrics should provide the information needed to calculate LCOE. In defining reliability, ask about the customers' needs (which may vary with the customer and application). In general, customers are looking for a return on investment, and reliability studies should help to assess that. Table 6 summarizes criteria for success, priority failure modes, issues/needs/priorities and recommended actions.

Failure Modes

Handouts on common failure modes for CPV were distributed to aid in the discussion. They are reproduced in Figure 23 below. The failure modes were discussed in relation to cell assemblies, packaging/optics, and structures.

FMs: Modules Technology Specific

Field returns and anticipated

CPV (both low X and high X):

- **Degradation of optics (abrasion, corrosion of mirrors, yellowing, soiling, etc.)**
- **Corrosion of mirrors**
- **High-flux damage to mirrors**
- **Abrasion of optics**
- **Voids or failures in solder bond between cell and heat sink**
- **Tracker mechanical breakdown**

High-X CPV:

- **Tracker pointing error**
- **Melting of or bubble formation in optical bond between cell and optic**
- **Cracking of optical bonding material**
- **Dopant or metal diffusion that affects electrical function**
- **Cracking of cells**

Figure 23: Failure Modes for CPV Handout

Table 6: CPV Breakout Results	
Success Criteria	• Predictable, competitive levelized cost of energy (LCOE). • Systems that demonstrate both high reliability and high availability. • Reliability that enables the customer to realize a return on their investment. • A 20-year lifetime would be consistent with many warranties. • Success, as defined in a power purchase agreement.
Failure Modes	**Cell Assemblies** • Sources of failure related to temperature, open circuit conditions, and a combination of thermal cycling and moisture. • Failure of bond between cell and heat sink. • Degradation of optical bond or encapsulation (especially when exposed to high-flux sunlight). • Moisture related corrosion, changes in conductivity and delamination, and shorts. • Latent defects in bypass diodes. • Inadequate dielectric strength between cell and ground, causing material breakdown and failure. **Optics/Packaging** • Degradation of optics, including abrasion, UV-induced discoloration, deformation of acrylic lenses, soiling. • Condensation. • Outgassing of adhesives on optics. **Structures** • Causes related to moisture, dust, high temperatures. • Failures in jack screws, gear boxes, motors, positional sensing (feedback) and limit switches.
Issues/Needs/ Priorities	• Understanding of cell/receiver reliability. • Highly accelerated tests to reduce the time to test and validate new designs. • An understanding of how these accelerated tests relate to field environments. • Specifically, industry needs to gain confidence that the failures seen in the field are all being identified by accelerated testing and analysis is not distracted by failures observed after accelerated testing that don't occur in the field. This correlation may vary with location. • An understanding of whether corrosion of contacts, degradation of AR coat, or other cell degradation is occurring.
Actions	• Testing of cells/receivers both in the field and under accelerated conditions in order to understand the relationship between these, including qualification tests. • Identify a method for accelerating light-induced degradation when the real-time degradation is already caused by highly concentrated light. • Field testing in a variety of locations for a variety of designs. • Identification of the failure mechanisms associated with failure modes observed in the field. • National Labs should develop tests that go beyond the standard qualification test sequences.

Cell Assemblies

For failures related to cell assemblies the first category of failures are those caused by temperature effects (sustained high T; thermal shock) and associated voids in solder bonds and defects in cells. The second category involves open circuit conditions leading to interconnect and cracking problems. The third category involves long-term degradation associated with thermal cycling and moisture problems.

Failures that are being observed include problems with improper bonding to heat sinks resulting in loss of thermal contact or electrical isolation. There are failures related to adhesives or conductive bonds, including problems caused by trapped air that can give a focal point for stress.

Moisture is associated with multiple failure mechanisms, including corrosion; moisture absorption by materials that causes change in conductivity or other properties; and delamination. If a cell is exposed to ambient conditions, moisture can cause shorts, which suggests the wet high pot test may need revision.

Intrinsic defects in the cells were reported. Failures in AR coating has caused short-circuit current drops. Cell assemblies have been damaged by abrasion. Metal grids fail for various reasons, including damage during handling, and Ag grids corroding in silicon modules. This could be a problem in multijunction cells as well.

In bypass diodes there are latent defect issues, and concern with what reverse bias they should be designed to withstand.

If the dielectric strength of materials between the cell and ground is not adequate, the material may breakdown and cause failures.

Packaging/Optics

Failures of packaging/optics include a number of lens-related problems including abrasion, UV-induced degradation, and deformation of acrylic lenses. Darkening of secondary optics degrade performance, and thermal expansion mismatches can cause secondary optics to explode. Condensation on optics, especially domed optics, may dry out slowly. Outgassing of adhesives onto optics can be either a long- or short-term problem.

Soiling causes a larger decrease in power in CPV than in flat plate PV and can be an especially bad problem in high pollution areas. The aerosols stick to the surfaces, then dust is more likely to collect on the aerosol-covered surface.

Structures

In general, structural failures are caused by moisture, dust, or high temperatures. Drive or hardware problems include failures in jack screws, gear boxes, motors, positional sensing (feedback), and limit switches. Sources of failure include backlash that can cause vibration, sand in gears, and abrasion on metal parts.

The only controller or electronic problems discussed involved systems that inappropriately stowed (at low wind speeds) which decreases availability and power production.

Issues/Needs/Priorities

Understanding the important sources of failures in the cell/receiver is a basic problem. Cell degradation is a concern, but the failure modes of the cells have not yet been adequately identified. Specifically, it is not yet known whether cell failures are related only to encapsulation and corrosion of the metal contacts or to the cells themselves.

The CPV industry is still evolving and developing its designs, so HALT tests that can quickly characterize new designs are important. Industry is not confident that failures seen in the field are being identified by accelerated testing and analysis, which impedes design improvements. This includes separating failures identified by accelerated testing that are not important failure modes in the field from those failure modes that are actually a threat to performance. Which failures observed during accelerated testing are accurate indicators of real problems in the field? Industry needs a better understanding of whether corrosion of contacts, degradation AR coatings, or other cell degradation is really occurring.

Actions

The group provided a long list of possible actions. The topic was the role of the National Labs, but some of the recommended actions were broader suggestions on what needs to be done. The group wasn't clear about whether all of these were intended specifically for the National Labs. The items that were clearly focused on the National Laboratories are included in Table 6. Five items that were at the top of the priority list in general were work on cells, bonding, optics, compounds and barriers. Other suggestions are included here to provide an expanded view of some of the specific problems and concerns the industry would like the broad actions in Table 6 to address, including:

- Understanding failure modes
- Life of adhesive compounds
- Use of ultrasonic testing to study voids – Laboratory work on how to apply and use it, with manufacturer implementation?
- Coating to protect cell from moisture
- Interactions between inverters and system
- Ensuring tracking accuracy
- Understanding whether accelerated tests are introducing irrelevant failure modes
- HALT
- Determine relevance of qualification tests to various applications (should damp heat test be the same for Florida and Arizona?)
- Identify key stresses (aerosols, salt content, etc., technical basis for qualification tests)
- Determine how to modify tests for different geometries
- Quantify operating environments. Could define Class A, B, C environments and develop different set of tests to match different stress environments.

D: Packaging, Design and Evaluation – Successes and Current Barriers

In general the current PV package (glass-glass) is viable. Glass is hermetic and strong, it passes Class A Fire hazard ratings, and so will be used for a long time. For glass a common problem is moisture ingress at edges and contact-lead holes – solutions to these problems would make current packages more robust.

EVA remains cheap, it is transparent, UV stable, and shock absorbing. There is interest in better alternatives, but EVA works. New polymers with lower WVTRs are starting to be used. There are also flexible package successes (United Solar Systems Corporation, USSC). Roofing and flexible designs have unique challenges, therefore reliability and testing needs to address something beyond the rigid, framed structures that have dominated sales to this point.

All packages need an emphasis on edge seals − butyl rubber has a lower WVTR but still has problems, including adhesion failures and oozing. EVA may continue to be acceptable for some products, while other technologies may need better alternatives. For example, acetic acid production is acceptable for some technologies, but not for others. Generally there is hesitation to adopt new approaches because EVA has a long history and is well understood. However, new ideas (e.g., barrier layers directly on semiconductors) should be considered.

PV is affected by market economics and the size of the PV industry in relation to its suppliers. For example, when glass manufacturers removed Ce it was not driven by PV manufacturers. The glass industry had inserted Ce for other reasons, found a better substitute, and stopped using it without any regard for its impact on the PV industry. This illustrates the limited influence PV has on some suppliers because the industry is still relatively small. By the same token, can the industry expect products other than EVA when most use EVA?

Failure Modes

Moisture ingress cut across the failure modes discussion, especially in relation to the extensive discussion of adhesion and delamination, as shown in Table 7. Adhesion is recognized as an important issue, but it is not well understood. The relationship with moisture ingress needs to be studied. Corrosion is inversely proportional to adhesion. The WVTR represented by delamination may far exceed inherent material WVTRs. Delamination needs to consider not only moisture but the different material interfaces involved because differences in thermo-mechanical as well as chemical properties induce different loading at interfaces.

Issues/Needs/Priorities

Tests should be based on function. The application should determine testing because different customers have different requirements. Roofing-flexible products may require modified tests, e.g., higher temperatures, flex tests. Simple tests for EVA replacements would be welcome. Are they as good as EVA (transparent, UV stable)? Are they cost-effective (some applications may afford higher cost)? Maybe a benchmark can be developed, although the needs are often product dependent because of the interface. This is something the industry would like to have, but there is no consensus on how to do it.

Table 7: Packaging, Design and Evaluation Breakout Results	
Failure Modes	• Moisture ingress. • Failures related to adhesion are important but not understood, including relation to moisture, corrosion. • Failures related to EVA adhesion to substrates, especially in thin films. • Failures related to delamination – not just from moisture but also associated with different material interfaces involved, differences in thermo-mechanical as well as chemical properties that induce different loading at interfaces.
Issues/Needs/Priorities	• Need to standardize adhesion measurements, and correlate them with field test data. • Need encapsulants that are better than EVA but still cost-effective. • Need to consider differences between framed, glass modules and flexible structures, and their applications as they relate to determining appropriate tests. New solutions and testing protocols may be needed. This has gone up in priority as more products use foil and other flexible materials. • Define critical levels of delamination. Modules may still work with considerable delamination, but what does it do to moisture-dependent degradation? • Better understanding and use of WVTR in testing – WVTR represented by delamination may far exceed inherent material WVTRs. • Understanding location dependences of moisture ingress – vulnerability of electrical feedthroughs and edges as high-risk areas for degradation. **Test Needs** • Tests based on function: mechanical, electrical, moisture requirements; current IEC tests covered these fairly well. • Tests sensitive to applications, because different customers have different requirements. • Tests for roofing-flexible products – do they require modified tests? e.g., higher temperatures, flex tests. • Need to determine "critical" levels: What represents "bad" adhesion; what levels of moisture can be tolerated; what tests are useful for the design of packages and encapsulants. • Industry needs simple tests for EVA replacements to determine if they are as good as EVA (transparent, UV stable); and cost-effective (some applications may afford higher cost).
Actions	• Laminate-material interface studies to understand adhesion. • Help define "critical" levels for moisture ingress; how to measure adhesion, how to manage moisture ingress if a hermetic seal is impossible. • Correlations between field-failures and packaging related degradation (e.g., moisture ingress, delamination, EVA yellowing). • Increasing access to data and literature on failure modes and testing for new entrants. • Analyzing the risk/cost tradeoffs involved in design choices – does all delamination cause significant loss of performance? How much does yellowing really impact output? • Analyzing convoluted failure modes – chains of reactions that end in failure. • Analysis of geography/environment/mounting to define packaging requirements and most important characteristics to consider for different installation sites.

Actions

As shown in Table 7, the recommendations for the national laboratories reflected the group's priority concerns:

- Laminate-material interface studies to understand adhesion
- Help define "critical" levels for moisture ingress; how to measure adhesion.
- Correlations between field-failures and packaging related degradation (e.g., moisture ingress, delamination, EVA yellowing)

The group went on to discuss other significant reliability challenges. First, business depends on information and therefore more field test results need to be presented.

Another challenge is the limited data in the literature to guide new entrants in the field, particularly approaches to testing flexible packages. Reliability data is sensitive, so the challenge is how to manage reliability information in "group" settings (e.g. limited attendance meetings; use of aggregated data reporting).

Are hermetic packages possible? If not, then moisture ingress needs to be managed and acceptable moisture levels need to be determined.

Degradation should be discussed in risk-cost terms. For example, removing Ce leads to more yellowing, but it is not clear how much it impacts performance. Delamination is not just aesthetic, but its real cost to performance is also unclear.

There needs to be a better understanding of convoluted effects. For example, removing Ce from glass may lead to more EVA instability, but the real problem may be water ingress and lack of glass/laminate adhesion.

The industry wants information on how geographical location and mounting options (flat, tilt, roofing) affect module environment (e.g., temperature, humidity, wind loading, etc.) The final application defines packaging requirements, and that is influenced by environment.

E: Manufacturing – Automation, Continuous Improvement, Diagnostics – Assuring and Improving Reliability

The discussion of failure modes and issues/needs/priorities was organized by PV type: CPV, Silicon and Thin Films. Each PV type had some unique manufacturing issues, but there were a number of issues that cut across the categories such as arcing and safety.

Failure Modes

The discussion tended to combine failure modes with issues/needs/priorities, but there were clearly key failure modes behind the discussion. There were frequent references ti failure modes leading to arcing because of their relationship to the safety of products in the field. Second, the silicon industry has experienced increasing problems with mismatched cells that degrade module performance or cause failures, despite supplier assurances that their products meet all specifications. Third, industry is increasingly concerned with the reliability of connectors. Fourth, failures related to packaging are a broad concern that relates very directly back to manufacturing quality control. Finally, failure modes introduced as a result of changes or problems in the manufacturing process are obviously a concern because if they are not identified and remedied quickly they can have a large-scale impact on a company's products in the field as production line throughput increases.

Issues/Needs Priorities

The CPV discussion started with the challenges inherent in the precise alignments required for effective, reliable concentration. The industry is still very small and therefore has to adapt existing manufacturing equipment to their needs, and deal with the limitations in machine vision and precision inherent in the adaptation. The industry also uses many different cells for different customers, which limits opportunities to standardize and leads to mistakes and variations in manufacturing.

For silicon there was considerable concern with variations in cells and raw materials now that the industry is manufacturing on a much larger scale. Handling so many cells from many different sources precludes the level of testing and quality control that manufacturers used to apply when they were handling far fewer cells. It is not possible for module manufacturers to evaluate each cell with an IR-camera. Module manufacturers don't understand exactly why cells from different suppliers that meet their specifications are not working consistently when packaged into modules. There may be interactions between the cells and the packages, or other causes. Different cells from different suppliers may also produce different yields in soldering machines. Diagnosing problems and separating deficient cells and modules costs money. When assembled into modules some of the cells will burn and create hot spots that degrade the module – if they are failing in endurance tests they are likely failing in the field.

Because of the silicon shortage module manufacturers have had little leverage to force their cell suppliers to identify the problems and improve quality, simply because they have many other customers willing to take their products regardless. It would be easier for the cell manufacturers to test their products with IR cameras, since they have to mount them to a test block for other testing anyway.

From the view of system integrators, they are impacted by any module that fails because of manufacturing problems because they are driven by customers' expectations for maximum energy production. The most significant concerns were with arcing problems, and its implications for both safety and reliability. The incidence of arcing could be reduced if automatic detection and shutoff devices could be developed for strings. Ultimately these will be needed for PV safety, even though they involve additional circuitry and complexity.

Ideally manufacturing quality control should insure good initial performance with no infant mortality and annual degradation at or below .5% per year, consistent with a 25 year life and 95% of initial output at life end. Most defects are visually detectable, and there are a very small number of modules with power production issues. Integrators are also concerned about the life of connectors. Most of the new connectors have only been in service 10 years or less and it is not certain that they are going to last for 25 years without maintenance or replacement. Current expectations are based on ALT, not field experience in the harsh environments where many solar energy systems are deployed.

Table 8: Automation, Manufacturing Breakout Results	
Failure Modes	• Failure modes associated with arcing – safety-related failures are a top priority. • Connector failures. • Failures and degradation caused by variations in cells packaged into modules. • Packaging-related failures. • Failure modes introduced in manufacturing process that can result in large-scale failure in field.
Issues/Needs/Priorities	**CPV:** • Exactness of manufacturing equipment – cell, optics, position, correct temperature. • Have to manufacture a lot of different cells for different customers that leads to mistakes and variability. **Silicon:** • Arcing issues. • Understanding power degradation behind 25-year life – still worth looking at old modules to understand mechanisms, even if they were manufactured differently. • Variations from crystal to crystal in raw materials and understanding why some cells work in one package but not another. • Having the whole process and product design idiot-proof – repeatable, so it does not repeat mistakes or lead to catastrophic failures like arcing/fires. • Calibration standards for cells – (also applies to CPV). • Protocols and best practices for testing packages. Typically do too much testing without package – testing loose cells has limited value. • Glass – most issues addressed by existing specs and processes for handling during and before manufacturing (for C-Si). **Silicon and Integrators:** • Integrators most concerned with arcing issues – any connection that is loose or fails will cause an arc, impacting both safety and reliability. • Could reduce incidence of arcing by developing automatic detection and shutoffs for systems or strings. • Production, production, production – power degradation over time is a problem. • QC to ensure good initial performance (no infant mortality) ½% per year is okay because it matches 25 year and 95% effective output at end of life goal. • Industry doesn't know if connectors have a long life – they have only been in field about 10 years. Europe is developing standards with little U.S. input. • Ease of installation – understanding what speeds or impedes installation – more careful design for installation. **Thin Films** • Glass interactions, what glass is acceptable, dimension and weight, cheap enough. Lack of manufacturing; small number and capacity, limited experience. • Encapsulant interaction with thin films – the chemistry issues, outgassing, ingassing, changes in formulas, additives and variation across suppliers. • Cycle time for qualifying suppliers. • Comparative studies provide good information, but even if they are done well long-term impacts, in year 15 or 20, are still unclear. • Online screening tests: How well do they predict what will happen in the field and how do they correlate with reliability and screening tests? • Process controls – uniformity of process, thickness – material qualifications.

Actions	• Diagnostic Tests
	    • Develop tool that gives an image of the cure, and says it is cured quickly, compared to current 48 hour process;
	    • Expand concept of “instant” measurement to other indicators/measures, efficiency, uniformity of resistance across each cell, series resistance, shunt resistance, soldering uniformity;
	    • Failure analysis – ways to test packaged thin films layer by layer, understand how materials have changed, coring techniques to look at EVA, non-destructive tests (NDT) if possible.
	• Automation, Common Processing Equipment
	    • For CPV, address challenge with machine vision, ability to discriminate defects on our products – alignment and inspection.
	    • Solar simulators could use more uniformity and flexibility – three different machines will give three different readings on a module. Also need:
	        • More capabilities, more compact, workable form factors;
	        • Common reference for thin film and crystalline technologies;
	        • Standardization of results;
	        • Rapid turnaround calibration services – let someone else do the round robin calibrations instead of the manufacturers;
	        • Need thirty party check – could be done by same facility, could help with process changes as well to verify references, suppliers could use it as well for new materials.
	    • Good methodology or tool for silicon cell characterization and segregation could help industry.

With increased emphasis on PPAs and performance-based incentives integrators need assurances from manufacturers that there will be low infant mortality and minimal degradation over module/system life. Their second broad area of concern is with safety-related problems, with arcing at the top of the list. A newly prominent concern is with the lifetime of connectors, and whether they will last for 25 years with maintenance or replacement. Greater attention to ease of installation would also reduce failures -- simple oversights like not smoothing out holes for zip ties has resulted in zip tie failures during installation. This is one specific problem that illustrates the broader issue of designing to reduce failures in installation.

For thin films there is simply a shortage of manufacturing experience to build upon. For most companies production has been very limited and therefore they don’t have the experience base and established specifications in place for qualifying suppliers and understanding the implications of different material formulations. This impacts cycle time for qualifying new suppliers, and the complexity of identifying root causes of problems. Screening tests in-line with manufacturing are needed, and correlations between their results and what can be expected in the field.

Considering all of the failure modes and reliability issues and needs across PV types, the group highlighted the following key items which are shown at the beginning of the appropriate sections in Table 8:

- Arcing
- Connectors and related problems issues

- Encapsulant interactions (thin films)
- Understanding power degradation and its relation to a 25-year life
- Glass
- Testing of loose cells, packages, and the right combination of tests and what useful information they can produce.

Actions

As shown in Table 8 industry called for more diagnostic tests with quicker turnaround times, starting with a test for cure that takes less than 48 hours and expanding to faster tests for efficiency, uniformity of resistance across each cell, series resistance, shunt resistance, and soldering uniformity. Ideally these would be non-destructive tests that could be used on packages, but even if they are destructive it would be useful to explore the most efficient, effective ways to extract and test samples, especially for thin films.

Another broad topic was automation and common processing equipment. CPV has a challenge with machine vision and its ability to discriminate defects with alignment in CPV products. Until the problems are solved they will hold back full automation. Because this is a very specialized market segment there is limited opportunity to apply equipment or approaches from other industries, although there may be some overlap with semiconductor manufacturers.

Work to make solar simulators more uniform was important. Currently three different machines may give three different readings on the same module. It would help the industry to have more options beyond the limited number of simulator manufacturers available now, and more competition to provide simulators with broader capabilities, that are more compact and have better form factors. Rapid turnaround calibration services might be even more important than a better simulator, to calibrate reference modules. Manufacturers may only need a dozen or half dozen reference modules per year – it would make sense to let the service providers do the round robin calibrations needed to set the references, instead of the manufacturers.

Finally, a methodology or tool for silicon cell segregation to address inconsistent cell performance from different suppliers could help the crystalline silicon industry.

F: System Design for Reliability – What Needs to Be Improved

Criteria for Success

Although the group melded discussion of failure modes with criteria for success, the two topics were clearly closely related. The failure mode discussion focused on decreased power, no power, and safety because these were critical factors in system design success.

Failure Modes

The Systems Design for Reliability group began by identifying the major failure modes. These modes were identified as: Decreased Power, No Power (System Shutdown), and Unsafe Systems. Within each broad category more specific problems were identified, as shown in Table 9.

Issues/Needs/Priorities

The discussion focused on how to address each failure mode, including what is currently being done and suggestions for new approaches. Some of the failure modes were not discussed for lack of time.

Table 9: System Design Breakout Results	
Success Criteria	• Minimizing power losses from failures/degradation. • Minimizing shutdowns that result in complete power losses. • Ensuring system safety.
Failure Modes	**Decreased Power** • Module Degradation. • Low performance versus nameplate. • Thermal limiting (inverters). • Blown Fuses. • Shading and Soiling. • Leakage current. • Tracker failure. **No Power (shutdown)** • Arcing. • Ground faults. • Inverter failure. • Wiring failure. • Module failure. **Unsafe Systems** • Loss of Insulation. • Grounding failure. • Tracking structure.
Issues/Needs/Priorities	**Decreased Power** • More certification tests to generate data combined with improved monitoring to develop understanding of surges, diode failures. • Balanced binning of modules to decrease power loss from mismatches. • Improved screening and pre-qualification tests for thin-film modules. • Inverter on-board diagnostics to address thermal issues. • Address blown fuses through better system design review. • AC modules as solution to shading, better preventative maintenance, design. • Improve thermal, UV performance of cables, connectors to reduce current leakage. • Quick processes to identify major problems and reduce costly qualification testing. **No Power** • Improve design review for arcing, failures at diode/fuse, terminal block and wire. • Improvements in NEC to address ground faults.

Actions	• Collect Failure Data – from large number of sites to characterize what is happening in the field, compile Pareto Charts with industry input. Monitor statistically significant number of field sites (at least five) with identical systems spread throughout country to correct for the effect of technology. • Labs need more end-user/customer perspectives to understand their priorities – for example concern with predictability and key failure modes. • Labs need to provide funds for more expensive test equipment that small companies may not be able to afford. In particular there is a need to develop/procure a PV array simulator to assist with large scale inverter design. • Labs should assist with analysis that will help industry in defining "Availability", and identify "Optimal Block Sizes" for different market segments.

Decreased Power

Decreased Power from Module Degradation is currently addressed by Certification Tests. Suggestions were to conduct more certification tests and use the data with improved (proper) monitoring to develop an understanding of surge/near miss and surge protection (lightning strikes), and develop certifications and specifications for diodes.

Decreased power from module mismatch is addressed during installation. Binning modules during system design could address the problem more effectively.

To address decreased power in thin film modules industry relies on module certification. Industry needs more/better screening tests and pre-qualification tests to identify problems before they are taken to qualification. Industry needs a process to identify major problems quickly and reduce costly qualification testing.

Decreased power due to inverter thermal limits is addressed by designing controls in the inverter. Industry needs on-board diagnostics from inverter manufacturers, and ways to alert operators and help them ameliorate decreased power from blown fuses. When power is decreased by blown fuses, industry sometimes just sends out boxes of fuses to the system owner, as this is less costly than troubleshooting the system. However it was recognized that chronic fuse failure is a symptom of a design problem. It would be preferable to conduct a system design review and fix the problem that is causing the fuses to blow.

Decreased power from shading and soiling could be solved by AC modules. Industry now relies on washing. Suggestions included conducting more preventive maintenance, and establishing best practices for preventive maintenance. For example, a recent UL specification that addresses the spacing allowed between the module lower frame edge and the cells could be relevant for prevention and maintenance. UL found that dirt accumulation at the bottom of the module could shade the bottom of the cells and cause hot spots, suggesting this might be a problem to target with either preventive maintenance or improved design. With the increased application of systems in the Northeast and other areas where there is a lot of snow, there is a need for specifications to deal with production losses due to snow cover. This could be viewed as a type of "soiling".

Decreased power due to leakage current has safety implications. Industry provides training on the issue and designs components and systems to minimize the problem. Design and installation practices need improvement, including greater attention to UV and thermal limits for cables and conductors.

No Power -System Shutdown

Some major causes of system shutdown are arcing, diode/fuses, terminal blocks, and wire failures. Solutions include more vigilant design reviews, addressing manufacturing issues, and developing best practices for O&M. A National Electrical Testing Association (NETA, recently renamed to the International Electrical Testing Association) Manual for O&M was cited as a potential starting point.

There are upcoming improvements in the NEC to address loss of power due to ground faults. Suggestions for addressing the problem include more education and conducting a Fault Tree Analysis of the problem.

Concerning safety issues, industry needs testing to better understand ground fault failure modes. Trackers need wind mapping and wind tunnel testing.

Actions

This discussion centered around what the National labs can do to assist industry. Some suggestions were:

- Collect Failure Data – have the labs collect and monitor failure data from a large number of sites in order to get a picture of what is happening in the field. The labs need to compile Pareto Charts of key failures, with industry input.
- There needs to be a statistically significant number of field sites established to generate reliability data (at least five sites) with identical systems spread throughout the country.
- The labs need to focus on getting more end-user/customer perspectives on failure modes and issues, for example problems associated with building integration.
- Labs need to acquire some of the most expensive test equipment that small companies may not be able to afford and make it available to industry. In particular there is a need for a PV array simulator to assist with large scale inverter design.
- The labs should conduct targeted analyses and studies that industry can use in defining the concept of “availability,” and also help determine the “optimal block sizes” for different market segments.

During the discussion of the group’s results a university participant noted that universities have not been discussed during the meeting. Industry is missing out on opportunities to work with the universities. Universities provide the future manpower of the industry. The Solar America Initiative (SAI) has significantly changed university participation. Industry and DOE should keep universities in mind when designing solutions to problems, for example in studying material interactions and the physics of failure.

Another commenter pointed out that the solar simulator discussed in this breakout group is different from the solar simulator mentioned by the manufacturing group. This group is talking about something that simulates PV array operation for inverter and BOS testing and design. The manufacturing group was talking about insolation simulators for testing cells and modules.

G: Field and Product Return Insights: Data Gathering Priorities and Best Practices

The discussion of field and product return insights had a few major themes: new challenges introduced by BIPV products; data gathering challenges associated with analyzing field returns; and challenges in diagnosing the causes of failures and applying them to improve accelerated tests. Table 10 summarizes the results.

Failure Modes

The main failure modes paralleled discussion of issues/needs/priorities, with an emphasis on problems with building integrated products, failures associated with connectors and junction boxes, solder bonds, failures caused by installations in challenging (sometimes inappropriate) environments, and failures caused by human errors and/or poor training.

Issues/Needs/Priorities

BIPV and cosmetic failures caused by scratches, wrinkles in bonding, and other mainly aesthetic concerns are a real issue that can't be dismissed. They result in returns and expenses. In some applications cosmetics trumps performance – PV is being installed on all sides of a building mainly for appearances, not for energy production. Some cosmetics, like scratches in ASi, are also performance issues. For BIPV applications industry must start recognizing PV as part of the building, which results in other requirements – if it is a roof, it has to meet roof requirements. For example house/building shifting stresses are a new issue. A change in tilt caused by foundation settling is another example. What are the temperature requirements for a PV shingle for roof temperature? Industry has heard 120^{o}C, but most have never seen temperatures above 80^{o}, and only test to 90^{o}C. When tests are done at higher temperatures it starts reaching the limits of EVA. Analysts and designers have to know the limits of the environment and the materials, so they can provide adequate design margins. There must be a relative thermal index (RTI) of 20^{o}C above expected temperatures if a PV shingle is going to get a safety rating. But above 100^{o}C the system is beyond breaking limits in the NEC, so there are conflicting standards. Rack mounted systems can simply adjust minimum air space between the roof and the modules. Industry will need an entire suite of applicable tests (e.g. roof) and may need new interactive tests. BIPV works best when integrators can get in early with architects/engineers to accommodate the PV systems' weight and characteristics. LEED certified architects and engineers are at least aware of PV because of points, and in LEED there are not as many problems with retrofits.

Failure at the connection to J boxes were cited as a growing problem, sometimes as a function of mishandling (bumping), sometimes as a result of design flaws. Junction boxes that are plastic or polycarbonate decay, but metal creates issues with grounding. The industry needs something better and more durable. Solder bonds are in the billions on the cells/packages, and they are automated, so a small percentage of failure in these bonds is tolerable. However, there are only a few thousand manual solder bonds, so even a small percentage of recurring failures is a big problem. For manual solder bonds companies are going way beyond requiring six sigma -- for example, at the J box -- because these are single points of failure. Companies are not necessarily using six sigma to deal with all reliability concerns. Six sigma can be subjective when a group is using brainstorming and fish-boning to analyze a process. Approaches are more oriented to parts and main effects, followed by other testing to get to root causes, some by using the Shainan analysis/methodology for root cause analysis.

Extreme environmental factors are another common cause of returns. Systems have been installed in the wrong climate – snow loadings, bird attacks, flat roofs with no drainage – places where they were never anticipated, at tilt angles that were never expected. Another problem is installers walking on the modules, an aspect of improper care in handling and installation. On metal roofing the systems cover the whole area so there is nowhere to walk, so workers have to step on the panels. For flat roof installations walkways are required. Human intervention is a growing problem – power washing, turning components and systems on and off, doing things that harm the modules. In comparison, glass and curtain wall companies do not warranty glass breakage. The PV industry should ask why glass is broken on PV modules and adjust their warranty response based on whether the damage is an act of nature or of man. For thin films that use non-strengthened glass this can be a particular problem.

Table 10: Field and Product Return Breakout Results	
Failure Modes	• Building Integrated Cosmetics, scratches, wrinkles as it is bonded – a real issue that can't be dismissed. • Lots of failure modes at connection to the J box. Sometimes a function of mishandling (bumping), some from design flaws. • Manual solder bonds where even a small % failure is a big problem – we are going way beyond six sigma – for example at the J box. • Environment: Installation in the wrong climate – snow loadings, bird attacks, flat roofs with no drainage – places where PV was never anticipated. • Human intervention – power washing, turning systems on and off, walking on panels, other.
Issues/Needs/Priorities	• Need entire suite of applicable tests (e.g. roof) and may need new interactive tests. • Define the temperature requirements for a PV shingle or roof temperature. • More durable module and parts labeling so field failures can be tracked back to manufacturing processes. • Need improvements in J-boxes to reduce failures and degradation. • Data on system configuration – voltage, wiring, geometry…. • Standards, especially for CPV, on what data to monitor and collect. • Standardization, translation of Data Acquisition System data streams so they are easier to use and more adaptable. • Cheaper, better irradiance sensors. • Approaches to communicate field and product return information through the value chain – to designers, to integrators, to suppliers.
Recommended Actions	• Common failure mode database broken down by technologies, locations/climates. • Information for integrators on failure modes to watch for – although manufacturers will be very reluctant to provide information, over time it impacts trust, so those that don't open up may be penalized. • Identifying/diagnosing ground fault problems -- communication protocols to transmit the information. • Information on what the environment and situation has been for installations to help find root causes. • Tracking system for the installation itself, not just the operation. Have a way for people to log what they have installed and documenting installations.

Gathering adequate data for product return analysis is a challenge. Weather or event data to track back to the failure, especially for events like lightning, is difficult to acquire. Some data acquisition systems do track wind speeds, temperatures and other information, but there is little uniformity. Inverter logs on ground faults, and other events can be very useful. Data collection stations often lack irradiance sensors, some sensors are very limited, and some have variable accuracy. A product that gives workable, reliable irradiance readings would be valuable. The industry needs some kind of independent calibration system for irradiance monitors and other sensing equipment it relies upon.

Tracking a product to its manufacturing site and date depends on whether the label and information on the returned model is legible. Without information on the manufacturing process and original product characteristics, finding root causes is sometimes impossible. BP has started putting barcodes within the laminate to make them survive. Component parts should have something more robust than an ink label. Of course manufacturers and installers have to be careful that the label doesn't contribute to other module defects. Analysts also need to know systems information: voltage, wiring geometry, who installed the system, notes from the installation log, and other contextual information. Very often analysts just get the module in a box without any context for the installation. There isn't even a best practice for what systems information should be collected and the proper format.

So far CPV systems have been going to active sites in target climate zones where they are heavily monitored. But they are starting to go into customer sites with less control. Are there best practices for monitoring, and where is the balance between just enough information and gathering too much information that is not worth the expense? IEEE had a draft on what data to collect, but it is not clear it ever became a standard. A FRACAS approach might work, so it may be worth looking at what other industries look for on failures and adapt them to PV.

California is requiring Data Acquisition Systems (DAS) on systems, like Fat Spaniel, to qualify for rebates. It is becoming a defacto standard. All Power Purchase Agreements (PPAs) require DAS: bankers want to know exactly what is going on. The banks and other sophisticated financiers are used to being more involved in monitoring because they are familiar with monitoring thermal plants. Working with utilities, the industry finds different DAS' collect data in different order, and different types of data. Campbell used to be the standard. Then internet connections like Fat Spaniel emerged. It might be possible to establish some standard that would only specify certain levels of information. If costs for monitoring are going to be reduced, a standard protocol would help that establishes the interface, data codes, and other parameters.

Another issue is where the DAS belongs in the system. Some functions have been incorporated into inverter products, but it probably needs to be above the inverter so it can provide broader data acquisition from the entire system. For example, it does not make sense to incorporate irradiance meters into the inverter. This DAS issue cuts across multiple manufacturers and components.

With all the net metering in power industry, it would be useful to have utilities report net metering information. Many utilities are also not shy about reporting performance of companies and products, which could help safeguard consumers. Large commercial systems install meters where the information goes to the customer for free, but can that information be shared with the manufacturers? Utilities might be willing to share, and are already being asked for the information. Use of the data could be facilitated with agreement on database structure and mechanisms to transmit information. Right now the information is not structured for analysis. Different utilities have different policies and views on sharing or not sharing data – the best practices are not universal.

Once product returns are analyzed and useful information is available, how to communicate it through the value chain becomes important. There were many different responses when participants were asked how effective they are in communicating information throughout their organization, with some mention of product development staff, quality control staff, suppliers, and installers. When asked about cost and affordability, here was no direct answer, but general support for better communications throughout the value chain. One company co-located various groups like product design, purchasing, and QA to further communication. Some form of FMEA might be useful for communication, especially for smaller companies, to provide a way to institutionalize communication. Xantrex and other inverter manufacturers are moving to automation to collect and disseminate performance information to target groups.

Encapsulant makers are left out of the communication process – they don't get much feedback from their customers. This is in comparison to the automotive industry where there is a constant feedback loop. One of the problems is that feedback from the field is way behind in the PV industry – EVA makers have usually changed their formulas long before they get the feedback. HALT feedback might be timelier.

Actions/Recommendations

It would be useful to have a common failure mode database broken down by technologies, (probably not companies) locations/climates. It is time to get serious about this: it has been discussed for years.

There is an issue with defining failures – are a few small bubbles a failure, or not? Maybe they increase the risk of delamination, but until the delamination occurs should they be treated as a failure? Manufacturers probably would say no, and would be loath to share information on whether some defects will lead to future failures. These kinds of defects are a commercial rather than a technological issue. Industry response to the issue is variable. Some defects may lead to failures that are a safety issue, which raise very serious concerns about obligations to alert installers and end-users.

This led to the observation that integrators need a "heads up" notice on potential problems to watch for during design and installation. Integrators would like to get some information prior to installation so they can anticipate potential failure modes, and what they should watch for in their PPAs. Manufacturers will be very reluctant to provide that notice because those that don't report are given an advantage while those that do are penalized. However, over time hiding information on faults reduces trust, so those that don't communicate openly may be penalized in the long-run. If the industry had a database that is based just on technologies, it could be used to make some of those alerts go out without attributing it to individual companies and products.

It is difficult to do diagnosis in the field, both in finding problems and in understanding their causes. Once an issue is found, the integrator has to decide whether they want to escalate it to the manufacturer. For example, identifying/diagnosing ground fault problems is an example of a major failure that has to be corrected. It depends on, and is limited by, communication protocols and means to identify and communicate information on faults. Manufacturers and integrators have to weigh the impact of the problem against the costs of diagnosis – does the problem warrant drilling down to modules, cells, etc. Portable IR cameras would probably be a very useful tool in the field.

Determining whether a fault is major should probably depend on the manufacturers doing the analysis. If a manufacturer gets enough information on what the environment and situation has been, then they can find out the root cause. If the manufacturer doesn't get the data, they can't, which goes back to earlier comments on the need for system history and effective monitoring, including a better, standardized way for installers to log installation details. USSC is doing that with very large systems, but some of their clients are putting out the equivalent of 320 houses per day. There is no way to keep up with documentation at those levels of installation, especially in housing markets. In the case of older returns, many of them are off-grid and there may be almost no information on where/what conditions they were operated in, including the manufacturing process used to make the components.

H: Test Protocols – Priority Challenges

The discussion of test protocols was organized by technology: crystalline silicon, thin films, CPV and inverters. The testing needs spanned the different stages of technology development. During the development phase, testing of materials and components can be less expensive and can generate powerful information for improving product design. However, there was agreement that it is also essential to test the finished modules and complete systems because components that may perform well in isolation may interact and cause failures within a completed system. Testing at different stages tends to produce complementary rather than redundant information. Also, at each stage of development, a range of types of testing were identified. For example, accelerated testing of finished products confirms appropriate design. Accelerated testing may be complemented by in-line testing that helps to ensure adequate control of the manufacturing process. Table 11 summarizes the results.

The biggest challenge is the quantitative correlation between accelerated stress testing and performance in the field. This is a huge challenge because the field conditions vary with location and time; the accelerated stress may or may not expose relevant failure modes; there are many possible failures each of which may have different dependencies on temperature, humidity, etc.; and the time constants that are of interest are much longer than the standard product cycle as well as longer than the average worker's assignment. Validation of a thirty-year service lifetime may span a worker's entire career. It will require many years to validate the quantitative accelerated testing that will be so helpful to the industry.

An increased interest in some types of in-line diagnostic testing reflected the increased manufacturing emphasis in today's industry. These tests must be very rapid, non destructive, and inexpensive.

Failure Modes

Although the group mainly discussed issues/needs/priorities it is apparent from the issues they emphasized that there were important failure modes behind their interests. Arcing is clearly addressed in many of their comments on test protocols, along with moisture problems, optical problems for CPV, and bypass diode failures.

Issues/Needs/Priorities

The priority issues and needs are highlighted for each technology area in Table 11. For crystalline silicon, arcing has been observed more frequently in the last year since the number of systems in the field (especially those operating at higher voltages) has increased. An accelerated testing protocol has not been developed partly because the origin of the problem is not well understood. Arcing is readily observable, but testing may be needed to identify the cause. The problem may be prevented to some extent by periodic exercising of all of the electrical connections within the system.

<table>
<tr><th colspan="2">Table 11: Test Protocols Breakout Results</th></tr>
<tr><td>Failure Modes</td><td>• Failures that result in arcing and safety concerns
• Moisture-related failures
• Optical degradation/failures for CPV
• Bypass diode failures</td></tr>
<tr><td>Issues/Needs/Priorities</td><td>Crystalline Silicon
• Arcing – thermal cycle with current, ribbon cell, j-box, bus bars.
• Diagnostic – IR imagining after thermal cycling.
• Bypass diode failure – addition of current causes failures – 61215.
• Dynamic Load – IEEE 1262.
Thin Films
• Damp Heat – degradation – need diagnostics to understand.
• Determine moisture content in EVA. What can industry use besides cobalt chloride?
• Layer-by-layer analysis of module.
• There is a need for in-line tools for:
    • Thickness/composition,
    • Electronic characterization,
    • Full module size image.
• Vibrational testing.
• Do standard tests need to be modified because of lack of bypass diodes?
CPV
• Define appropriate damp heat test for cells.
• Lens transparency.
• Corrosion effects.
• Use of forward bias current during stress needs to be defined.
• Acceleration of high-flux light degradation (UV test for all materials).
• 24/7 stress test.
Inverters
• Need standard communication protocols – IEEE, IEC 3 and 6, electronics group.
• Efficiency Standards, need task group to look at this.
• No standards for testing lifetime.
• Safety is there, but not endurance.
General
• Inexpensive camera for field use.
• Small, portable I-V curve tracer.
• Discoloration – standards exist and should be applied to PV.</td></tr>
</table>

Actions	• Failure Database that can be used to develop a quantitative relationship between accelerated testing and field performance. • Pre-screening is very valuable: abbreviated test to give quick feedback would be useful in speeding product design and quickly addressing problems. • More study on arcing, how to test to prevent it. • Access to expensive diagnostic equipment, for example to address partial discharge, surge/impulse voltage inputs.

The application of current during temperature cycling provides more reliable testing of solder bonds, but it also causes increased heating of the bypass diodes. In some cases, this is causing the bypass diodes to be stressed outside their normal operating range, and, therefore, bypass diode failure is being observed much more frequently after stress testing. However, it is not clear that these diode failures are relevant to field failures. An appropriate test protocol would stress the solder bonds without overstressing the bypass diodes.

Windows in buildings are tested (ANSI/IEC) by swinging a lead ball against them to ensure that a person falling against the window would not break it. This test is an important safety test for windows in buildings, but it is unclear that it is appropriate for testing PV modules.

Testing needs for thin-film technologies are diverse. Arizona State University reported that a significant percentage of thin-film modules recently failed the damp heat test. This implies that a substantial amount of testing is needed to identify the causes of the failures. One big request was to be able to take a module or module section and selectively remove each layer. This would allow detailed analysis of each layer after stress has been applied, facilitating identification of failure mechanisms. Generally, thin-film modules are qualitatively different from silicon modules. For example, how does the lack of bypass diodes in most thin-film modules affect accelerated testing? Thin-film products must be understood and tested to understand the materials, device structure, monolithic interconnections, and module packaging. Tests developed for silicon are probably not optimal for thin-film products.

The details of application and curing of EVA can result in widely varying properties. A quick test that would quantitatively indicate the moisture content inside the module package would be very helpful on the manufacturing line.

Even though test procedures for CPV products have been defined in an IEC standard, there is very little experience with how these correlate with field performance. The form factors and components of CPV systems can be qualitatively different from those of flat-plate PV and may require different tests. CPV cell assemblies are expected topass a more stringent temperature cycling test, but the number of hours of survival in damp heat may be reduced. These expectations need to be quantified by correlating accelerated testing with field testing.

Perhaps the biggest testing need for CPV is to identify how to accelerate the effects of high-flux illumination. CPV systems are designed to operate at as high a flux as can be achieved reproducibly, so increasing the flux with an on-sun system has very limited potential. A 24/7 test would give acceleration by about a factor of four. However, an indoor mechanism for applying the high-flux is a challenge. The UV component of the high-flux may be delivered practically, or acceleration of outdoor testing may be facilitated by running the system hot.

Inverters have qualitatively different testing needs. The primary issue for inverters was the need for standards development, including how to determine efficiency and service lifetime.

Inverters are in a position to help diagnose overall system problems. Standardizing the protocol for communicating various fault states would immensely help the community reduce the time it takes to respond to failure conditions.

Testing tools that would be widely useful included a low-cost IR camera to use in the field; a small, portable, I-V curve tracer; application of discoloration standards to PV; and a method for determining the water content inside a module.

Actions/Recommendations

The discussion above provides many opportunities for follow up. The highest priorities focused on the quantitative relationship between accelerated and field testing, development of a failure database (as mentioned in most of the other breakout sessions) and sharing of expensive equipment to reduce costs.

I: Reliability Predictions – How Better Correlations Can Be Achieved

Breakout I discussed the value and possibility of building a predictive model for reliability. It followed a different structure than the other breakout sessions that tried to move from priority failure modes through needs and then to recommended actions. Instead the facilitator started the discussion by asking the group to consider the supply chain (Materials→Modules→ Inverters→BOS→Integrators→Owners→PPA), then the technology dimension (Crystalline, CIGS, CdTe, a-Si, CPV III-V and c-Si, inverters). Finally, the group was reminded that applications include residential, commercial and utility scale.

The question for the group was: Given all these dimensions, is it possible to put together a reliability predictive model and is the DOE/National lab reliability program on the right track? The majority of the participants indicated that a predictive model was possible and valuable, both to the customer and to the manufacturer. Discussion of the value to customers revolved around the warranty as the marketing tool they understand and the reality that manufacturers use warranties to set customer expectations. Internally, manufacturers need predictive models to assure that warranty liabilities are adequately covered. This consequently makes the predictive capability important because to manage warranty programs manufacturers need supporting information. Failures are the root cause for loss of business reputation, so predictive capability is important.

Discussions then moved to whether manufacturers make predictions, what type of predictions they make, and what predictions are based on. No one volunteered more than warranties as predictions. The basis for predictions is accelerated tests, FMEA's, database of failures; and stress tests including light, thermal and humidity. All agreed that qualification tests offered little more than a 1-3 year predictive capability. An important metric for making predictions is the Acceleration Factor (AF). Not many participants indicated they had acceleration factors but acknowledged that they are important to the specific product that they manufacture. There was no interest in generating acceleration factors for specific materials nor making existing factors public but it was suggested that some existing standard properties manuals could be used for approximations. Standard specifications for some cross cutting products like diodes could ease the burden of procuring subcomponents and integrating their reliability into predictive models. Additional accelerated tests and associated field data are also needed as a basis for additional predictions. Concerning lessons to be learned from other industries, one suggestion was to look at the automobile sector. The group also advocated performing tests early in development and use of FMEA methodologies.

Customers for large systems need to set the requirements for performance/reliability, and do. Their needs drive qualification programs, certifications, standardized tests, and warranty requirements – all of these could also be passed on to component manufacturers. Most manufacturers do not have the resources to carry out predictive functions individually.

Issues/Needs/Priorities

Some needs did emerge during the discussion. Participants recognized the risk of producing and fielding substandard products and the need to maintain a high level of reliability to maintain their reputation and access to financing. Industry wants a database that details failure modes encountered both in lab testing and in field observations. The labs were clearly seen as a central point to collect and disseminate the data. The group clearly stated that qualification tests do not provide the needed information for predicting reliability beyond the 1-3 year range. Predictive models need information developed from accurately designed accelerated life tests. Many of these test do not exist or are developed by each manufacturer for a specific application. The group did not support developing standard Acceleration Factors (AF's) and making them public, because they relate to a specific process/product. Instead it was suggested that relative thermal index (RTI) values could be used to select materials that provide low reliability risks.

Table 12: Reliability Predications Breakout Results	
Issues/Needs/Priorities	• A database of broad failure modes across all technologies is needed (high priority) • Information is needed from extensive field testing and accurately designed Accelerated Life Tests to build a predictive model(s) • Accelerated Life Tests need to be developed to provide accurate information that adequately portrays field induced degradation and failures; (high priority) • Manufacturers and system integrators need specifications that can be used throughout the supply chain to influence reliability from the conceptualization of a system to the design/installation and finally the operation and maintenance of a system(high priority) • Substandard products with reliability issues can damage individual manufacturers and entire industry • Predictive model(s) can be built to and used for customer and internal manufacturing needs • Manufacturers do not have the resources, breadth, and capabilities to build reliability predictive models • Predictive models from other industries should be investigated. • Qualification tests do not provide mid or long term predictive capabilities; clarifying the value of qualification tests versus the need for a predictive model. • Manufacturers and DOE's reliability program needs to include entire supply chain to improve reliability
Actions	• Develop accelerated tests based on FMEA's and failure mode data. • Increase field surveillance data for combined effects failures. • Develop Failure mode Database. • Address emerging needs resulting from large system designs and deployments. • Increase scope of work to include entire supply chain involvement. • Continue to work on developing a predictive model.

An underlying theme was the need to distribute the reliability related requirements into the entire supply chain; effectively distributing responsibility. This brought forth a need to develop standards/procedures/specifications, similar to qualification test procedures that could easily be passed onto suppliers. An example was leveraging American Society for Testing and Materials (ASTM) standards for materials and developing specifications that could be passed on to the supply chain. PV examples could include specifications for yellowing or thermal cycling of encapsulants or specifications for products like diodes and ground connections. Effectively, manufacturers need to develop specifications that assist predictive modeling. These specifications would likely be derived as a result of FMEA's, Fault Tree Analyses, accelerated tests and failure information from fielded system studies and be applied to component manufacturing, component procurement, system designs, installation, and operation and maintenance.

Actions

One of the key recommendations, which also came from the 2006 meeting, was developing a system to collect and analyze data on fielded system data. The recommendation for more ALT's, accurately designed to meet the needs, and the activation energies related to failure modes were also repeated recommendations from 2006. The new emphasis was customer orientation, specifically the increased focus on large system integrators and the need for predictive capability to substantiate warranty programs and assure production for PPAs. Additionally, a new emphasis on involving the entire supply chain in assuring reliability emerged.

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Appendix B: Final Agenda

ACCELERATED AGING TESTING & RELIABILITY IN PV WORKSHOP II		
Workshop Focus: **Sharing insights into recent progress, status, challenges, and needs in PV system reliability and accelerated aging testing**		
AGENDA TUESDAY, APRIL 1, 2008		
Time	**Presentation / Activity**	**Presenters**
8:00	DOE Welcome	Dan Ton, Building/Grid Integration Lead, Solar Energy Technologies Program, U.S. Dept. of Energy
8:10	Reliability Vision & Program	Michael Quintana, Member Technical Staff, Sandia National Laboratories
8:40	Large-Scale Systems Integrator - Reliability Needs	Laks Sampath, Executive Director of Technology, SPG Solar, Inc.
9:10	Perspectives on Thin Film PV Reliability and Initial Product Introduction	Kurt L. Barth, VP Product Development & Co-Founder, AVA Solar
9:40	CPV Reliability - Reliability in an Expanding Technology	Robert McConnell, Director of Government Affairs & Contracts, Amonix, Inc.
10:10	**Break**	
10:30	**Breakout Groups**	
A	Reliability Challenges in Thin Film & Emerging Technologies	
B	Silicon Reliability Issues	
C	Concentrator Systems Reliability Questions	
12:00	**Lunch**	
1:15	Summaries of Breakouts A, B, & C	
1:45	Let's Build a RELIABLE System - Panel of Industry Representatives - each will bring their insights into the reliability/testing status and needs for their part of the industry; extensive Q&A will follow 10 minute presentations by each panelist	**Panelists**
	Modules: Remaining Reliability Challenges	Akira Terao, Principal Reliability Engineer, SunPower
	PV Safety Issues: Key to a Reliable, Viable Industry	Tim Townsend, Sr. Mechanical Engineer, PE BEW Engineering
	Initial Reliability Considerations for Design of Commercial PV Systems	Mike Fife, Director of Reliability, PV Powered
	System Availability: A Must for Profitable Large-Scale Systems	Steve Voss, SunEdison
	Q&A from Audience - Let's Build a RELIABLE System	
3:10	**Break**	
3:30	**Breakout Groups**	
D	Packaging Design & Evaluation - successes and current barriers	
E	Manufacturing - Automation, Continuous Improvement, Diagnostics -assuring and improving reliability	
F	System Design for Reliability - what needs to be improved	
5:00	**Adjourn**	

ACCELERATED AGING TESTING & RELIABILITY IN PV WORKSHOP II		
AGENDA WEDNESDAY, APRIL 2, 2008		
Time	**Presentation / Activity**	**Presenters**
8:00	Summaries of Breakouts D, E & F	
8:30	Progress since First Workshop: what's new & what's needed	Tom McMahon, Technical Staff Member, National Renewable Energy Laboratory
9:00	Best Practice for Achieving High Reliability with PV Systems	Carl Carlson, Reliability Consultant
9:30	Field Observations & Product Returns - What can we learn?	John Wohlgemuth, Senior Scientist, BP Solar International
10:00	**Break**	
10:20	**Breakout Groups**	
G	Field & Product Return Insights - data gathering priorities and best practices	
H	Test Protocols - Priority challenges	
I	Reliability Predictions - how better correlations can be achieved	
11:30	Summaries of Breakouts G, H & I and Final Wrap-up	
12:15	**Adjourn**	

Appendix C: Presentations

Industry Input

- What have we heard from industry?
  - Great input, interest, and guidance from first workshop
    - Priorities established for Accelerated Aging Test Improvements
    - Systems, Modules & Cells – summarized status, needs, and priorities in each area
  - SAI solicitations (and other industry interactions) resulting in collaborations for testing/evaluation of new products/technologies
- What have we done about it?
  - Requested (and received) additional funding and prioritized these activities
  - Embarked upon a reliability program to support the PV industry in light of SAI

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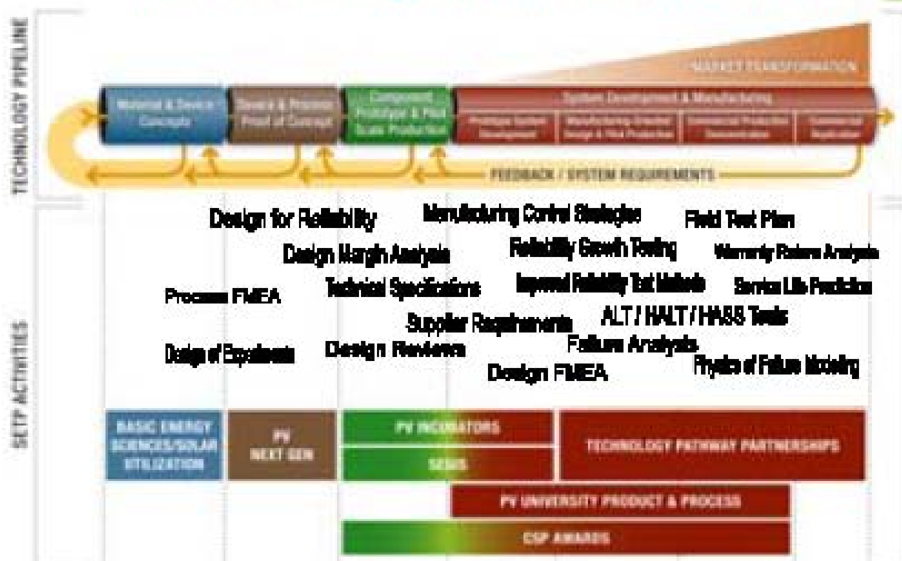
Reliability is Important Throughout the PV Technology Pipeline & SETP Activities



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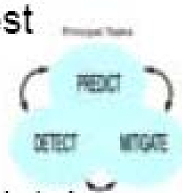
DOE's Vision for Reliability

- DOE Working through National Laboratories and Industry Partners
- Identifying, applying, and improving best practices:
  - Reliability Engineering
  - Testing



- Active Partnerships gathering, appropriately sharing, and analyzing data
- ***End Goal:*** Industry adopting and applying these practices to produce even more reliable and cost-competitive products

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Accelerated Aging Workshop

- What do we need from this workshop?
- We need Industry input on needs and priorities in reliability-related:
  - Testing, including protocol development or improvement
  - Data Evaluations, especially field observations of failure modes
  - Predictive Analyses, demonstrating its value
- We also need feedback on how DOE can best support the PV industry in the area of reliability.

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Questions?

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DOE Photovoltaics Reliability Project

A Teamed Effort at:

Sandia National Labs and the National Renewable Energy Lab

Accelerated Aging and Reliability Workshop

Denver, CO April 1-2, 2008

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E. C. Collins	C. R. Osterwald
M. J. Mundt	G. J. Jorgensen
J. R. Tillerson	

How do you spell reliability?

1. System owner/operator with a Power Purchase Agreement
   - Availability?
   - Maintainability?
2. Integrators
   - No call backs?
3. Module manufacturers
   - Zero product returns?
   - No major recalls?
4. Inverter manufacturers
   - Zero product returns?
   - No major recalls?
5. BOS manufacturers
   - Not here?

Market segmentation and technology development are driving diverse and comprehensive needs.

DOE Labs Focus on Providing the Industry Information and Tools

Alex Mikonowicz (formerly Shell Solar now Solar World), AA I, Feb '06:

What we do not have?

- A meaningful test to predict end of life
- (As a manufacturer we have neither the resources or time to accomplish this).
- Suggested tests for life affected performance, i.e. UV degradation of polymers, cables, junction boxes etc.
- Suggested tests for EVA, back sheet materials, RTV etc.

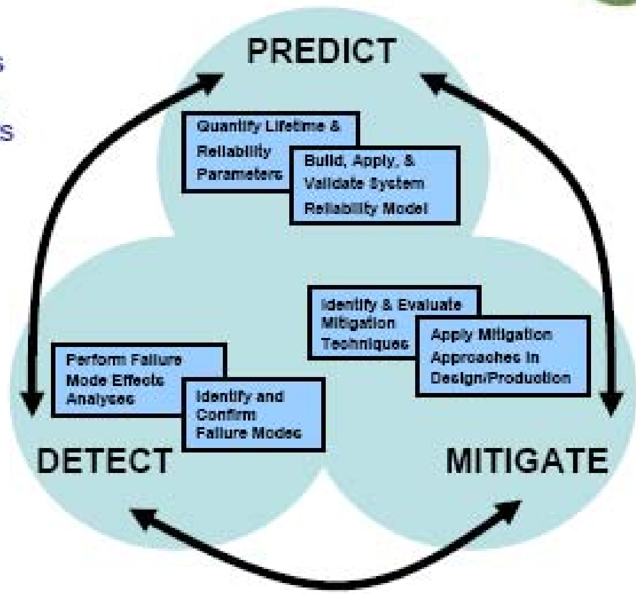
What can the labs do for manufacturers?

- Any series of "suggested" tests that can be correlated to the life expectancy of module performance (not standards)
- Operate long term site installations and measure performance over time
- Operate long term site installations and measure performance in several environments within the US

Proliferation of markets and technology make Alex visionary!

DOE has expanded and linked reliability across the entire PV program

Three major elements will be applied across materials, components and systems.



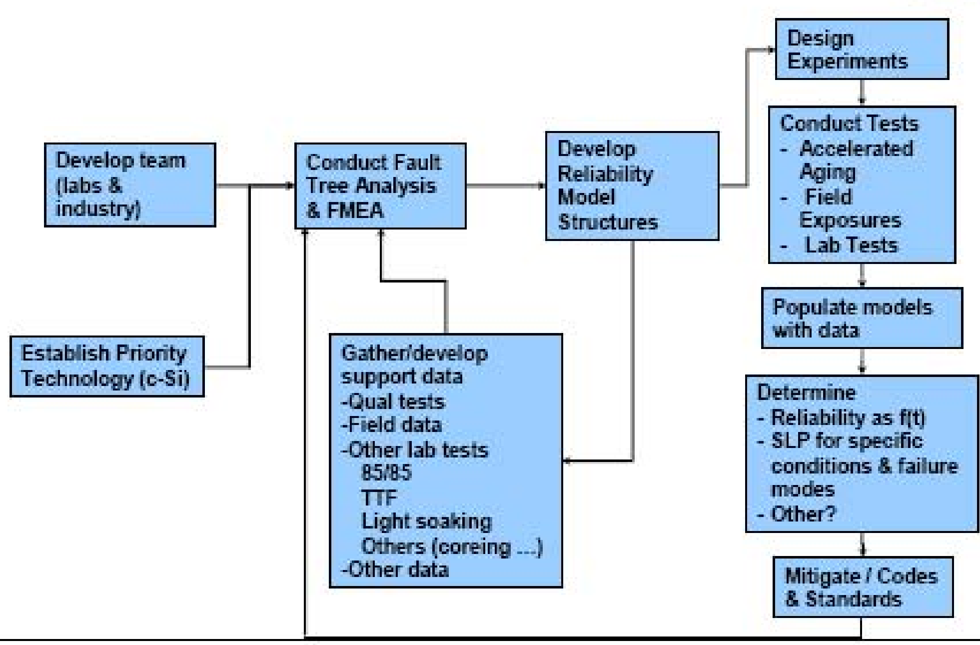
Project Objectives

- Accelerate development and adoption of methodologies that increase reliability of PV components/systems
- Develop and facilitate use of rigorous pre-qualification screening protocols
- Develop a predictive model capability that industry can own and apply
- Develop accelerated tests/standards that facilitate product development
- Develop system availability functions
- Develop criteria for design-for-maintainability strategies
- Identify barriers and solution-oriented R&D opportunities
- Assist SAI participants to meet Stage-Gates

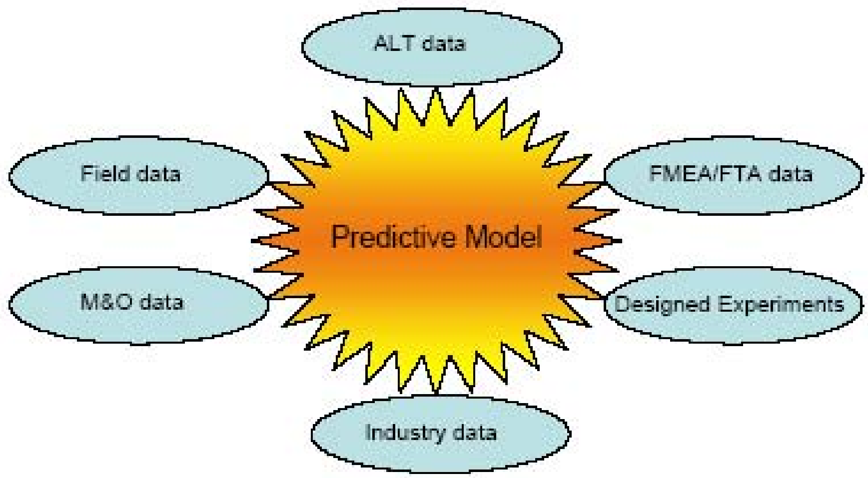
Project Scope for FY08

1. Failure Modes and Effects Analysis: Apply to c-Si modules, CIGS, and inverter to define and/or understand and review potential failure modes
   - Pursue commercial partners for FMEA application
2. Fault Tree Analysis: Define foreseeable/undesirable system events
   - Pursue commercial partner(s) to define inputs
3. Long-Term Exposure: Invest in understanding degradation of newer products/technologies
4. System Studies: Invest in field installation data to assess reliability issues
5. Accelerated Tests: Increase development of tests that address new technologies and greater understanding of mature technologies
6. Screening Protocols: Develop and apply protocols that provide valued pre-qualification T&E + diagnostics
7. Predictive Model: Develop data needs and model architecture
   - Pursue collaboration with commercial partner(s)

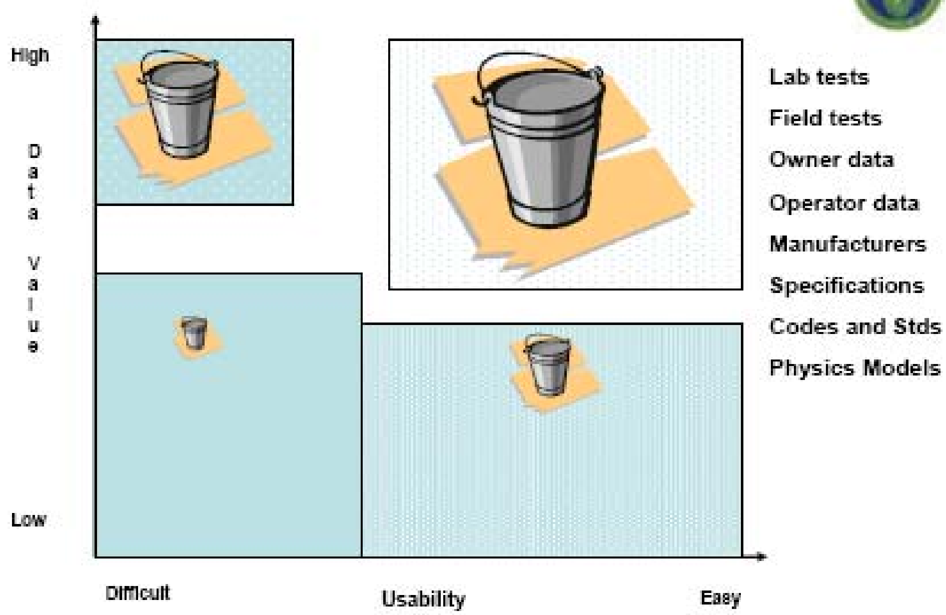
Reliability Project Flow Diagram



Data is the driver



Targeting data sources



Failure Modes and Effects Analysis

FMEA is a bottom-up approach to systematically identify, analyze and document possible failure modes within a design and the effects of such failures on system performance and personnel safety.

Approach:

- Field data will be used to identify potential failure mechanisms
- Subject Matter Experts examine and review the materials used to build components
- Potential Failure Mechanisms will be identified and ranked based on perceived risk

Objectives:

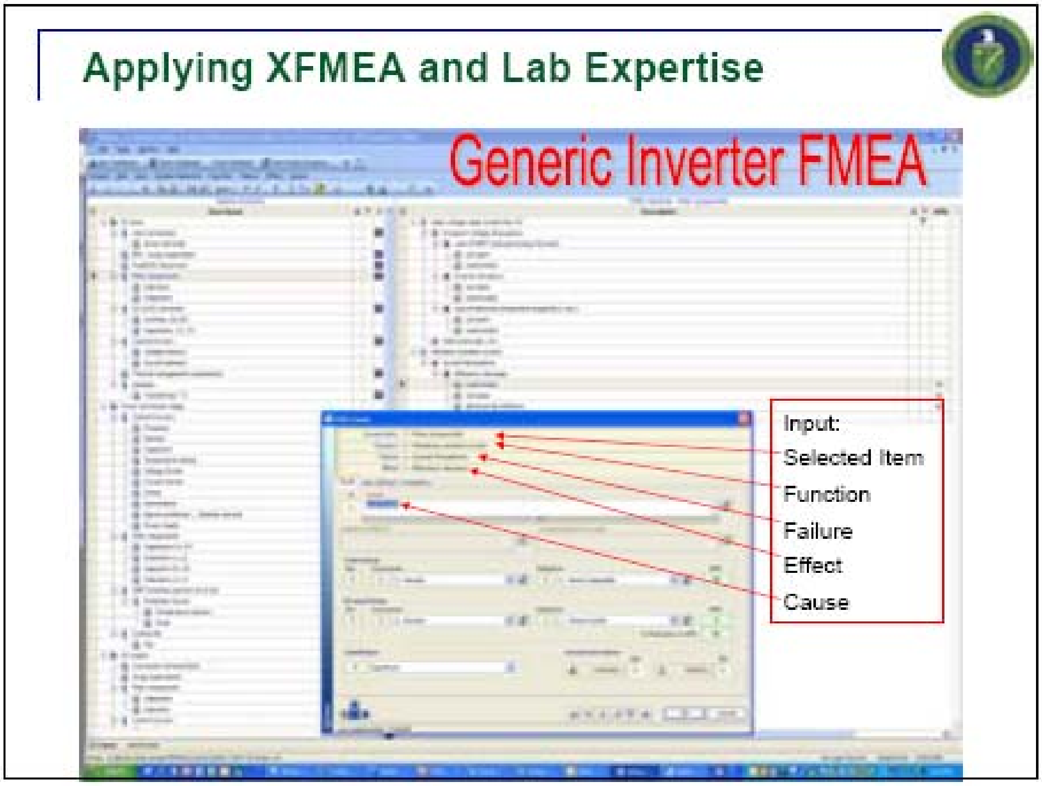
- Identify dominant failure mechanisms
- Develop theoretical models that predict failure
- Identify candidate items for accelerated life tests

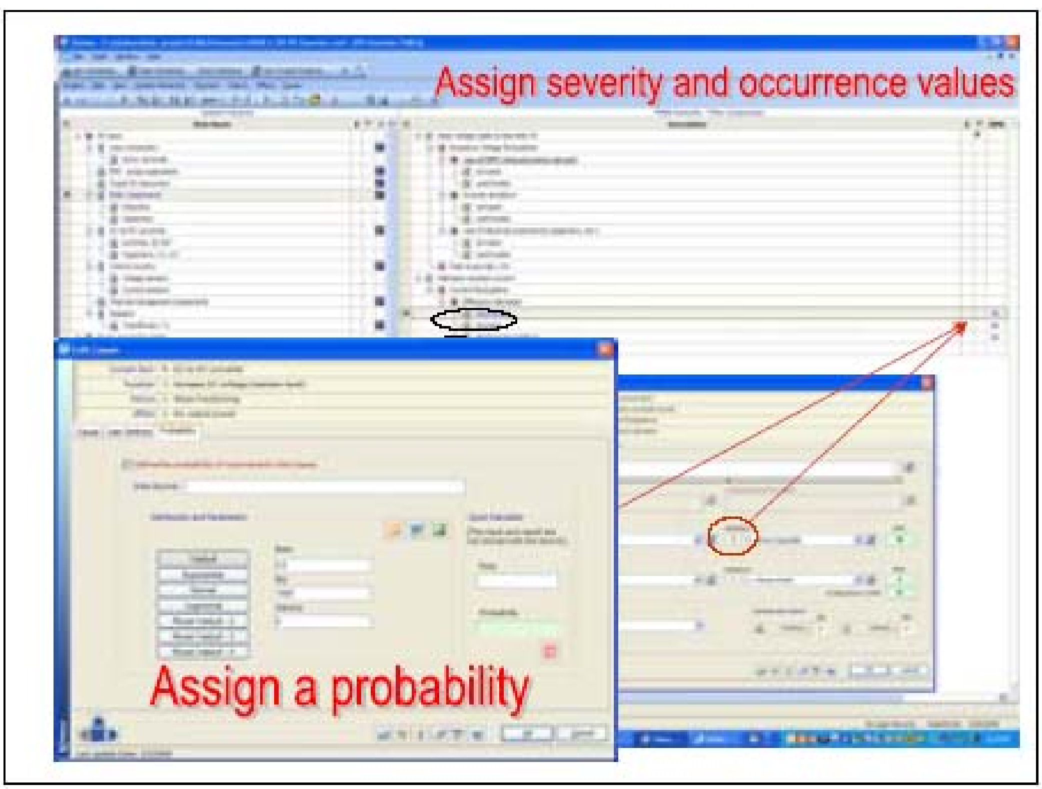
Failure Modes and Effects Analysis

- FMEA includes “cost and actions” elements
  - Scheduled maintenance actions
  - Maintenance costs
  - Replacement schedules
- Tool: XFMEA (can be imported into ALTA and RBD packages)

✓Some Early Results Follow

✓We Will be Soliciting Review from Industry


Applying XFMEA and Lab Expertise
Generic Inverter FMEA
Input:
Selected Item
Function
Failure
Effect
Cause


Assign severity and occurrence values
Assign a probability

Identifying High Risk Elements

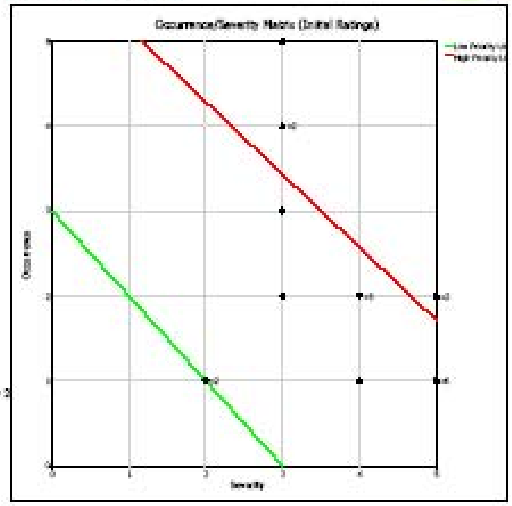
Database: E:\photovoltaic project\FMEA\[illegible]\Crystalline Silicon Device.rxt
Project: Crystalline Silicon Device

Selected Items:
3 - Cell Strings
3.4 - Ribbons
3.5 - Busbars
3.6 - Insulation (Dielectric Material)
3.7 - Solar Cell
3.7.17 - Silicon substrate
3.7.18 - Dopant
3.7.19 - Metallization lines
3.7.19.20 - Bus lines
3.7.19.21 - Gridlines
3.7.22 - Backsurface Field
3.7.24 - Silicon Nitride

High Priority Causes:

Medium Priority Causes:
electromigration (Item: 3 - Cell Strings) Sev = 5, Occ = 1
deterioration of metallization adhesion (corrosion) (Item: 3.7 - Solar Cell) Sev = 4, Occ = 2
metallization diffusion or migration (Item: 3.7 - Solar Cell) Sev = 4, Occ = 1
Cracked cell (Item: 3.7 - Solar Cell) Sev = 4, Occ = 2
Cracked cell (Item: 3.7 - Solar Cell) Sev = 5, Occ = 2
Full delamination of metallization lines (Item: 3.7 - Solar Cell) Sev = 5, Occ = 1
Partial delamination of metallization lines (Item: 3.7 - Solar Cell) Sev = 4, Occ = 2
Broken bus bar (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Broken ribbon (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Short circuit to ground (fault current) (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Solder bond failure (Item: 3 - Cell Strings) Sev = 5, Occ = 2
Increased series resistance due to solder joint degradation & or failure at gridline interface (Item: 3 - Cell Strings) Sev = 3, Occ = 4
Decreased power in a single cell (Item: 3 - Cell Strings) Sev = 3, Occ = 3
Corrosion (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Shunting (cell to cell shorting) (Item: 3 - Cell Strings) Sev = 3, Occ = 2
One or more cracked cells (Item: 3 - Cell Strings) Sev = 3, Occ = 5
Fatigue due to thermal cycling (Item: 3 - Cell Strings) Sev = 3, Occ = 4

Low Priority Causes:
encapsulation material leaching (Item: 3.7 - Solar Cell) Sev = 2, Occ = 1
contamination from plating or corrosion products (Item: 3.7 - Solar Cell) Sev = 2, Occ = 1



Address highest priority issues!

System Reliability Modeling

A system reliability model is a diagrammatic representation of all functions, in terms of subsystem or component events, that must occur for a successful system operation.

Approach:
- Reliability Block Diagrams and
- Fault Tree Analysis

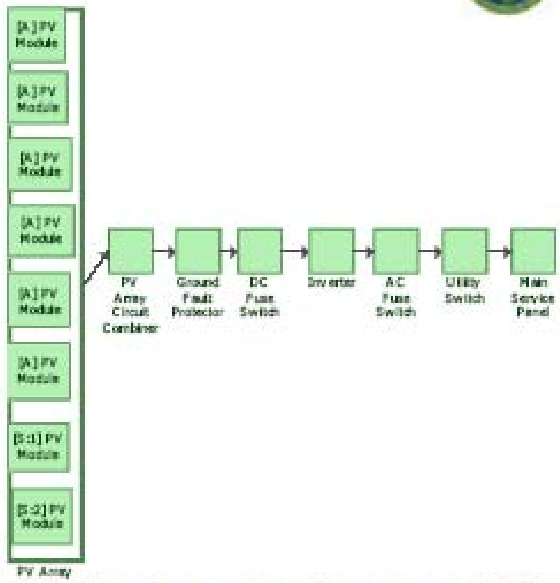
Objective:
- Quantify reliability/availability for a system
- Determine life cycle cost of system

Tools:
- Reliasoft Block Sim 7, Weibull++, and ALTA
- Computer-Aided Fault Tree Analysis (CAFTA)

Service life prediction--a time period in which the system degrades to a specified unreliability

Reliability Block Diagram (RBD)

- RBD: used to quantify System Level Reliability for a specified period of time.
- Model can be used to predict the number of failures
  - Develop maintenance schedules/spares inventory
  - Identifies "weak link(s)"
  - Identifies designs for maintainability/availability
  - Identification of major contributors to the unreliability
  - trade-offs between cost and unreliability
  - predictions for unscheduled maintenance cost

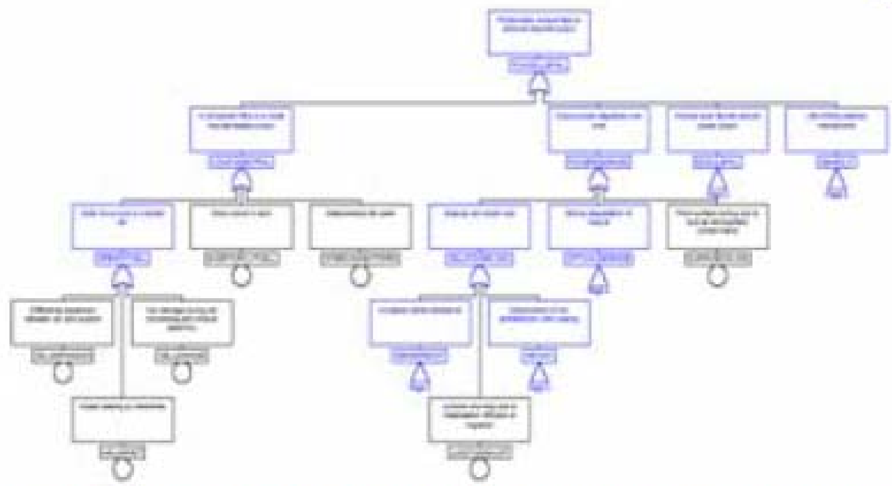


This is early work!

Fault Tree Analysis (FTA)

- FTA is a system-to-component top down analysis.
  - An undesired behavior event at the system level is hypothesized
  - Events at subsequent lower levels are then identified that can result in the undesired behavior
- Blocks in the RBD that do not have sufficient data available for quantification will be analyzed with FTA.
  - The objective is to identify lower level data that may be available to allow quantification.
- If the fault tree is developed sufficiently FTA may provide insight into those manufacturing processes that influence field reliability.

Initial Fault Tree Analysis



This is early work to be expanded in collaboration with PV community!

Accelerated Life Tests (ALT)

ALT's increase the rate of degradation processes such that quantifiable changes occur in months rather than years/decades to identify kinetics under accelerated aging conditions. Field validation tests plus these accelerated degradation rates are used to estimate service lifetimes under normal operating conditions—AF's.

Objective: Apply lab-based tests to increase use rate, aging rate or stress level of a product to quantitatively estimate long-term performance

Approach:

- Identify/prioritize failure modes using
  - FMEA
  - Field data
  - Physics models
- Identify mechanisms & associated stresses
- Accelerate aging without changing the mechanism or introducing other failure modes
- Correlate field data to ALT data to determine acceleration factors

Tools – ALTA, Design of Experiments

Accelerated Life Tests (ALT) - Step 1

Identify/prioritize failure modes

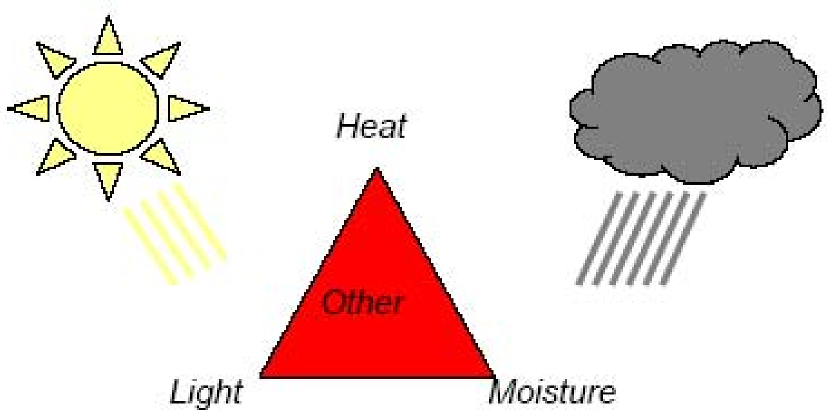
Table 1. Reliability Concerns Associated with PV Technologies

Technology	Known and Anticipated Failures & Degradation	Priority /Prob. of Success /Impor-tance of work at Labs	Cell/ Module/ System	Diagnostic Technique / Qual Test? (e.g., chamber tests, HVTB)	Acceleration factor determination (schedule for development & validation) None? Start on?
Wafer Si	Wafer breakage issues during manufacture/handling etc. (highest priority for industry); cell cracking as wafer thickness is decreased	H/M/H	C/M	Flexing of cells	
	Improved reliability must accompany new processing innovations (reduced wafer breakage, tighter performance distributions, and higher throughput)	M/H/L	C		
	Development of encapsulation materials that reduce module cost and maintain reliability	H/M/H	M	UV and damp heat exposure	
	Wafer breakage caused by bonding of conductors (front contact, interconnects, etc.)	M/H/M	M	Thermo-mechanical stressing	
	Effect of lead-free solders (higher process temperatures)	L/M/L	M	SNL?	
	Corrosion of grid lines	M/M/M	M		
Film Si	Slow degradation of I_{sc}	M/M/L	C/M	Light soaking	
	Electrochemical corrosion of SnO_2:F	L/L/L	M	Voltage biased damp heat (1)	
	Initial light degradation (a-Si)	L/L/L	C/M	Light soaking	
	Annealing instabilities (a-Si)	L/L/L	C/M	Light soaking	
	Contacting of thin Si (breakage)	?/?/?	C/M		
	Reliable low cost packaging options	H/?/?	M		
	Corrosion of grid lines and solder	H/?/?	C/M	Damp heat	

Prioritize according to importance and needed R&D

Accelerated Life Tests - Step 2

Identify failure mechanisms & associated stress(es)

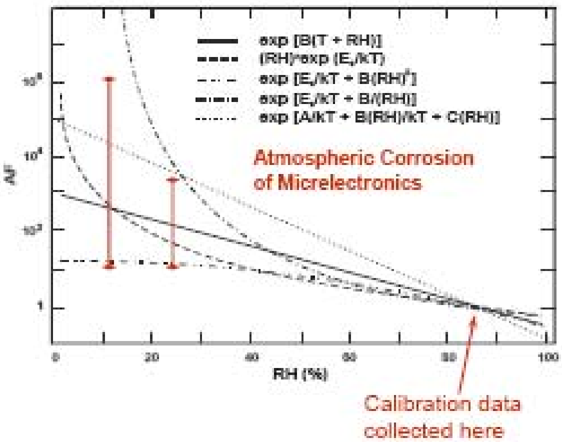


Accelerated Life Tests - Step 2

Identify Applicable Models

Example:

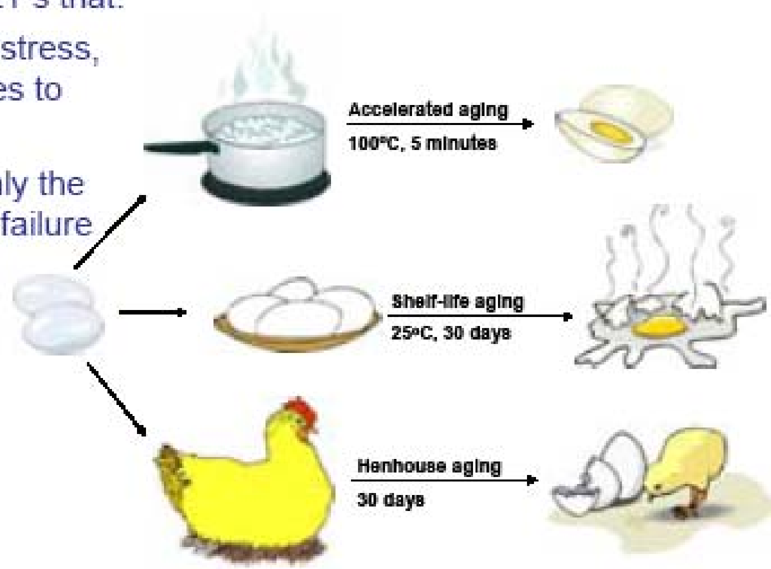
- Three recognized models for corrosion in micro-electronics
- All agree at 85%RH
- Disagreement at 10%-30% prevent uniform application of either model



Accelerated Life Tests - Step 3

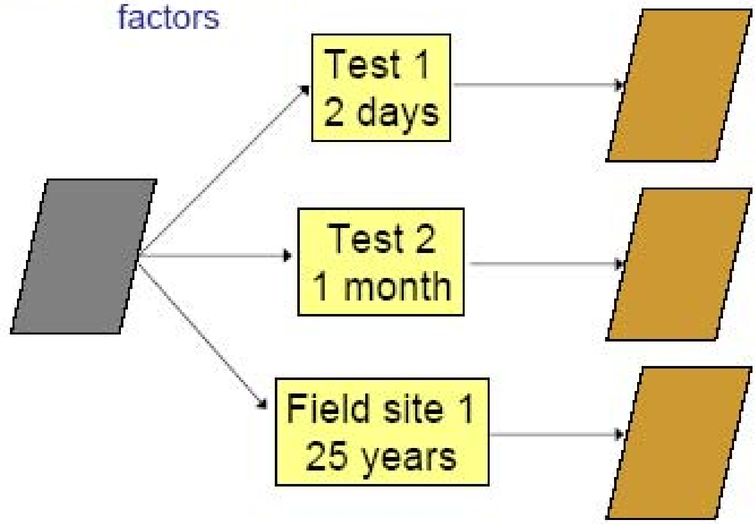
Develop ALT's that:

- Increase stress, sometimes to failure
- Stress only the intended failure mode(s)



Accelerated Life Tests - Step 4

Measure acceleration factors



Step 5. Apply acceleration factors to site-specific stresses

Test-to-failure protocol

Objective:
- Quantitative testing of failure rates
- Comparison of different designs

Approach:
- Leverages years of experience with qualitative testing
- Repeat test multiple times; record time of failure
- In-situ monitoring can pinpoint time of failure

Tools:
- Damp heat; temperature cycling

Details:
- Published at: http://www.nrel.gov/docs/fy08osti/42893.pdf

Comparison of these tests with field data will can yield acceleration factors

Field-based Surveillance Studies

- Module and inverter long term exposure in severe climates will be implemented to further develop data on degradation rates
- Industry return data will be mined—partners are being solicited
- Fielded systems will be evaluated for module, inverter and BOS data that assists analyses
- Validation tests will be conducted to assist in ALT and model development
- Coupon/samples will be fielded in extreme environments
- Short and intermediate outdoor exposure at labs

Summary

- The photovoltaics industry is evolving rapidly
- Reliability is a key element in everybody's growth plans
- DOE Labs are heavily invested in promoting robust reliability methodologies to:
  - Assist industry in meeting development needs
  - Assist DOE in administering the Solar America initiative
  - Elevate the value proposition that photovoltaics brings to America's energy landscape

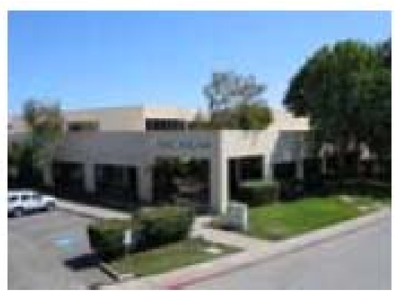
Large-Scale Systems Integrator - Reliability Needs

April 1, 2008

Laks M. Sampath
Executive Director of Technology

SPG SOLAR

SPG Solar - Company Overview



- SPG Solar is a turnkey solar PV system developer/integrator
- Business Sectors Served:
  - Residential, Commercial, & Public Agency
- Founded in 2001
- High Growth
  - Entrepreneur Magazine Hot 100 Fastest Growing Companies
  - 150+ Employees in 7 Regional facilities throughout California
  - Expansion underway into Oregon, Nevada & Arizona
  - Over 1,000 "net-metered" Interconnected Projects
- Bonded California General B, Electrical C-10 & Solar C-46 Contractor. #759086

SPG SOLAR

Services Performed

- Feasibility Studies
- Analysis + System Design
- Engineering + Permitting
- Construction
- System Commissioning
- Financing / PPA's
- Real-time Online Performance Monitoring
- Customer Care Program

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Importance of Reliability

- Performance Based Incentives
- PPA and their Financial Models
- "Production Guarantee"

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Areas of Concern

- Uptime
- Warranty Terms
- Repair Response Time
- Customer Care

Components that have failed

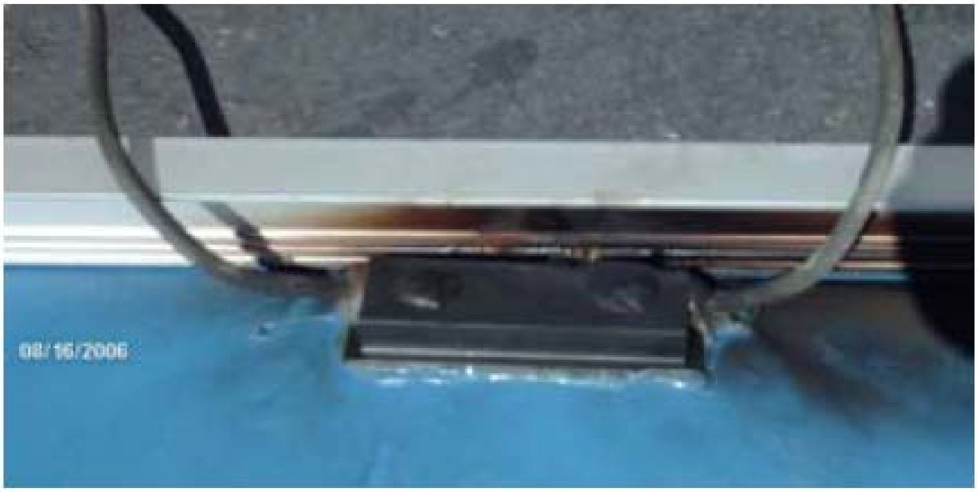
- Modules
- Inverters
- Combiner Boxes
- AC Disconnect
- Fuses
- Foundation in Ground Mounts
- Roof Penetration Leaks

Modules – Failure Points

- Weak Links
  - ✓ Burn through
  - ✓ Junction Box failures
  - ✓ Poor soldering
  - ✓ Tab failure
- To a lesser extent, theft and vandalism have played a part.
- Finding Replacement Panels

Modules – Junction Box

Modules – Junction Box



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Modules – Junction Box

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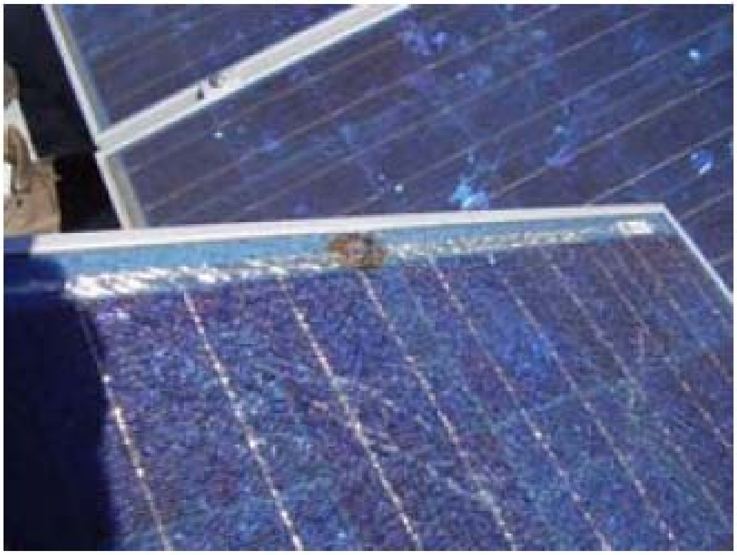
Modules – Junction Box



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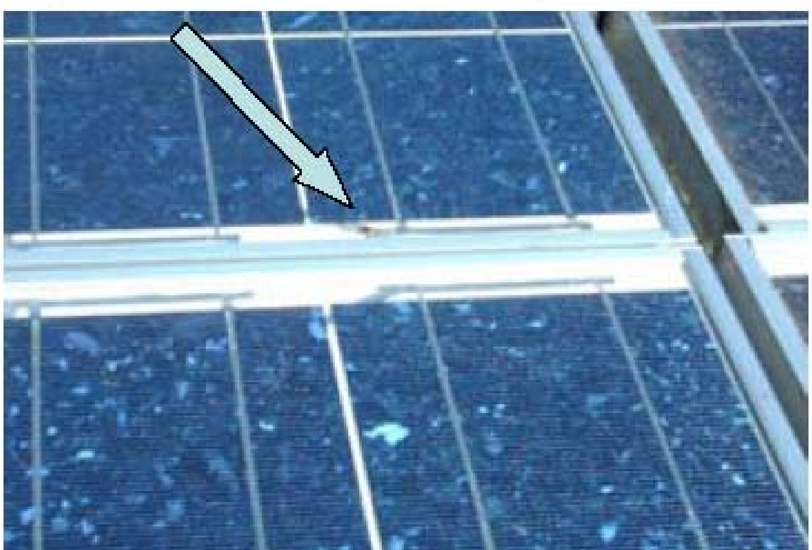
Modules – Tab failure



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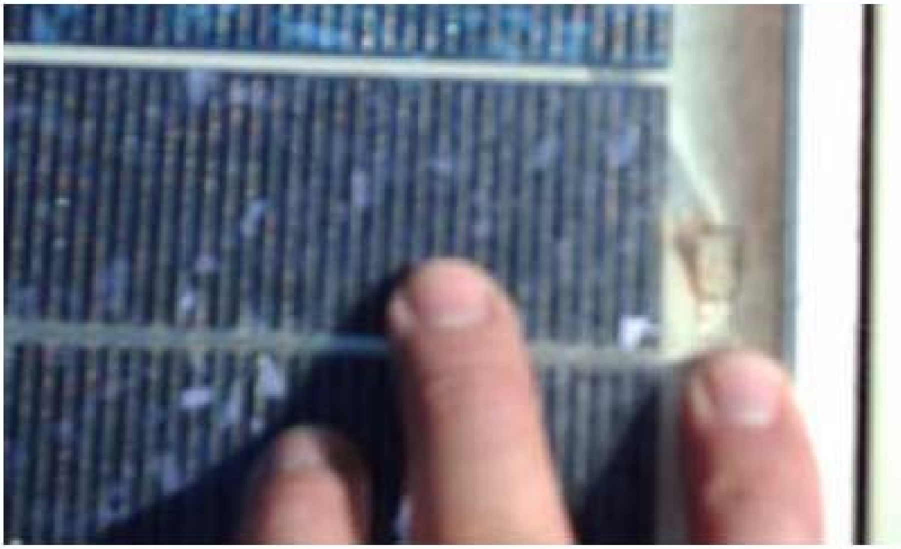
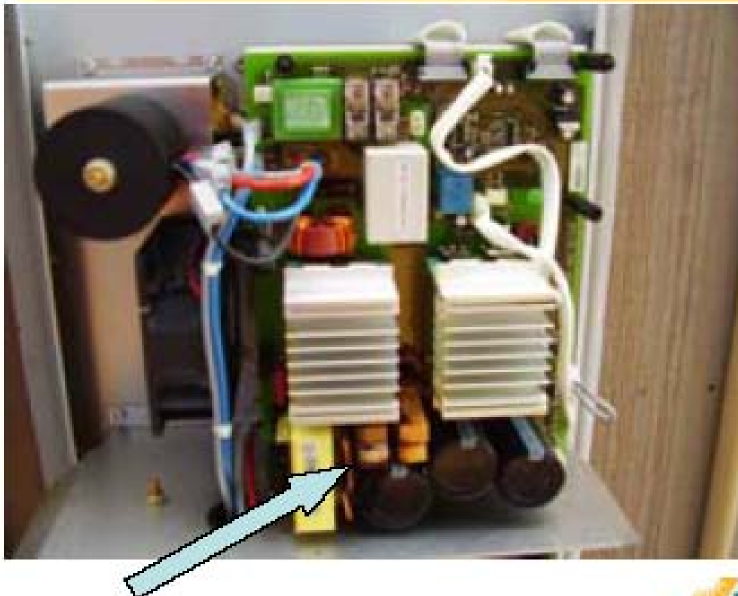
Modules – Tab failure



Inverter

- Weak Links
  - ✓ Component shorting
  - ✓ Loose connections
  - ✓ Voltage windows
- First Line Support Training
- Escalation Support

Inverter



Inverter

Inverter

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Inverter

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Inverter

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Combiner Box

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Combiner Box

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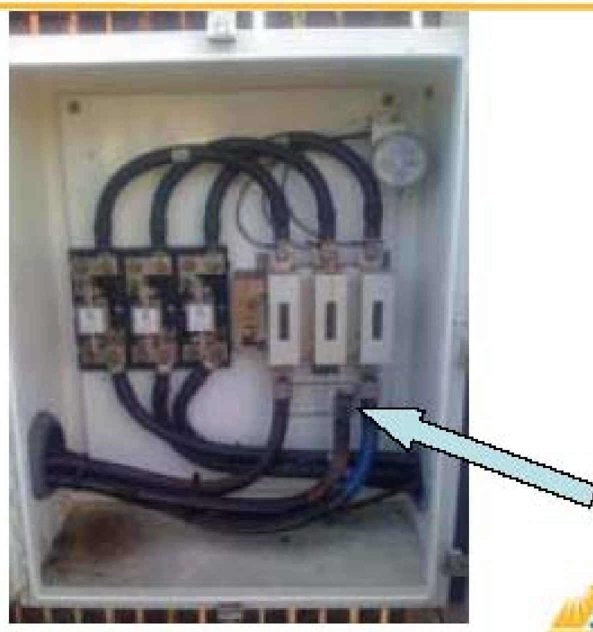
AC Disconnect



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AC Disconnect

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Combiner Box Fuses

- Fuse most likely to fail
- One String of 2 KW in a 1 MW

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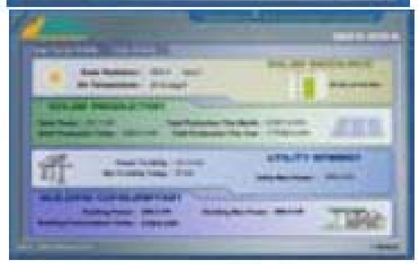
Monitoring as a solution

- Monitoring of system performance
  - power flow
  - accumulated energy usage
  - solar insulation
  - ambient temperature
- Real-time Web access
- String sensitive monitoring
- Ability to guarantee annual power output
- Key in today's "performance-driven" incentive environment



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Failure points in Monitoring

- Range from the trivial to the complex
  - On the trivial end of things
    - Customer forgets to pay their DSL bills and Internet service is terminated
  - On the Complex end
    - Revenue Grade meter burns out repeatedly

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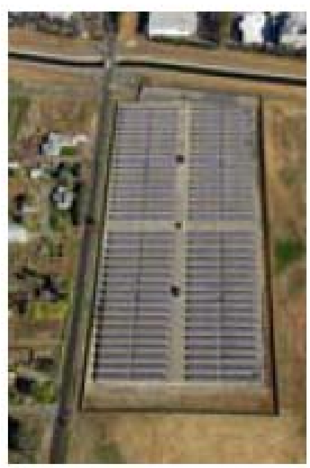
Conclusion

- PV Power Plant – Production… Production… Production.
- MTBF numbers from Manufacturers
- Accelerated aging tests of Modules and Inverters
- Reliable systems are key to continued acceptance of PV Systems

- Questions and Answers

Single-axis Tracking PV Arrays

- Ground-mounted, provides 15-25% more power (kWh's) annually than a fixed tilt system
- Delivers the lowest installed cost per kWh
- Up to 250 kW AC driven by a single motor & screw drive
- GPS-driven Controller
- Remote Operation



Floatovoltaic™ Mounting System

The Floatovoltaic™ PV System is designed to float on water retention ponds and basins. Uses previously unbuildable space to generate clean, renewable power and mitigates and reduces extensive water-born algae, reducing facility operation and maintenance costs.

The first commercial Floatovoltaic system is currently installed at a Northern California Winery.

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Perspectives on Thin Film PV Reliability and Initial Product Introduction

Accelerated Aging and Reliability in PV Workshop
Lakewood, Colorado

April 1, 2008

Kurt L. Barth
V.P. Product Development and Co-Founder
AVA Solar Inc.

Overview of Discussion

- Introduction to AVA Solar Inc. / Technology Description
- Importance of reliability
- Components of reliability
- Best practices / Challenges
- Advancements / Opportunities
- Summary

AVA Solar Inc.

Technology	• **CdTe thin film photovoltaics**
Mission	• **Produce solar energy at costs competitive with conventional electricity**
Product	• **120x60 cm modules (~10% efficiency)**
Market focus	• **Utility and commercial scale applications**
History	• **15 years in development** • **Spun out of CSU 15 months ago**
Location	• **Headquartered in Fort Collins, CO**

Time to market is a major business driver

Technology description: Thin film CdTe

One-step semiconductor manufacturing

- Single tool (modest vacuum)
- Thin film CdTe semiconductor
- Semi process is dry, in-line, continuous, and automated
- High throughput: glass in device out

Technology description: Package

Key package characteristics:

- Glass/glass package
- Semiconductors on "superstrate"
- Leads out hole in back glass
- CdTe PV: increased moisture sensitivity compared to c-Si
- Frameless

Glass into a PV device
Glass/Glass package

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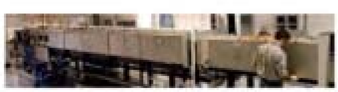
Scale-up roadmap

Importance of reliability in rapid growth environment

Pilot line



2008
Single PV line with all value-added processes

Initial factory

>100 MW
2009
Multi-line, fully automated facility

Large scale complex

Toward 1 GW
Integrated glass and PV factory complex

Aggressive production volume expansion
Rapid product introduction

Product reliability and qualification testing is critical

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Target Market: Customer Expectations

Go-to-market strategy focused on grid-tie applications, market determines reliability expectations

Initial markets:

Utility-scale solar power plants
(1-100+ megawatts)

Commercial installations
(~100 kilowatts to 1+ megawatt)

Customers help drive reliability requirements

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Importance of Reliability for AVA Solar

- **Utility and Commercial PV Customer Expectations**
  One of the largest thin film PV integrators: "We build PV power plants, modules should produce energy and that's it."
  - Cost of energy produced: dominate
  - Predicable, stable energy production needed for economic analysis
    - Warranty
    - Certifications
    - Reliability data
- **Manage Risk: New Company Growth**
  - Reputation: New company / new technology
  - Cost: Limited capacity for recalls/warranties
- **Investor**
  - Reliability key for access to capital

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AVA Solar's Approach to Reliability

- **For Development: Semiconductor and Package**
  The semiconductor and package were considered individually
- **Initial Emphasis: Semiconductor Device Reliability**
  - Device is fundamental to module
  - Reliability of the device difficult to separate from full module
  - Device reliability is tied to processing,

semiconductor reliability testing → **Define package requirements**

AVA Solar was formed after demonstration of semiconductor device reliblitiy

Best Approaches: Insuring Semiconductor Device Reliability

- **Highly Accelerated Stress Testing**
  - > 500 devices tested stress performance
  - "Indoor" controlled conditions
  - Higher temperatures studied: indications of mechanism shift

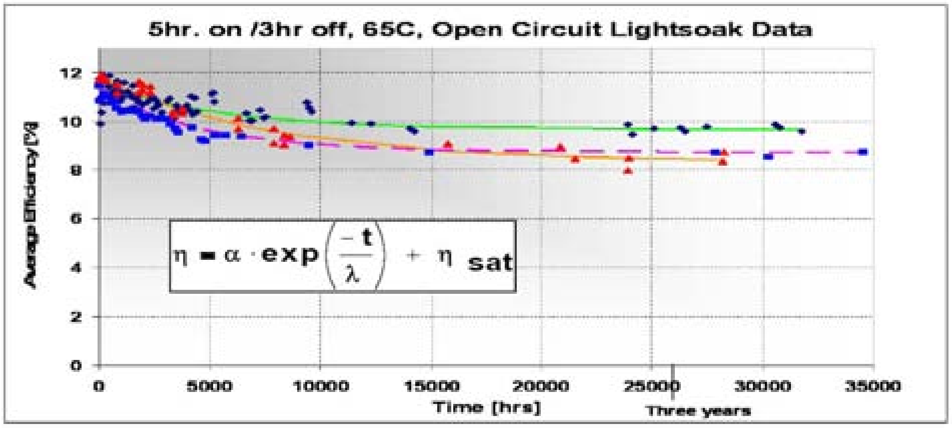
Conditions:
- 65 ˚C closed loop controlled
- One sun illumination
- 5/8 hr. cycled illumination
- Desiccated air
- Open Circuit

- **Accelerated "Outdoor" Stress Testing**
  - Fixture exposes un-encapsulated devices to field temp. illumination without package
  - Bias applies significant stress

Conditions:
- Ambient temperature
- Ambient illumination
- Desiccated air
- Open Circuit

,* Hitner and J. Sites., NCPV PV Program, AIP 1999, p. 170

Very Long Term Accelerated Stress Testing



- Extremely long term testing under stressful temperature and bias *
- Process conditions ($CdCl_2$ anneal) influence the rate and ultimate leveling efficiency

Process dependant even using same hardware

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,* Enzenroth et. al. 19th European Photovoltaic Solar Energy Conference, 7-11, June 2004 Paris, France.

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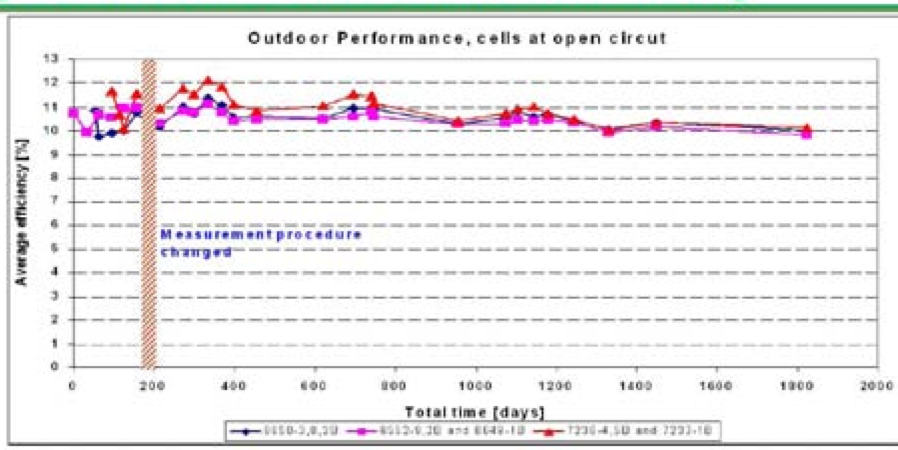
Long Term Outdoor Accelerated Stress Testing



- Minor change on average, seasonal variation
- Many X acceleration for open circuit compared to max power *

Differences in indoor and outdoor behavior significant: >20 + life

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,* Hitner and J. Sites., NCPV PV Program, AIP 1999, p. 170

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Semiconductor Device Reliability Challenges

- **Stress Testing Challenges**
  - Time, time and .... **time**
  - Accelerating with temperature: Risk
    - Max module temp < 100 C
    - Mechanism shift at higher temp

Faster method required

Metric to Ensure Consistent Stability

A relationship between unstressed device performance and long-term stability developed

The stability of devices with intentional Cu can be predicted from the light JV data of identically processed devices without intentional Cu

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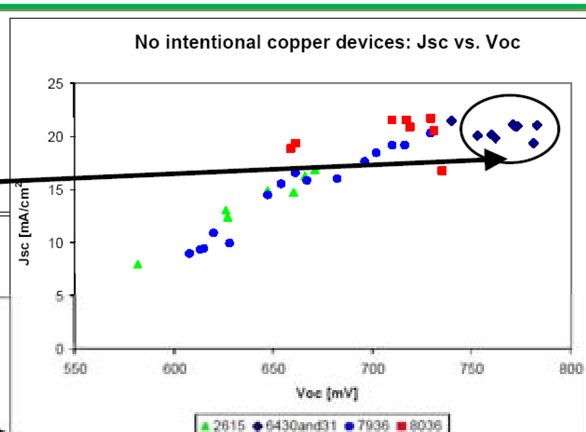
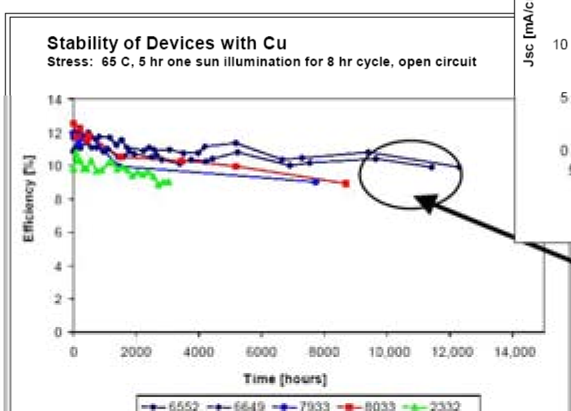
Stability Metric

During fabrication Process conditions which lead to the highest average Voc and Jsc for devices...





... lead to the best stability when fully processed with Cu back contact

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Source: Barth et. al. 31 IEEE PVSC

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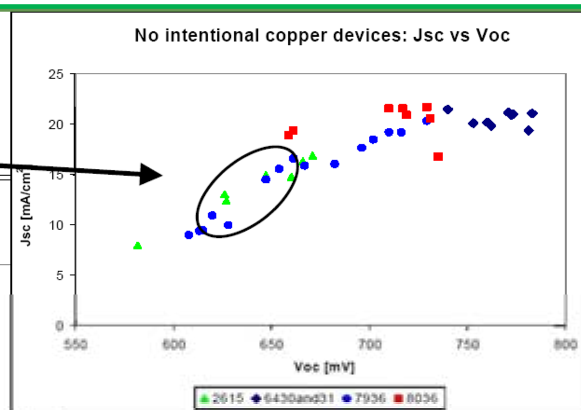
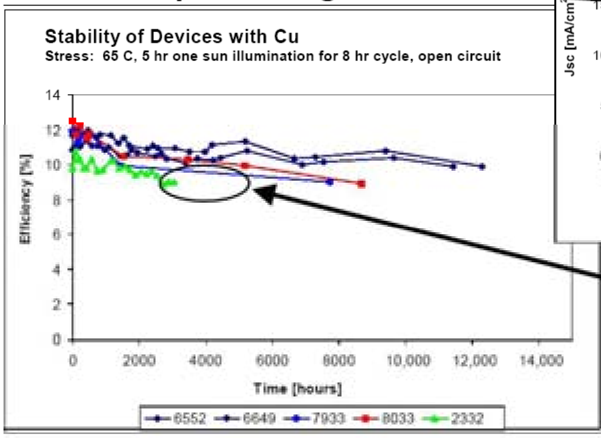
Stability Metric

Process conditions with lower average Voc and Jsc for devices without the Cu back contact processing...





... Have reduced stability when fully processed with the Cu back contact

Package Reliability: Requirements

- **Package Requirements**
  - Performance: IEC 61646
  - Safety: IEC 61730, UL
  - 20+ years of warrantable life
    - Requires testing beyond certification

Customer driven

- **Product Requirements**
  - Low cost
  - Fast time to market

Business environment driven

Objective: Extremely reliable, low cost product

Package Reliability: Challenges

- **Identify Key Challenges**
  - Internal testing
  - Internal Modeling
  - Literature review
  - NREL, Consultants, Industry experts

- **Most Package Requirements**
  - Utilize existing best practices
  - Process development
  - Testing program

Process engineering needed, but solutions exist

- **Moisture Ingress: Key issue**
  - Significant failure in ASU-PTL tests
  - Internal testing shows moisture degrades device
  - Accelerated stress tests performed under desiccation

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Package Reliability: Moisture Ingress

- **Develop moisture specification: level seen in accelerated testing**
  - Ambient moisture can hurt un-coated, non-encapsulated device
  - Moisture level during accelerated stress: Acceptable
    - Indoor and Outdoor
    - Controlled with desiccant

- **Package Design**
  - Maintain moisture levels below that seen in accelerated testing
    - Calculated field conditions
    - Qualification testing
    - Accelerated testing
  - EVA alone and other laminates: do not meet spec.
  - New designs being investigated
    - Glass/Glass seal
    - Back hole

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Advancement Opportunities

- **Understanding Effects of Moisture**
  - CdS/CdTe films
    - Materials
    - Electronics
  - TCO and electrodes: expand current efforts
- **Materials Developments:** Encapsulation materials for "thin film"
  - UV performance
  - Low - MVTR
  - Transparency not needed for CdTe
- **Certification/Standards**
  - Streamline certification: Regional, UL, IEC,
  - Reduce certification lead time
  - Specifically recognize frameless modules
  - Correlate performance tests to field conditions
    - (85/85 Damp heat)

Summary

AVA Solar
- Rapid expansion requires proven reliability
- Time to market critical

Reliability requirements
- Risk reduction for company
- Customer, investors, access to capital

Approach / challenges: Semiconductor device
- Accelerated stress: stability, leveling
- Stability metric needed
- Determines package requirement

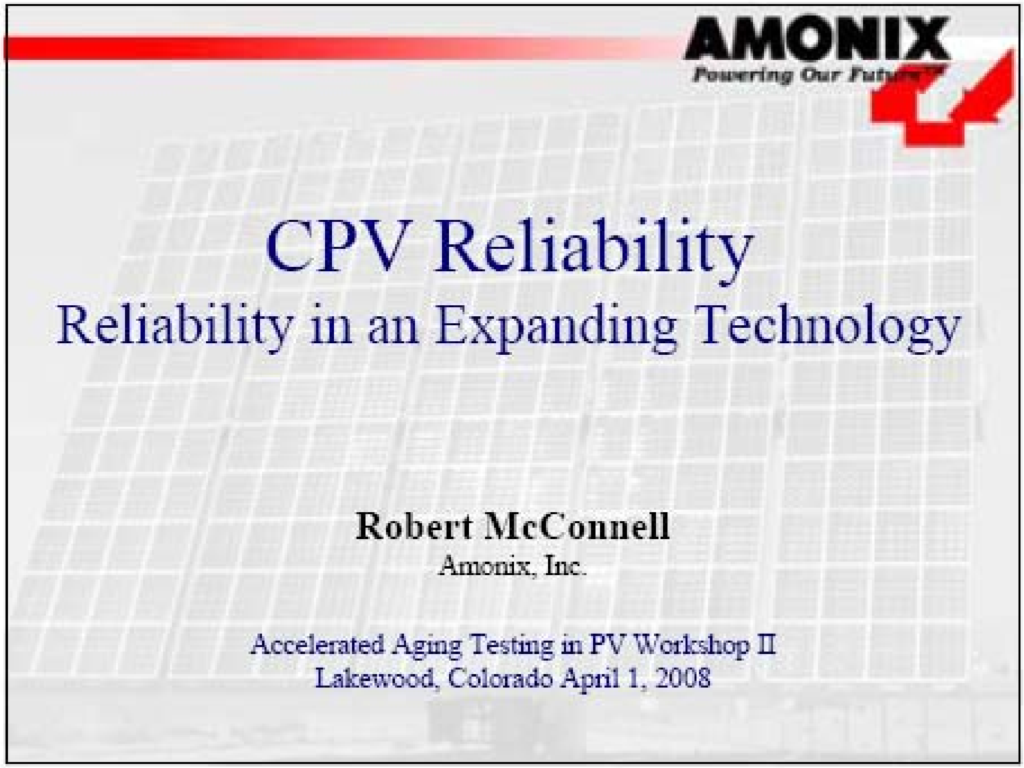
Approach / challenges: Package
- Engineering/best practices for design
- Moisture ingress critical: new design

Advancements opportunities
- Understand CdTe device / moisture interaction
- Thin film lamination / encapsulation materials
- Streamline, update certification process

AVA SOLAR

AVA Solar Company Confidential

- 20 -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CPV Reliability
Reliability in an Expanding Technology
Robert McConnell
Amonix, Inc.
Accelerated Aging Testing in PV Workshop II
Lakewood, Colorado April 1, 2008


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Reliability Importance
• Minimizing risk of failure during deployment
• Assuring investors
• Assuring reliability of totally new products, design improvements and manufactured products
• Failure of one company's product can have impact on all companies.
• Evolving business model
• Drives need for international collaboration and international reliability standards

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Early Technology Deployment Without Qualification Standard

60 kW stand-alone system near San Diego in 1981--before the first PV standards were available---removed completely after 6 months due to encapsulant failure and power loss.

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Early Technology Deployment Without Qualification Standard

6 MW low concentration PV system installed in 1984 to sell electricity in the Pacific Gas and Electric Company grid--later dismantled due to encapsulant failure and power loss.

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Early Technology Deployment Without Qualification Standard

- 440 kW high concentration PV system installed in Tenerife, Spain in 1998 suffered early losses due to mirror failures and PV solar cell shorting in high humidity salt air
- Only the trackers work today
- IEC CPV standards working group visited the project in 2004

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Early Technology Deployment Without Qualification Standard

Early 1970s wind turbine

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Early Technology Deployment Without Qualfication Standard

1970's wind turbine failure due to lack of safety standards

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Challenges

- Identification of failure modes
  - Convene specialists from balanced group of manufacturers, customers and testing labs
- Identification of appropriate reliability tests
  - Convene specialists from balanced group of manufacturers, customers and testing labs
- Test time and cost
  - Balance achieved through negotiation between manufacturers, customers and testing labs

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Best Approaches

- Work closely with existing standards organizations (IEC, IEEE, ASTM, UL, Solar ABCs,…)
  - Set up working groups with membership balanced among manufacturers, customers and test labs
  - Meet, discuss and revise
  - Meet, discuss and revise
  - etc.
- Define your terms
  - IEC Working Group 1
    - AA and ALT not in IEC dictionary

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IEC Qualification Standard

- In general, standards specify minimum requirements for such issues as performance, safety and qualification.
- Qualification standard, subject of this presentation, targets reliability of long-term operation in the field.
- Qualification minimizes risk of deployment failure for manufacturer, customer and investor.
- Tests in the standard can be adapted by manufacturer for quality assurance of product coming off assembly line or by customer to inspect products received.
- This is an international CPV standard developed under the aegis of the International Electrotechnical Commission (IEC based in Switzerland) and its Working Group 7 (17 members from 9 countries) within Technical Committee 82 (PV).

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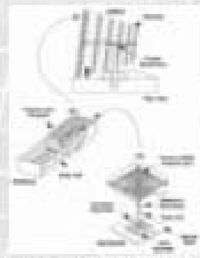
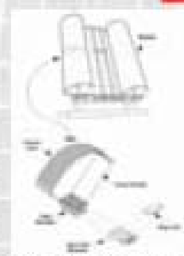
Wide Range of CPV Configurations

Point-Focus Dish



Point-Focus Fresnel Lens



Linear-Focus Fresnel Lens

Linear-Focus Trough

Heliostat

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Terms for CPV

Primary optics		CPV Module – prefabricated and the focus point is not field adjustable, like most Fresnel lens systems.
Secondary optics	CPV Receiver	
CPV Cells	CPV Receiver	
Electrical energy transfer means	CPV Receiver	
Thermal energy transfer means	CPV Receiver	CPV Assembly – needs some field installation and the focus point is field adjustable, like most reflective systems.
Interconnection		
Mounting		

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Why Specify Representative Samples?
A Whole Module is too Large.

Amonix, USA

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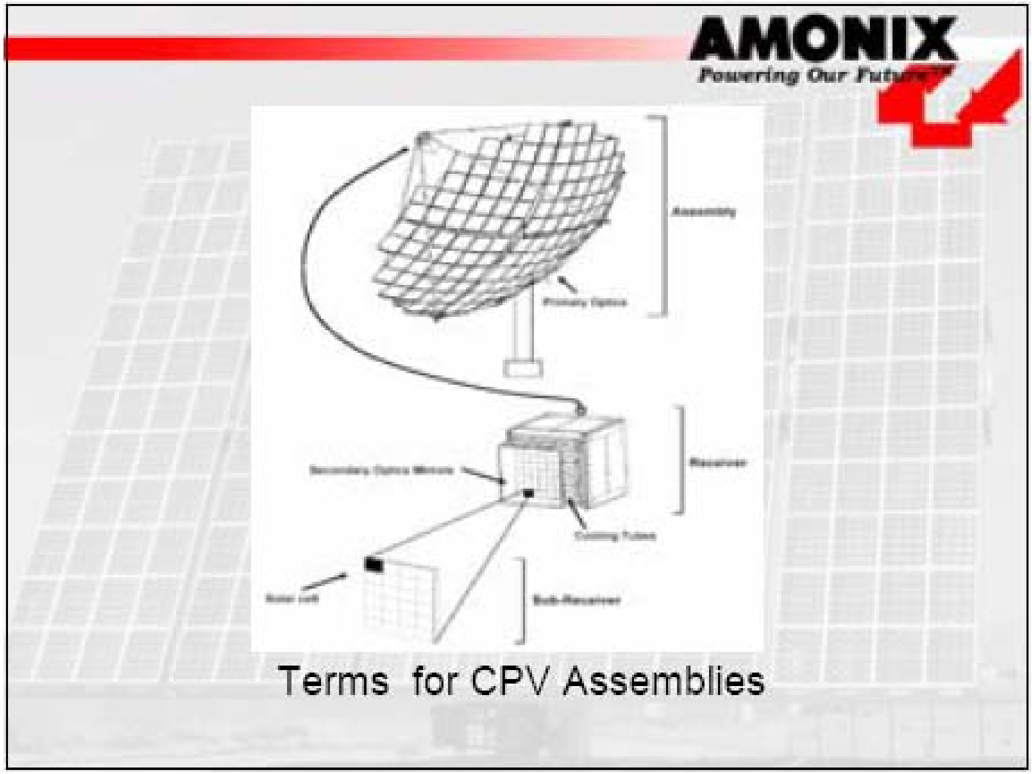
Why Specify Representative Samples?
A Whole Assembly is too Expensive.

Solar Systems, Australia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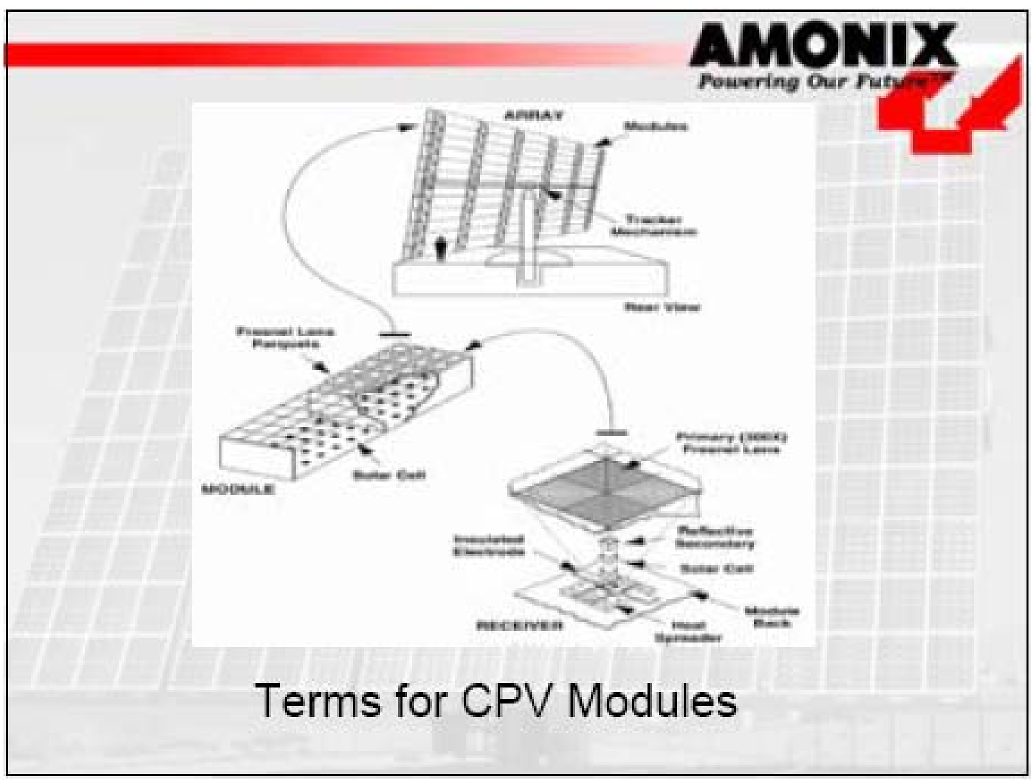
Terms for CPV Assemblies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ARRAY
Modules
Tracker
Mechanism
Rear View
Fresnel Lens
Parquets
MODULE
Solar Cell
Fresnel Lens
Reflective
Secondary
Insulated
Electrode
Solar Cell
Module
Back
Heat
Spreader
RECEIVER
Terms for CPV Modules

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Tests Targeting the Failure Modes

- Thermal cycling (e.g. 2500 cycles from 85ºC to -40ºC)
- Damp heat (e.g. 85% humidity at 85ºC for 1000 hours)
- Humidity and freeze (e.g. 20 cycles of 85% humidity at 85ºC for 20 hours then to -40ºC and back in 4 hours)
- Hail impact
- Water spray
- Heat protective diode (module heated and current applied)
- Robust connectors
- Mechanical loads (e.g. wind, snow, ice and engineering analysis)
- Off-axis damage (focal point moves off of solar cell)
- Ultraviolet exposure
- Outdoor exposure (full-size module or assembly tested and witnessed)
- Hot-spot (not needed if each cell has protective bypass diode)

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Before and After Measurements to Identify Degradation

- Visual inspection
- Electrical performance measurement
  - Side-by-side I-V using a reference sample
  - Solar simulator
  - Dark I-V
- Ground path continuity
- Electrical insulation under dry operation
- Electrical insulation under wet operation

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Side-by-Side I-V Measurement

Method based on assumption that changes of reference module's electrical performance are negligible during whole qualification test period.

Test condition variables (e.g., irradiance [DNI] level, spectrum, ambient temperature, wind speed) are self-correcting, and complex translation procedures are eliminated.

This method evaluates relative power before and after stressing a representative module.

Absolute power measurement will be covered by "Power and Energy Rating" standard. (subject of IEC TC82 WG7 meeting in San Francisco on May 19 and 20, 2008)

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Advancements Needed

- Lab/field correlation?
  - Convene balanced group--as before--and designate/delegate lab/field correlations
- Quantify degradation rates?
  - Major degradations usually lead to design changes
- ALT protocol?
  - Extend qualification tests (Extend test limits: more cycles, higher test voltages, lower insulation resistance pass/fail, etc.)

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Conclusion

- Qualification standards provide assurance to both customers and manufacturers that products are likely to operate reliably for years.
- Qualification standards specify minimum requirements for passing rigorous test procedures meant to identify weaknesses and failures that could occur during deployment.
- The first IEC qualification standard draft for concentrator PV was approved by international vote in September 2006. The final standard was approved by international vote and made available for purchase through www.iec.ch in December 2007.
- Safety, Performance and Tracker standards under development next for CPV systems (WG7 meeting in May 2008)

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Acknowledgements

- 16 members from 9 countries collaborating jointly for the development of international CPV standards
- International Electrotechnical Commission
  - www.iec.ch
- Technical Committee 82 (Photovoltaics)
- Working Group 7 (Concentrator Photovoltaics).

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Country	Organization	IEC TC82 WG7 Key Contact
US	NREL	Robert McConnell (Convener)
Norway	REC Group	Helge Aamodt
Spain	IES-UPM	Ignacio Anton-Hernandez
Japan	Daido Steel Co.	Kenji Araki
UK	Whitfield Solar	Roger Bentley
Germany	Fraunhofer ISE	Andreas Bett
Spain	Isofoton	Vicente Diaz-Luque
US	Underwriters Laboratories	Liang Ji
Australia	Solar Systems	John Lasich
Canada	Day4 Energy	Rubin Leonid
Spain	Inspira	Ignacio Luque-Heredia
Germany	ZSW	Hans-Dieter Mohring
Spain	IES-UPM	Gabriel Sala-Pano
US	PTL ASU	William Shisler
Japan	Sanyo	Ebara Toshiyuki
Korea	TS Corporation	Se-Wang Yoon

Guascor Foton: 10 MW Installation in Spain

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Smarter Solar

Modules: Remaining Reliability Challenges

Akira Terao, Principal Reliability Engineer

"Remaining" Challenges

- 25 year warranty
- Ill-defined field conditions
- Harsh and varied outdoor conditions
- Materials used near their limits
- Limited acceleration factor → long tests
- Large samples, small sample size
- Subtle polymer chemistry
- Cumulative effects, positive feedback loops
- New materials, new structures

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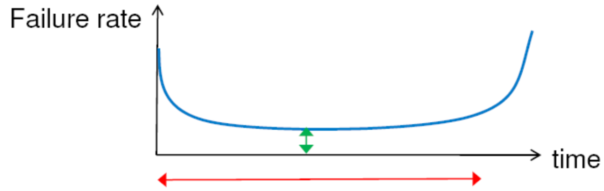
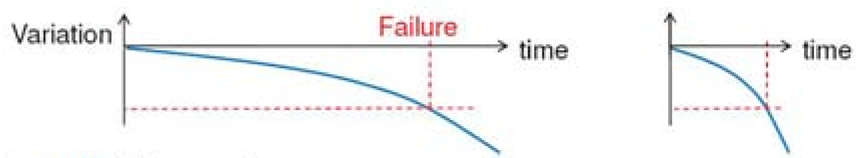
Best approaches

- Reliability is easy, lifetime is not



- Physics of failure
  - Degradation rate: and acceleration factor:



…for each failure mode

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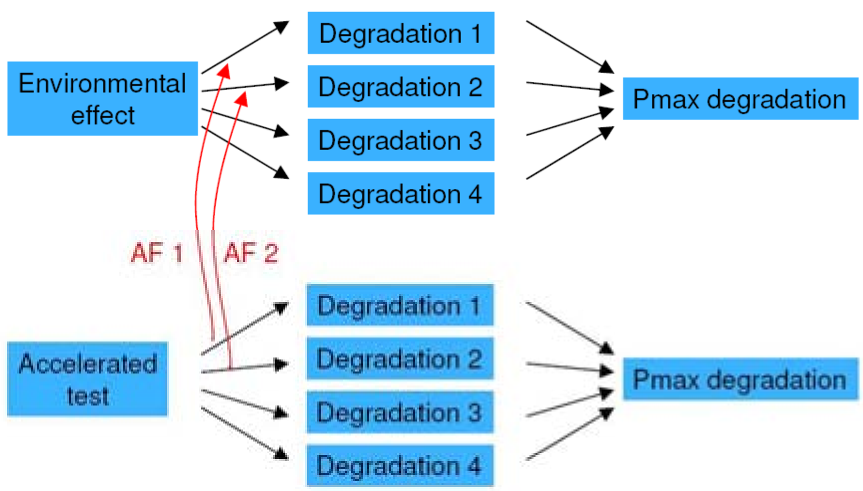
Physics of failure (cont'd)

- Decomposition:



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Physics of failure (cont'd)

- Advantages:
  - Each failure mode can be studied separately
  - Smaller samples can be used
  - Each failure mode can be fully accelerated
  - Different field conditions can be simulated
  - Degradations can be measured even before they affect performance

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Advancements needed

- Acceleration factors
  - Standardized definition of field conditions?
- Certification tests
  - Increasing number of designs and materials
  - Increasing range of applications
  - Increasing harshness of environmental conditions (pollution, global warming)
  - Parametric tests?
    - E.g.: TC based on maximum temperature measured

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PV Safety Issues: Key to a Reliable, Viable Industry

Tim Townsend, Sr. Mech. Engr.
BEW Engineering, San Ramon, CA

April 1, 2008
Accelerated Aging in PV Workshop II

B=W

Safety in context: Today's outline

- Our overlap with reliability and availability
- Safety fundamentals and PV
- Contemporary perspectives on PV safety

B=W

1: Safety's overlap w/reliability and availability

- The overlap with reliability and availability is clear
- Except when you're not thinking about it
- Safety-based Codes and Standards promote but do not ensure high performance
- **Safety is Prerequisite** to both R and ψ
  - "Safety has priority over service continuity, equipment damage or economics" - *IEEE*
  - "Safety First!" - *your mom*

1: Safety overlap- reliable meets viable

- Safety information is out there
  - Are we teaching it (yes)
  - Are we heeding it (mostly)

- PV "Not young, not old; but a viable, die-able age" *(w/apologies to author A. Roy)*

Topic 1: Overlap

- Overlap with reliability and availability
  - The ORF, or Operating Reliability Factor, was authored by a different A. Roy. (Lakewood, CO '89). It is a dimensionless measure of both R and ψ.
  - ORF and/or the similar Performance Index, PI, answer the all-important "did I get what I expected?" Other common yardsticks don't.
  - Hard to measure safety.
  - Easier to measure un-safety. Un-safety causes extended shutdowns. Big PV systems are down today because of it. It affects system economics in direct $$ and perhaps 4-8 times more in indirect $$ (Bussman guide, 1998)

Topic 2: Safety Fundamentals

- Education
  - "Working Safely With PV" Sandia/Daystar
  - Bussman Safety Basics
  - IBEW training; others cover safety, too
  - Wiles: "Recommended Practices"
  - CPR training and refreshers
  - Proper PPE
- Codes and Standards
  - OSHA: 29 CFR, Parts 1910, 1926, subs e.g. LOTO 1910.147
  - NFPA70 (NEC): esp. Sec 690.
  - IEEE, IEC, ANSI, ASTM, NESC, UL (& NRTLs), NEMA

Topic 2: Safety Fundamentals

- Electrical Safety
  - Shock (dc and ac thresholds vary; 10ma lethal)
  - Arc (burn susceptibility)
  - Blast (vapors, impact injuries, hearing damage)
- Non-electrical Safety
  - Heat/Sun (UV, dehydration, heat exhaustion)
  - Cold (hypothermia)
  - Falls/Impacts (wind loads less well understood than grounding)
  - Bites
  - Conditions are inhospitable, subjecting installers to near-homeless stresses. The work is repetitive and it can be difficult to stay alert.

Topic 2: Safety Fundamentals

- Safety issues arise
  - During design
  - During installation
  - During servicing
- Design:
  - Codes and Standards (minimums...not design guides)
  - Constructability and serviceability (e.g., NEC does not require rooftop dc disconnects)

Topic 2: Safety Fundamentals

- Installation:
  - Need vigilance and commitment to overcome cultural and traditional barriers
    - El Nuevo - expanding industry, unfamiliar staff
      - But it's cloudy out
      - It's only dc
    - El Macho - grade school posturing, now w/real Tonka Toys
    - El Dinero - pressure to just get it done is pervasive
- Servicing:
  - Buddy system, procedures, equipment
  - Need Code-compliant *permanent* labeling
  - Need accurate as-builts

Topic 2: Safety Fundamentals

- Tools:
  - Multimeter, megger, hot stick, cell phone, fire extinguisher for Class C fires, Listed torque drivers
- PPE:
  - Helmet, gloves, footwear, harness, eye protection, face shield, gauntlets, Nomex as applicable

Topic 3: Contemporary Perspectives

- PV's safety history is pretty good
  - As far as we know (see El Macho on previous)
  - No deaths?
  - Relatively few injuries
    - PVUSA experience helped prompt closer attention
    - UL 1703 and 1741 have improved safety
  - However, enough close calls and recurring installation flaws to warrant renewed emphasis

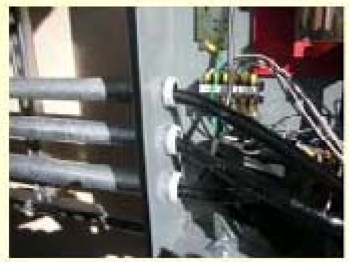
---

Topic 3: Contemporary Perspectives

- Recent issues
  - Roofs have had burns (several occasions)
  - Structures have failed
  - Connections, fuses, boxes have failed

Topic 3: Contemporary Perspectives

- Modern hurdles to safety
  - Some 600 V disconnects not load-break rated
  - Mistaken use of 600 Vac/300 Vdc fuses in 600 Vdc locations
  - Licensed electricians not willing to use torque wrenches, adamant about the darn-tight rule
  - Single-phase installers installing 3-phase equipment (single phase, wire(s) in separate conduits)



Topic 3: Contemporary Perspectives

- Modern hurdles to safety
  - Designers' disdain for NEC 690-8 (156% Isc)
  - Electrical gloves are not stylish enough
  - Inspectors are not uniformly trained well enough to enforce NEC compliance
  - Schools (at least in CA) have a diminished AHJ role and PV vendors don't always follow best practice
  - 600 Vdc fuse susceptibility to reverse wiring and 1,200 Vdc arcing at very low currents. Arcing, at voltages and currents within the design ratings of the components is seen to be an issue of increasing importance (http://labs.ti.bfh.ch/index.php?id=2125&L=2); Fire hazard from shorted panels to metal and even non-metal roofs

Topic 3: Contemporary Perspectives

- Modern hurdles to safety
  - Grounding is dismissed as overkill. Part of the problem is the ambiguity of the requirements, and 2008 NEC is not any better.
  - Laborers are not trained extensively and more prone to burn-out and accidents
    - Improper footwear
    - Improper other PPE for handling glass and heavy equipment
  - Roof leak tests are standard before turnover but dc circuit checks are not necessarily done first
  - Reluctance to conform to NEC wire color coding
  - Theft and vandalism are safety issues, and PV is vulnerable: visible wires, simple mountings.

ALL ABOVE-CITED ITEMS OCCURRED IN 2007!

Topic 3: Contemporary Perspectives

PV Safety Issues: Conclusion

- Industry viability is absolutely dependent on safety, and we are doing pretty well
  - In design
  - In installation
  - In maintenance
- Viability requires vigilance
  - Commitment from management
  - Commitment from field staff
  - Training and supervision

BEW

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Overview of PVP Inverter Development Activities

BACKGROUND

- Since 2004, PVP has developed and marketed over 16 different residential grid-tie inverter models ranging in power from 1.1 to 5.2 kW, as well as two 30kW commercial models.
- All current PVP models offer leading-edge remote web-based data monitoring options.


PVP2500

RELIABILITY PUSH

- PVP has always used low parts count and simplicity as a reliability advantage and continued to improve the reliability of their residential product line, resulting in a third generation platform.
- Recently, PVP has redoubled their reliability assurance effort for new commercial inverter designs culminating in the 100kW inverter, which is designed for a 20-year service life.
- The PVP reliability program has also benefitted directly from our partnership with Boeing in the DoE Solar America Initiative (SAI):
  - Multi-MW high-concentration PV system
  - Low-cost production using multi-bandgap cells
  - $5.9M first-year contract


PVP30kW

PVPowered

Overview of PVP Inverter Reliability Plan

RELIABILITY IMPROVEMENT CYCLE

- DESIGN FOR RELIABILITY
- QUALIFICATION TESTING (HALT)
- PRODUCTION QUALITY CONTROL AND ASSURANCE (HASS)
- FIELD MONITORING / FRACAS
- NEXT GEN

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Overview of PVP Inverter Reliability Plan (Cont.)

- Design for Reliability – 95% of reliability gains are achieved during this phase – requires abnormal engineering diligence.
  - Fully analyze worst-case product usage environment.
  - Build a reliability model for every subsystem and component.
    - Use reliability data from suppliers; MIL-HDBK-217 as a last resort.
    - Perform computational modeling that captures time-dependent stresses and predicts failures in the system.
  - Design the thermal management system with focus on meeting reliability specs.
  - Collect extensive thermal data from prototypes.
  - Redesign subsystems showing low reliability predictions.

INITIAL DESIGN LOOP

- Validate predictions with HALT
  - Use the predictive reliability model to calculate stress acceleration factors.
  - Do not be afraid to break prototypes.
- Assure quality in manufacturing using well-known practices including HASS.
- Perform field verification of performance and reliability using data monitoring, root cause fault analysis, and other tools.

PVP100kW

PVPowered

SunEdison
simplifying solar

System Availability: A Must for Profitable Large-Scale Systems

Accelerated Aging Workshop II
Steve Voss

April 1st and 2nd, 2008

Founded in 2003 to:
- Make solar a meaningful worldwide energy source
- Deliver electricity at or below existing retail prices

The first provider to offer solar energy as a turnkey service
- No capital outlays
- No impact on existing services
- No ongoing customer maintenance costs

The largest solar energy service provider in North America
- 38 MW of 100% renewable electricity under management
- Predictable electricity prices for 10 to 20 years
- Complementary services to existing utility offers

A rapidly growing business
- Maryland Headquarters
- 7 offices in Spain, Canada, US (MD, CA, NJ, HI)
- 350+ employees

SunEdison
simplifying solar

2

Our customers

PORT OF OAKLAND

KOHL'S expect great things

SMUD SACRAMENTO MUNICIPAL UTILITY DISTRICT The Power To Do More.

STAPLES that was easy

Xcel Energy

COSTCO.COM

California Department of Corrections and Rehabilitation

WHOLE FOODS MARKET

STEVENS Institute of Technology

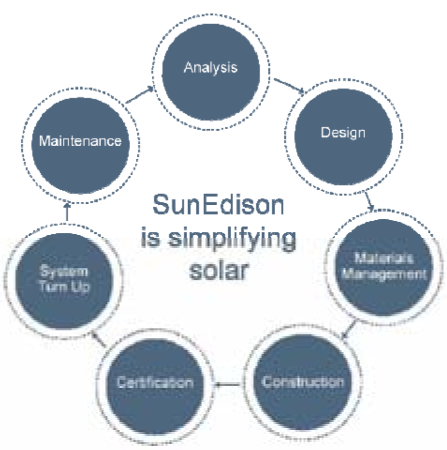
sea gull lighting

SURE SAVE USA SELF STORAGE

SunEdison

3

SunEdison in the value chain



1. **Analysis**
   - On-site engineering evaluation
2. **Design**
   - Comprehensive engineering design
3. **Materials Management**
   - Complete system provisioning
4. **Construction**
   - Total installation management
5. **Certification**
   - Performance validation
6. **Activation**
   - Utility connection and commissioning
7. **Monitoring and Maintenance**
   - Full service, operations and maintenance program

SunEdison

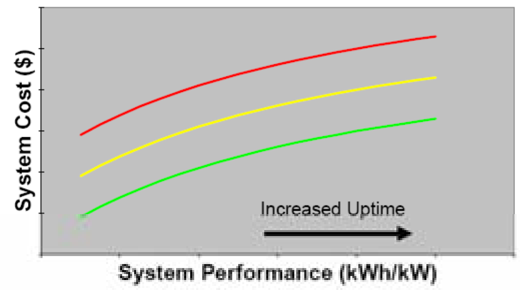
4

The economics of system uptime

SunEdison Fleet Performance Characteristics:

- 2007 fleet energy production was 102% of expected;
- 2007 fleet availability exceeded 97.5%;
- Inverter faults were the most frequently observed events;
- Grid related outages were the second most frequently observed downtime events;
- < 5% of all events caused more than 50% of lost production
- **Real time monitoring and service is essential to minimizing the impact of minor events**

Project Rate of Return



Project IRR:

- Each line represents an equivalent Project IRR
- Lower lines represent higher IRRs
- **Annual degradation rate is another major driver of IRR**

5

Progress since the first workshop: What's New & What's Needed

Tom McMahon and Carl Osterwald

NREL

Purpose

- Review of Progress since first AA mtg.
- Review of NREL reliability capability
- Coring technique to evaluate interface toughness/outdoor weathering correlation.

2

Activities since AA I

- **FMEA study initiated**
- **Coring technique to evaluate interface toughness/outdoor weathering correlation.** *PIP April 2008 pp.1-9*
- **TTF report completed.** *NREL report*
- **Failure mechanisms for the different PV technologies itemized**
- **Expand small systems capability**
- **Added chamber capability**
- **Convene AA II**

3

Standard qual/safety testing:

- Damp heat – 42 days
- 200 thermal cycles – 34 to 50 days
- UV/TC/HF – 35 to 40 days
- Outdoor exposure – 30 to 40 days
- Mechanical load – 2 to 4 days
- Ice ball impact – 1 to 2 days
- Hot-spot protection – 14 to 21 days
- Intermediate tests (I-V, hi-pot, etc.)

4

Other accelerated tests:

- Damp heat with high-voltage bias: thin-film corrosion
- Lengthen standard tests, such as 2000 hours of damp heat or 500 thermal cycles
- Combine damp heat and thermal cycling
- Larger ice balls
- Higher mechanical loads > 2400 Pa
- 24 hour/day light soaking under load

5

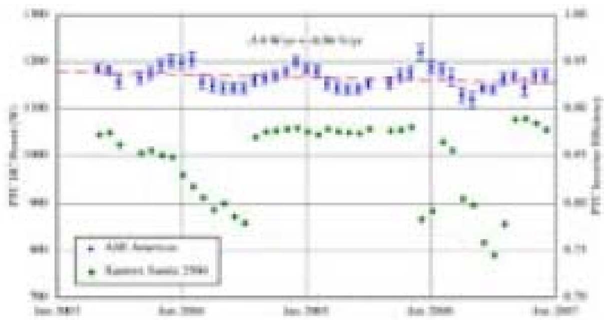
Real-time testing:

- Time-consuming, but absolutely vital
- Should be started as early as possible
- Many times will uncover problems that are not seen with standard tests
- Degradation rates – only way to measure

6

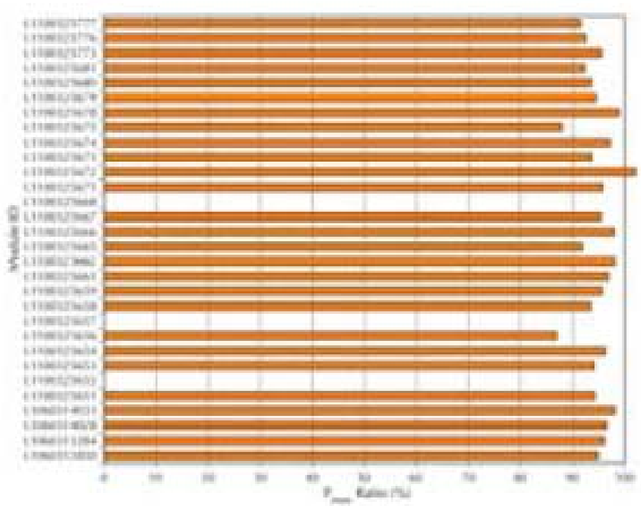
Array degradation rates:

- Module/array power logged real-time
- Monthly multiple linear regressions to PTC equation
- PTC ratings – 1000 W/m^2, 20°C ambient, 1 m/s wind speed
- Linear fit gives degradation rate
- Important for true LCOE



7

Thin Film P_{max} 0-y Data



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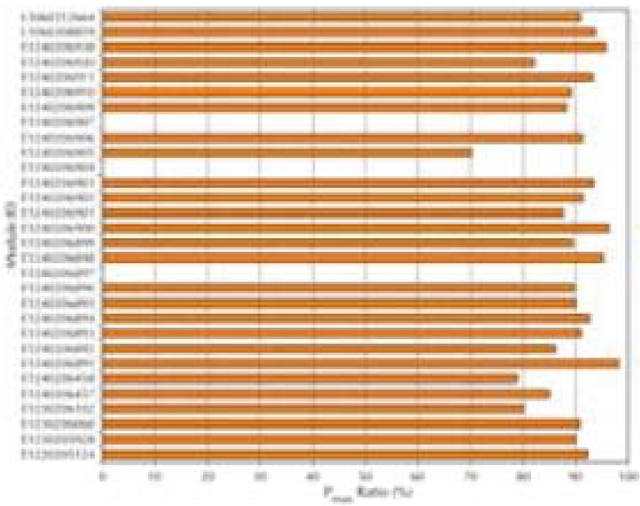
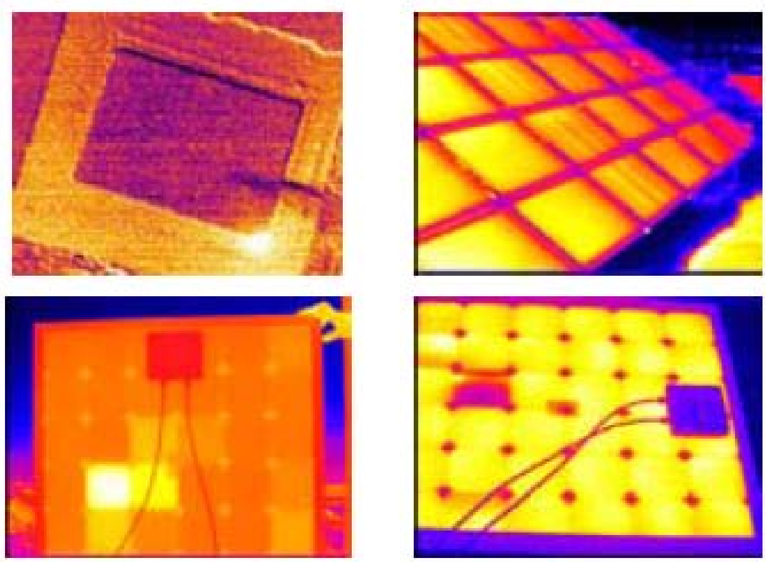
Thin-Film P_{max} 5-y Data



9

IR Camera Diagnostics

Cells to Systems, 0.2 to 50 □C

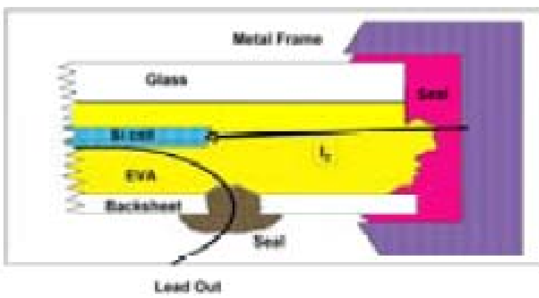


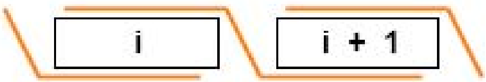
NREL Packaging Team Capabilities

- Characterization
  - Adhesion, cohesion, and toughness; peel, butt and lap shear strength, and torque vs angle
  - Electrical conductivity; surface and bulk
  - WVTR; water transmission, solubility, diffusion
  - Rheology; modulus
- Accelerated tests
  - UV, temperature, damp heat, acceleration factors
- Module and cell diagnostics
  - IR imaging, individual cell shunt, coring , transient currents, internal resistance
- Modeling
  - Moisture ingress and egress
  - Cell-to-frame leakage current
  - Device(AMPS) and Module(PSpice)

11

Wafer Type Module

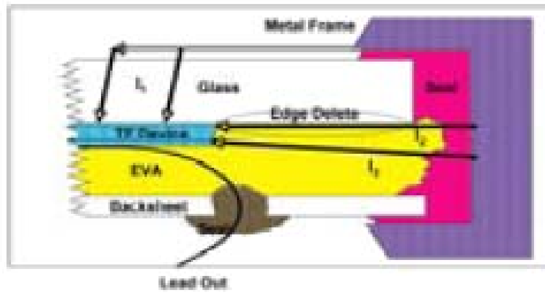


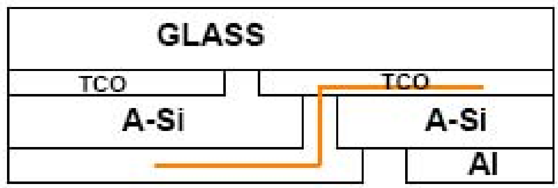


Cell Interconnect

12

Thin-Film Type Module



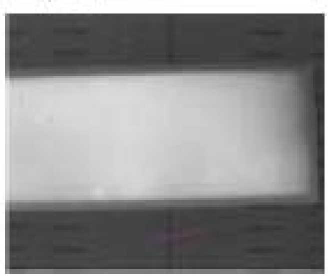


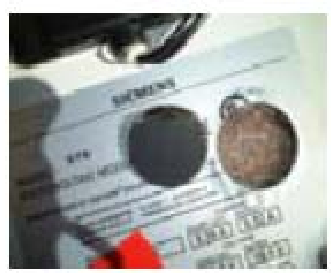
Cell Interconnect

13

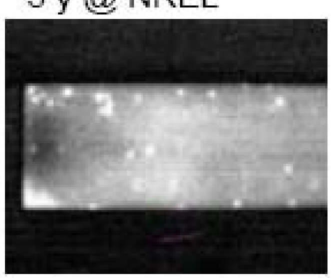
Thermal Imaging, Forward Bias

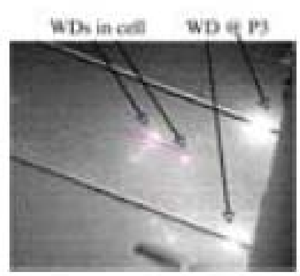
0 y @ NREL





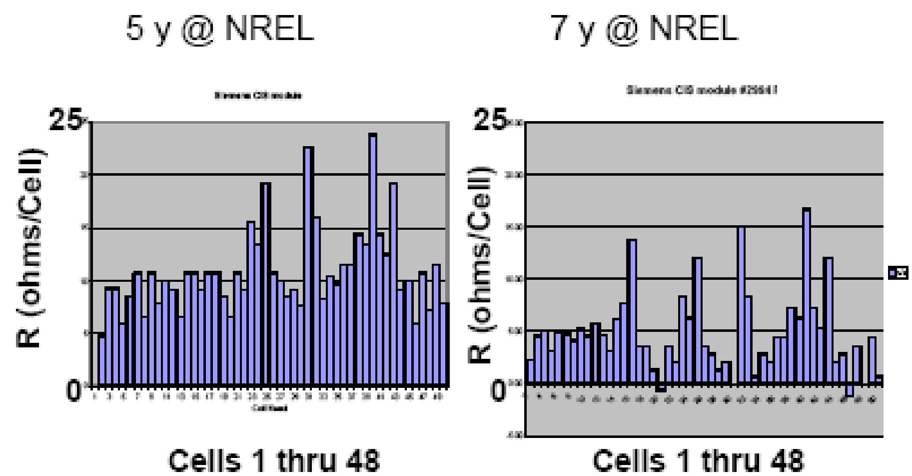
5 y @ NREL





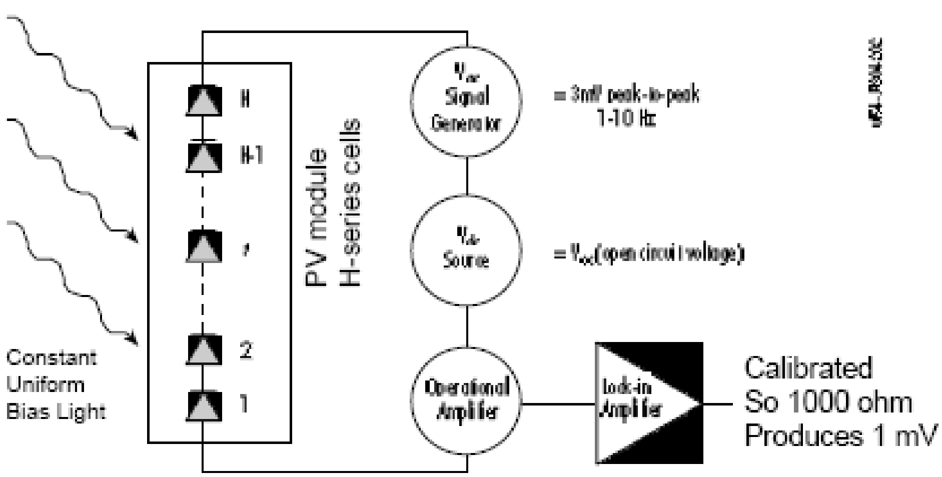
14

Two-Terminal, Non-destructive Shunt Resistance Technique



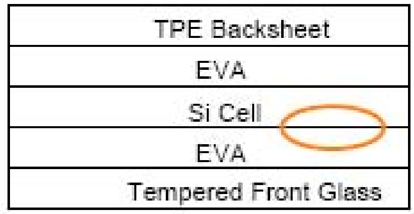
15

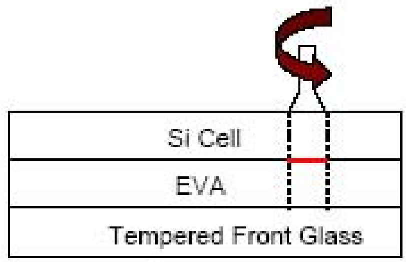
Two-Terminal, Non-destructive Shunt Resistance Technique



16

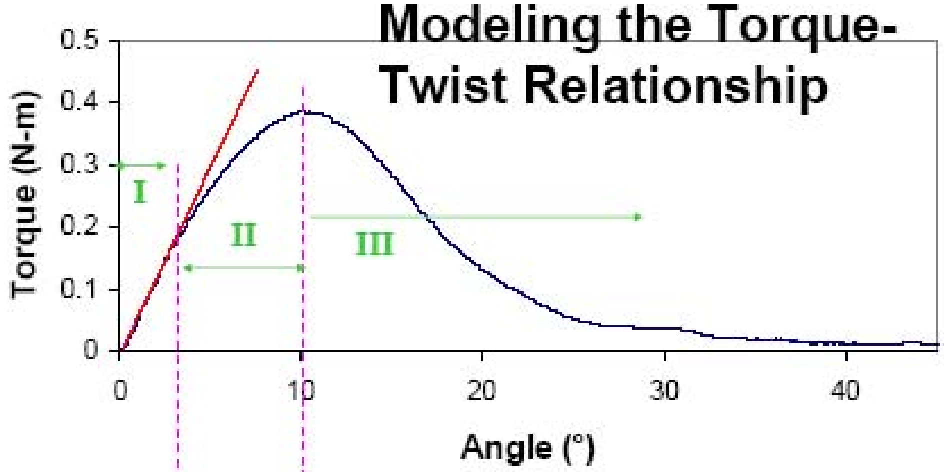
Shear Strength Measurement at Front Cell/EVA Interface

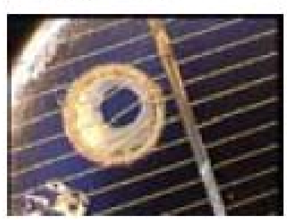


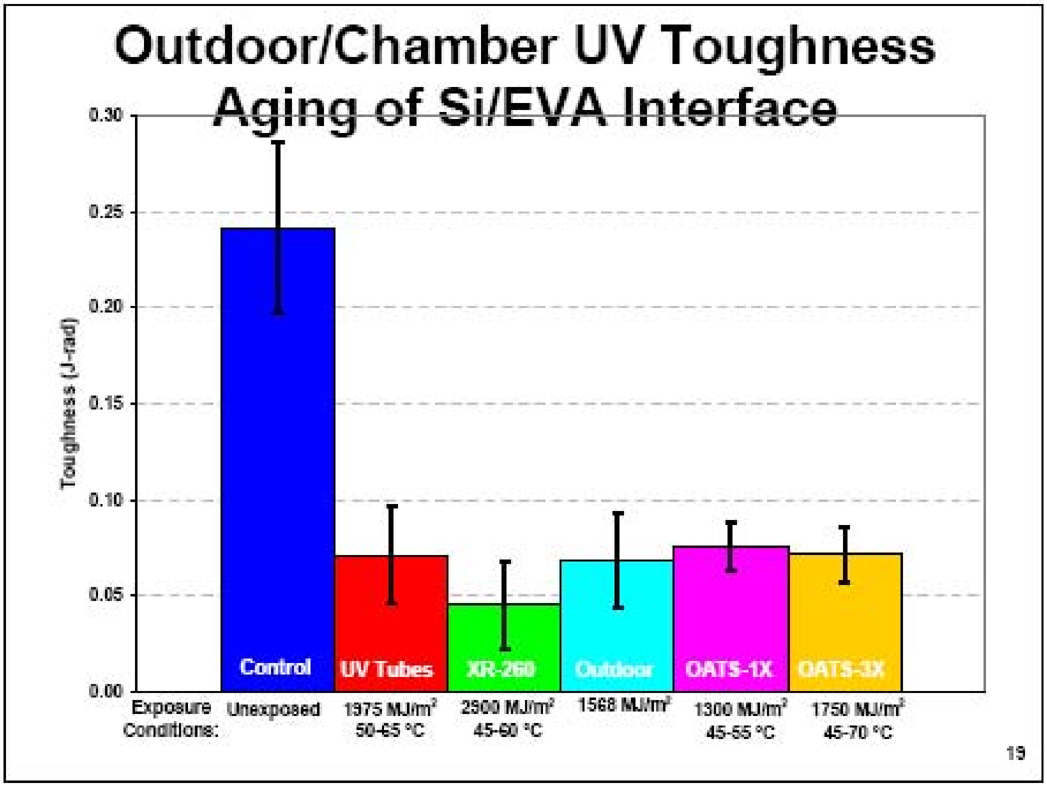


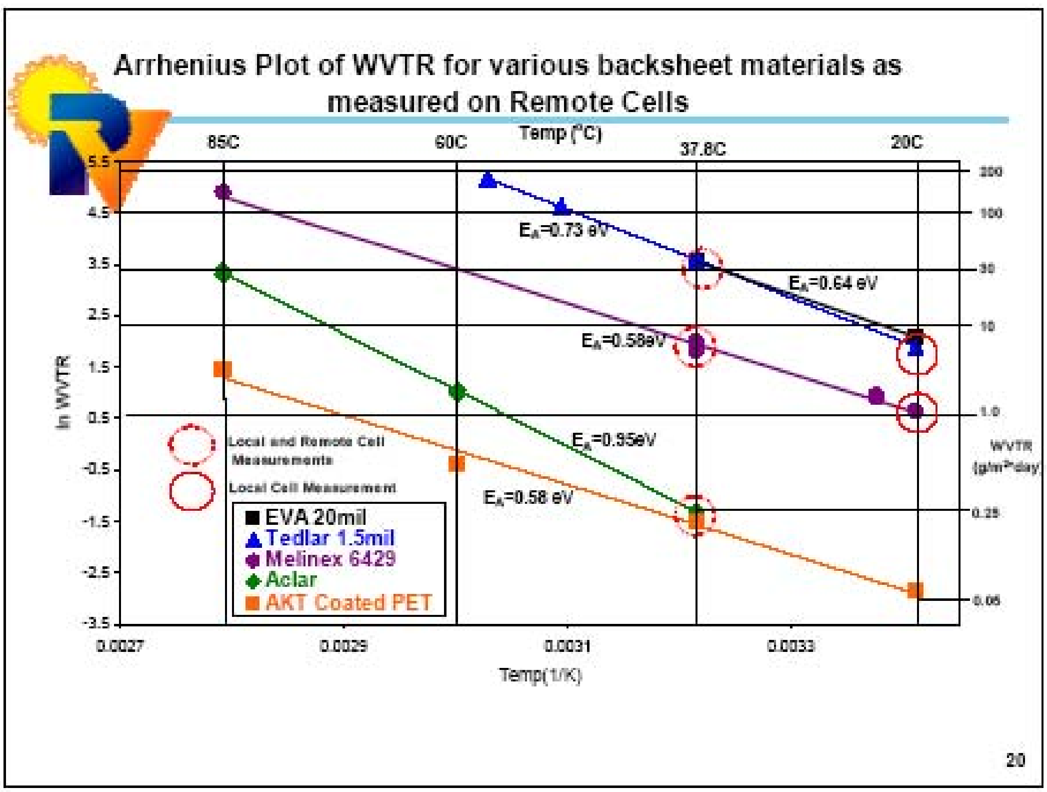
17

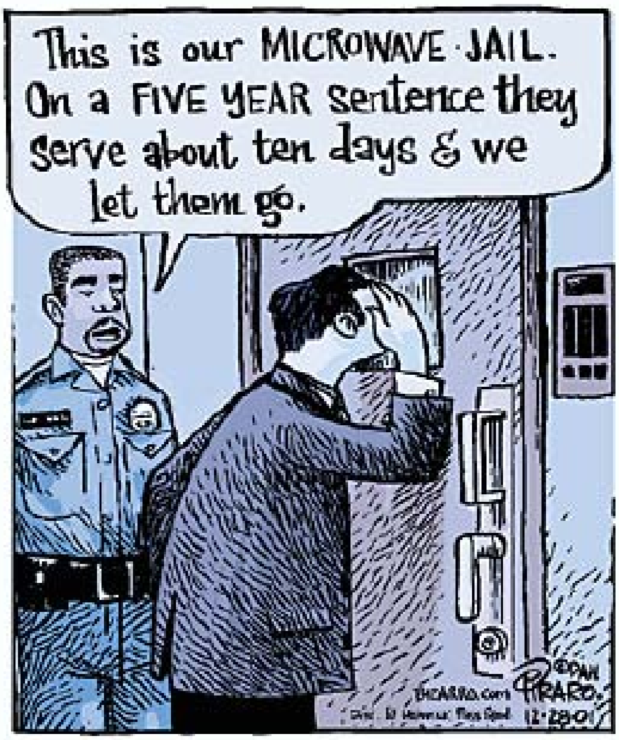
Modeling the Torque-Twist Relationship






Outdoor/Chamber UV Toughness
Aging of Si/EVA Interface
Toughness (J-rad)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Control
UV Tubes
XR-260
Outdoor
OATS-1X
OATS-3X
Exposure Conditions:
Unexposed
1975 MJ/m² 50-65 °C
2900 MJ/m² 45-60 °C
1568 MJ/m²
1300 MJ/m² 45-55 °C
1750 MJ/m² 45-70 °C
19


Arrhenius Plot of WVTR for various backsheet materials as measured on Remote Cells
Temp (°C)
85C
60C
37.8C
20C
ln WVTR
Temp(1/K)
0.0027
0.0029
0.0031
0.0033
E_A=0.73 eV
E_A=0.64 eV
E_A=0.58eV
E_A=0.95eV
E_A=0.58 eV
Local and Remote Cell Measurements
Local Cell Measurement
EVA 20mil
Tedlar 1.5mil
Melinex 6429
Aclar
AKT Coated PET
WVTR (g/m²*day)
200
100
30
10
1.0
0.25
0.05
20



The Universal Need for Correlations with Accelerated Exposures

21

Best Practice for Achieving High Reliability With PV Systems

Accelerated Aging Workshop 2, April 1-2, 2008 Carl Carlson Slide 1

Questions to Consider

- How can a maturing industry benefit from application of reliability engineering?
- What are some of the best practices from other industries?
- What are some of the techniques / approaches that will likely be applicable in PV
- Can reliability engineering be cost-effective?
- Can service life predictions ever be made without enormous amounts of testing?

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Achieving High Reliability is a Business Necessity

Achieving high Reliability requires FOCUS

1. Set well written Reliability requirements
2. Understand the entire system
3. Design in Reliability to products and processes
4. Properly use Accelerated Life Testing as part of overall test plan
5. Ensure supplier parts are reliable
6. Ensure manufacturing processes are free of defects that impact Reliability
7. Execute all tasks through a Best Practice Reliability Program Plan, aligned to Product Development Stages and staying within cost and timing requirements

Link to ALT *All of these Reliability tasks are necessary for successful Accelerated Life Testing*

Accelerated Aging Workshop 2, April 1-2, 2008 Carl Carlson Slide 3

First - What is Reliability?

Reliability is the probability that an item will perform its intended function for a designated period of time without "failure" under specified conditions.

- Statistical measure
- Intended function
- Designated time
- Specified conditions
- Requires precise definition of failure

Traditional "Quality Control" assures that the product will work after assembly and as designed. Reliability looks at *how long* the product will work as designed.

Link to ALT *Always begin with a good definition of Reliability!*

Accelerated Aging Workshop 2, April 1-2, 2008 Carl Carlson Slide 4

"Experience is the name everyone gives to their mistakes"

Oscar Wilde, Irish Playwright

At each stage of the presentation we'll look at some of the major lessons learned from industry

Concept Stage

During the Concept Stage of Product Development it is important to develop and agree on Best Practice Reliability Requirements and get them properly incorporated into Technical specifications and flowed down (allocated) to subsystems and components. Properly specifying reliability at system and component levels can drive the right tasks both internally and with suppliers in order to achieve high system reliability.

Vital Few Reliability Tasks That Support *Concept Stage*

1. Generate System Conditions of Use Operating Profile
2. Develop System Level Reliability Requirements
3. Flow Down Reliability Requirements to Subsystems and Components
4. Generate a System Reliability Model (also called Reliability Block Diagram, RBD)
5. Identify "Reliability Critical" Components and Subsystems
6. Perform System FMEA

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Concept Stage Task Example

Set Well Written Reliability Requirements

1. Reliability requirements are more than numbers
2. Good reliability requirements include certain key elements, such as
   a. Probability statements that are measurable by testing
   b. Linked to functional product requirements
   c. Clear statement of time
   d. Defined customer usage and operating environment
   e. Definition of product failure
3. They must be based on correct statistical models and included in technical specifications
4. One of the best ways to flow down system reliability to components is with a System Reliability Model (Reliability Block Diagram)

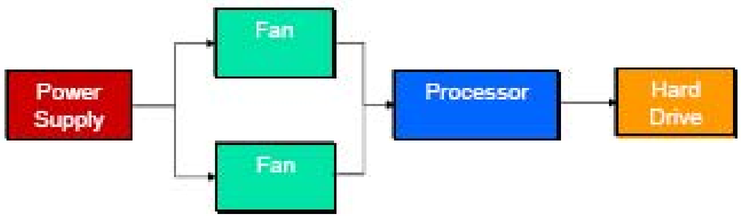
Link to ALT *The information from Reliability requirements is a primary input to Accelerated Life Testing procedures*

Accelerated Aging Workshop 2, April 1-2, 2008 Carl Carlson Slide 8

Concept Stage Task Example

Reliability Block Diagrams
What Are They?

1. A system is made up of subsystems and components that are called "Blocks".
2. Once the block's reliability characteristics have been determined, they can then be connected in a reliability-wise manner to create a Reliability Block Diagram for the system.
3. Each "Block" has its own Reliability distribution and RBD software can integrate into one system level distribution.



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Concept Stage Task Example

Reliability Block Diagrams
How Are They Used?

There are 3 uses for RBDs with PV systems

1. Flowing down system Reliability requirements to subsystems and components so that the overall system meets it's objectives
2. Making system reliability predictions based on individual component life predictions and/or actual test results.
3. Showing areas of highest risk and where to get the most benefit from investing in reliability improvements

Link to ALT *The RBD can be used to set Reliability requirements that become input to ALT and to help with system Reliability predictions based on results from ALT*

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3 Lessons Learned *Concept Stage*

1. Assuming that failures are exponentially distributed and using metrics such as MTBF without data that supports that assumption.
2. Treating all parts as equally important rather than doing risk assessment to identify the "vital few" that are critical for special handling.
3. Failing to properly define the environment and stresses that a product is expected to see as part of Reliability requirements, which can result in lack of robust design or improper test procedures.

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Design Stage

During the Design Stage of Product Development, the vital few tools that support Design for Reliability will be identified for implementation. It is usually not possible to focus only on Reliability testing as the primary way to achieve reliability objectives. It is important to focus on achieving reliability in design, when there are greater opportunities from a cost and feasibility basis. Many of these methods and tools are variously called Robust Design or Design for Six Sigma.

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Vital Few Reliability Tasks That Support *Design Stage*

1. Perform Design Margin Analysis
2. Perform Design and Process FMEAs
3. Address Root Cause of Known Reliability Problems
4. Develop and Use Product Design Guides
5. Incorporate Reliability Input Into Design Reviews
6. Identify and Execute Specific Robust Design Tasks, such as Design of Experiments (DOE), Physics of Failure Modeling and Highly Accelerated Life Testing (HALT)

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Design Stage Task Example

Perform Design Margin Analysis

1. Review the risk assessment for the list of safety and performance critical areas
2. Best Practice is to provide design margin for safety and performance critical design parameters such that these issues do not show up within the system target life.
3. Establish and implement adequate design margins for each critical area. Many companies use a design margin of 2 as a "rule of thumb".

Link to ALT *ALT can verify that adequate design margins have been achieved thus ensuring that serious problems do not show up during product life*

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Design Stage Task Example

Perform Design FMEAs

1. Design FMEAs should begin as soon as subsystem concepts are identified and complete before design freeze.
2. For each FMEA, use best practice procedure
3. Require FMEA to meet FMEA Quality Objectives
4. Include FMEA status and recommendations as part of ongoing management reviews
5. FMEAs that are to be performed by suppliers for reliability critical parts must be reviewed and approved by project core team .

Link to ALT *Results of Design FMEAs are a key input to ALT procedures, helping to ensure that testing discovers all failure modes of concern*

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FMEA Quality Objectives

DESIGN IMPROVEMENTS *FMEA adequately drives Design Improvements*

HIGH RISK FAILURE MODES *FMEA addresses all high risk Failure Modes*

DVP&R PLAN *Comprehends failure modes from the Design FMEA*

INTERFACES *FMEA scope includes integration and interface failure modes*

LESSONS LEARNED *Warranty, Campaigns, Hardy Perennials included*

KCDS CONNECTION *The FMEA identifies appropriate KPC candidates*

TIMING *The FMEA is completed during the "Window of opportunity"*

TEAM *The right people participate as part of the FMEA team*

DOCUMENTATION *FMEA document is completely filled out "by the book"*

TIME USAGE *Effective & efficient use of time by FMEA Team*

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3 Lessons Learned *Design Stage*

1. Waiting for testing to discover design weaknesses; the result is too many problems that have to be fixed with program delays and cost overruns.
2. Using FMEA as a "check-off" rather than doing them properly and reducing risk to an acceptable level (reference FMEA Quality Objectives)
3. Inadequate Design Margins for safety or performance critical parameters, resulting in field problems due to product or process variation.

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Assurance Stage

Improving the effectiveness of reliability assurance and testing will ensure your company develops and launches products with the highest possible system reliability. Properly analyzing test data will markedly increase the effectiveness of all forms of testing to improve product and process reliability. With Product Development times getting shorter and shorter it is essential to accelerate test methods. Doing this properly will not only yield more effective test results but will also facilitate buy in from customers.

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Vital Few Reliability Tasks That Support *Assurance Stage*

1. Develop Improved Reliability Testing Methods, including ALT
2. Develop and Get Approved Reliability Test Plan
3. Conduct Reliability Component and Module Level Testing
4. Conduct System Reliability Growth Testing
5. Verify that Suppliers Meet Supplier Reliability Requirements
6. Implement Ongoing Management Reviews to include test failure data

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Understand Different Types of Reliability Tests

Many types of testing can be used in a Reliability program

1. Qualitative Accelerated Life Testing quickly discovers product weaknesses
2. Quantitative Accelerated Life Testing determines product life using accelerated stresses
3. Reliability Growth Testing can be used to find and fix problems and estimate the eventual product reliability
4. Reliability Demonstration Testing is used to ensure product reliability is demonstrated
5. Etc.

Link to ALT

Accelerated Life Testing is one of many types of testing and it is important to understand when and where it is used

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Assurance Stage Task Example

Develop Improved Reliability Testing Methods

Reliability test procedures should be well researched

1. With direct input from
   a. Technical Specifications
   b. System & Design FMEAs
   c. Field history knowledge transfer
   d. Conditions of use profiles, etc.
2. Based on correct statistical models
   a. Note: Be careful when assuming constant failure rate as this is often incorrect
3. Ideally there is no gap between test results and actual field results and testing reveals actual failure modes

Link to ALT

Use the earlier Reliability tasks to ensure that ALT procedures are correct

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Assurance Stage Task Example

Perform Accelerated Life Testing

Accelerated Life Testing typically includes steps such as

1. Set up test regimens for both normal conditions of use and accelerated stresses, with the appropriate sample sizes.
   a. Remove non-damaging time and events.
   b. Increase stresses such as temperature, humidity and/or vibration, as appropriate.
2. Determine appropriate Life-Stress Models
3. Perform tests at both normal and higher stress profiles
4. Correlate results back to conditions of use operating profile.
5. Publish upgraded Accelerated Life Test protocol.

Link to ALT

The key to planning ALT is a thorough understanding of Life-Stress models and Reliability statistics

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Assurance Stage Task Example

Ensure Supplier Parts are Reliable

1. Select suppliers who are capable of achieving reliability objectives
2. Ensure that reliability requirements are understood and agreed upon by suppliers.
3. For Reliability Critical parts:
   a. Require suppliers to demonstrate that reliability requirements are met
   b. Require project core team review and approve all supplier FMEAs and supplier testing
4. Best Practice is to require these approvals before parts are shipped

Link to ALT *Ideally system testing is performed with reliable components, therefore it is important that suppliers properly use ALT*

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3 Lessons Learned *Assurance Stage*

1. Not modifying test procedures based on expected environments, conditions of use, field histories or FMEAs.
2. Doing system testing with parts that have not been reliability tested by suppliers, which prevents system testing from discovering interface and integration problems.
3. Lack of understanding of Life-Stress models before doing Accelerated Life Testing.

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Manufacturing and Launch Stage

Well done Design for Reliability tasks still need to be supported by Manufacturing and Field Support tasks to ensure that the inherent design reliability is not degraded or unstable. The following are minimum tasks that need to be done to support Manufacturing Reliability.

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Vital Few Reliability Tasks That Support *Manufacturing and Field Support Stage*

1. Develop Preventative Maintenance Plan (advanced application would be Reliability Centered Maintenance)
2. Develop Manufacturing Control Strategies
3. Develop Screening & Monitoring Plans
4. Develop and Implement Field Test Plan
5. Verify All Requirements Met Before Launch
6. Document Field Lessons Learned

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Manufacturing Stage Task Example

Ensure Manufacturing Reliability

Manufacturing processes can be improved and controlled to ensure maximum reliability

1. Use Process FMEA and Process Control Plans
   a. Identify specific reliability Key Characteristics and control them through a manufacturing control plan
2. identify appropriate stress tests to screen or monitor component or batch fitness, as needed
   a. Environmental Stress Screening (ESS)
   b. Highly Accelerated Stress Screening (HASS)

Link to ALT

Manufacturing processes can reduce inherent design Reliability, therefore it is important to implement proper manufacturing controls and screening

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3 Lessons Learned
Manufacturing and Launch Stage

1. Assuming that the inherent design reliability demonstrated during testing will be equivalent to field reliability, and not understanding how manufacturing processes can degrade design reliability.
2. Not taking advantage of preventative or predictive maintenance methods.
3. Using costly 100% screening when other techniques may suffice.

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Program Management

The objective of the Reliability Program Plan is to focus on the significant few tasks that are most effective and applicable to the business of providing highly reliable equipment. The plan specifically avoids a long list of tasks that may exceed company resources and capabilities. In other words, the effort is to stretch and do the right things to achieve high reliability, but to avoid the unrealistic goal of too many tasks requiring too many resources.

Pull It All Together With a **Reliability Program Plan**

Develop and execute a comprehensive Reliability Program Plan

1. Pulls together all necessary resources and tasks
   a. Uses the "Vital Few" Best Practice Methods
   b. Addresses high risk areas
   c. Closes gaps
   d. Strengthens organizational shortfalls
   e. Detailed: What, who, when, where, how
2. Must be approved by management and supported through regular reviews

Link to ALT *Execution of many Reliability tasks are necessary for successful Accelerated Life Testing*

Heroes

"Heard at a seminar. One gets a good rating for fighting a fire. The result is visible; can be quantified. If you do it right the first time, you are invisible. You satisfied the requirements. That is your job. Mess it up, and correct it later, you become a hero."

W. Edwards Deming

Out of the Crisis

Management Role is to create the environment that encourages and supports the correct behaviors to prevent problems and achieve world class reliability.

3 Lessons Learned *Program Management*

1. Lack of management support for reliability tasks, including staffing, software and training.
2. Failure to write and get approved a Best Practice Reliability Program Plan.
3. Not executing the Reliability Plan with regular oversight, debugs and support.

Biography – Carl Carlson (page 1 of 2)

- Currently Senior Consultant and instructor in areas of FMEA, reliability program planning and other reliability engineering and management disciplines, supporting ReliaSoft clients.
- 20 years experience in reliability engineering and management positions at General Motors, with responsibilities including
  - Senior Manager for the Advanced Reliability Group.
  - Design and Process FMEAs for North American operations
  - Developing and implementing advanced reliability methods to achieve/demonstrate reliability requirements
  - Managing teams of reliability engineers.
- Previous to General Motors, worked as a Research and Development Engineer for Litton Systems, Inertial Navigation Division.
- Co-chaired the cross-industry team to develop the Society of Automotive Engineers (SAE) J1739 for Design and Process FMEA

Biography – Carl Carlson (page 2 of 2)

- Participated in the development of the SAE JA 1000/1 *Reliability Program Standard Implementation Guide*.
- Chaired technical sessions for the Reliability Track of the Annual SAE Reliability, Maintainability, Supportability and Logistics (RMSL) Symposium
- Member of the Reliability and Maintainability Symposium (RAMS) Advisory Board for 4 years; received Best Tutorial Award
- Vice Chair for the SAE's G-11 Reliability Division for 5 years
- B.S. in Mechanical Engineering from the University of Michigan
- Completed the Reliability Engineering sequence from the University of Maryland's Masters in Reliability Engineering program.
- Completed more than two dozen short courses in Quality & Reliability tools
- ASQ Certified Reliability Engineer and Senior Member of ASQ

Field Observations and Product Returns – What can we learn?

John Wohlgemuth, BP Solar

INTRODUCTION

- PV modules are designed to work outdoors, therefore observations of the performance of fielded modules are important.
- But why should we be interested in determining how and why fielded modules fail?
- How can we use field and return data to improve our products?
- How can we use field and return data to develop better accelerated tests?

2

Field Observations

- Active – Install product in various climates and observe performance.
- Semi-active – Monitor fielded systems to determine energy production and any long term decrease in output.
- Passive - Analyze product returns

3

Product Return?

- Equate product return with warranty return. Companies promise to replace module under certain conditions.
- Not all returns are "failures".
- Some "failures" are of the system not the product – for example;
  - the wrong product was shipped or
  - Product was damaged during shipment.

4

What is a Failure?

- Customer service definition – Product failed to meet the customer's expectation.
- Technology definition –Product failed to meet specification and terms of warranty.
- Failure can be in terms of different criteria not being met. For modules these are typically:
  - Power/Performance
  - Functionality
  - Safety
  - Workmanship
  - Cosmetics

5

What is a Failure Analysis?

- Determination of why a module was returned ("The claim"). – For example low power
- Determination of whether it is really a failure. – Does it still meet the specification and/or warranty conditions?
- Identification of root cause for failure.
- Remember – Decision to accept a warranty claim is a commercial decision.

6

Why do failure analysis of fielded modules?

- To determine if the sky is falling- That is, are all of the modules you have manufactured and sold likely to fail before the warranty expires.
- To estimate what fraction of fielded modules are likely to suffer the same failure mode. – What warranty reserves ($) do we need?

7

Why do failure analysis of fielded modules? (cont)

- To determine what product changes are necessary in order to eliminate or reduce the potential for this failure.
- To help establish accelerated tests to screen new products for this failure mechanism.
- To identify and communicate potential safety issues with your product.

8

Observations and Measurements Tools

- PV Performance (I-V curve)
  - Normal
  - With shadowing on selected cell(s)
- Dry Hi-Pot
- Wet insulation resistance
- Visual inspection: Looking for any evidence of
  - Discoloration
  - Delamination
  - Embrittlement
  - Corrosion
  - Overheating or burning
- IR camera – forward and reverse bias to see non-uniform heating
- Adhesion of layers, boxes, frames, etc.
- Photoluminescence – Junction integrity and cracked cells
- Materials Analysis

9

Mechanisms for Power Loss

- Broken interconnects
- Bad solder bonds – cells, bus bars or wires
- Cracked cells
- Corroded contacts – cells or wiring
- Corroded thin film layers
- Inadequate isolation scribe lines
- Shorted bypass diodes
- Cell hot spots leading to shunting
- Arcing – ground fault or open circuit due to one of the other causes
- Discoloration of Encapsulant

10

Mechanisms for Functionality

- Glass Breaks – Why?
- Structural Failure – Frame, mounting structure, adhesives
- Junction box/Output Leads no longer attached to module.

11

Mechanisms for Workmanship

- Delamination of Encapsulant
- Frames loose
- Junction box loose
- Any of items from Power or Functionality list before they have reached critical level.

12

Mechanisms for Cosmetics

bp solar

- Discoloration of encapsulant, frames, cover sheet or back sheet
- Foreign items within package
- Misalignment – Cells in package, glass in frame, etc.
- Variations in thin film coating thickness (Semiconductors within thin film modules, AR coatings on cells or on glass)

13

Safety

bp solar

- Exposure to High Voltage
  - Holes in front or back sheet
  - Adhesion of junction box
  - Faulty connectors
- Potential for Fire
  - Ground faults
  - Open circuits: DC arcing
  - Cell Hot Spots

14

Identifying Cause

- Determining root cause (for example low power because of broken cell interconnects) is only the beginning.
- Next question is why did the failure occur?
- Look at samples history.
  - How long in field?
  - Where deployed?
  - What sort of system (anything unusual).
- Is this an isolated occurrence or have we seen this particular failure mechanism before?
- Have you seen this failure as a result of accelerated stress test?

15

Understanding Cause

- To truly understand the cause you must be able to duplicate the failure.
  - This may be done by selecting the appropriate accelerated test.
  - Sometimes it requires longer exposure than normal – for example 500 thermal cycles versus 200 from IEC 61215 or 61646.
  - Sometimes it requires combining stresses – for example adding applied voltage during damp heat to accelerate corrosion.
  - Sometimes it requires adding new tests – for example adding dynamic mechanical loading before TC/HF to see the effects of cracked cells.

16

Using the Understanding

- Once you can duplicate the failure you can use accelerated testing to determine if the failure was due to:
  - A design flaw
  - Poor material selection or out of spec material
  - Workmanship problems
  - Overstressed deployment

17

FUTURE

- Make changes in design, process and/or materials to reduce or eliminate the failure.
- Use your new test methodology to assess future changes in product to assure that failure mechanism doesn't reoccur in later generations.

18

Acknowledgements

- Acknowledge work of those at BP Solar doing the failure analysis work.
  - Jay Miller
  - Danny Cunningham
  - Jay Shaner
  - George Kelly

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Appendix D: Glossary of Terms and Acronyms

AC alternating current
AES Advanced Energy Systems, an inverter manufacturer
ALT accelerated lifetime testing
AR antireflective
a-Si amorphous silicon
a-Si:H hydrogenated amorphous silicon
ASTM American Society for Testing and Materials
ASTM: G154 Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials
ASTM B117 Test Method of Salt Spray [Fog] Testing
ASTM D903 test methods for peel or stripping strength of adhesives
ASTM D1002 standard test methods for apparent shear strength
BIPV building-integrated photovoltaics
BNL Brookhaven National Laboratory
BOP balance of plant
BOS balance of systems
BP – British Petroleum, a PV manufacturer
BSF back-surface field
Btu British thermal unit
c-Si crystalline silicon
CCGT combined-cycle gas turbine
CdTe cadmium telluride
CIGS copper indium gallium diselenide
CIS copper indium diselenide
CPV concentrator photovoltaics
DAS data acquisition system
DC direct current
DER distributed energy resource
DHW domestic hot water
DNFA Determination of Noncompetitive Financial Assistance
DOD U.S. Department of Defense
DOE U.S. Department of Energy
EERE DOE Office of Energy Efficiency and Renewable Energy
EFG edge-defined, film-feed growth
EPAct Energy Policy Act of 2005
EPRI Electric Power Research Institute
EPV – Energy Photovoltaics, a PV manufacturer
ES&H environment, safety, and health
EVA ethylene vinyl acetate encapsulant
FMEA failure modes and effects analysis
FSEC Florida Solar Energy Center (see also RES)
FTA fault tree analysis
FY fiscal year
GaAs gallium arsenide
GaInNAs gallium indium nitrogen arsenide
GE General Electric, a PV manufacturer
GFDI ground-fault detection/interruption
GW gigawatt
GWp peak gigawatt
HALT highly accelerated lifetime testing
HASS highly accelerated stress screening
HCE heat-collection element
HF humidity-freeze test
HF10
HIT heterojunction with intrinsic thin layer
Hi-pot high potential (or high voltage) testing
IEC University of Delaware Institute for Energy Conversion
IEC International Electrotechnical Commission
IEC 60034-18-33 Functional Evaluation of Insulation System-Multifactor Functional Evaluation
IEC 60529 Degrees of Protection Provided by Enclosures
IEC-61215 Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval
IEC 61646 Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval
IEEE Institute of Electrical and Electronics Engineers
IEEE CPMT Institute of Electrical and Electronics Engineers Components, Packaging and Manufacturing Technology Society
IEEE Std 1 Recommended Practice for Temperature Limits and the Rating of Electrical Equipment and for the Evaluation of Electrical Insulations (IEC 60085),
IEEE 98 Std For Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials,

IEEE 101 Guide for the Statistical Analysis of Thermal Life Test Data.
IEC60216 Guide for the Determination of Thermal Endurance Properties of Electrical Insulating Materials
IEEE 1043 IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils, Conduit, Wire, Fittings
FRACAS failure reporting and corrective action system
III-V materials are chemical compounds with at least one group III (International Union of Pure and Applied Chemistry group 13) element and at least one group V element (International Union of Pure and Applied Chemistry group 15).
IGBT integrated gate bipolar transistors
IPP independent power producer
IR infrared
I_{SC} short circuit current
ISO International Organization for Standardization
I-V curve current-voltage curve
kV kiloVolt
kW kilowatt
kg kilogram
kWe kilowatt electric
kWh kilowatt-hour
kWht kilowatt-hour thermal
LCOE levelized cost of energy
LEC levelized energy cost
m^2 square meter
LTE long-term exposure
MBE molecular-beam epitaxy
MMBtu million Btu
MPPT maximum power-point tracking
MTBF mean time between failure
MTBI mean time between incident
MYPP Multi-Year Program Plan
MYTP Multi-Year Technical Plan
MW megawatt
MWe megawatt-electric
NAS National Academy of Sciences
NCPV National Center for Photovoltaics
NDT non-destructive testing
NEC National Electrical Code
NEMA 250 National Electrical Manufacturers Association standard 250 for Enclosures for Electrical Equipment (1000 V Max)
NETA National Electrical Testing Association (renamed to the International Electrical Testing Association)
NFPA National Fire Protection Association
NOCT nominal operating cell temperature
NRC National Research Council
NREL National Renewable Energy Laboratory
O&M operations and maintenance
ORF operating reliability factor
ORNL Oak Ridge National Laboratory
PCU power control unit
PI performance index
PPE personal protective equipment
PPMA polymethyl-methacrylate
PV photovoltaics
PWF present worth factor
QA quality assurance
QA/QC quality assurance/quality control
QC quality control
QD quantum dot
R&D research and development
RBD reliability block diagram
RES photovoltaic residential experiment station (SWTDI and FSEC)
RH relative humidity
RTI relative thermal index
RTV room temperature vulcanizing sealants
S&TF Science and Technology Facility
SAM Solar Advisor Model
SBIR Small Business Innovative Research
SDA systems-driven approach
SET Solar Energy Technologies
SETP Solar Energy Technologies Program
Si silicon
SNL Sandia National Laboratories
SnO – tin oxide
SolarPACES Solar Power and Chemical Energy Systems
SRCC Solar Rating and Certification Corporation
S-W Staebler Wronski cell degradation
SWTDI Southwest Technology Development Institute (see also RES)
TC-ASTR Technical Committee – Accelerated Stress Testing and Reliability, of the IEEE CPMT
T temperature
T-cycling temperature cycling
TBD to be determined

TC-50 IEC Technical Committee 50 Environmental Testing (transformed into TC104)
TCO transparent conducting oxide
TTF test to failure
TMY typical meteorological year
UL Underwriters Laboratories
UL 1703 Underwriters Laboratories standard for flat-plate PV modules and panels
USH2O Utility Solar Water Heating Initiative
UNDP United Nations Development Programme
USSC – United Solar Systems Corporation
UV ultraviolet
V voltage
V_{OC} open circuit voltage
W watt
W_p peak watt
WGA Western Governors' Association
WVTR water vapor transmission rate
XFMEA software tool for failure mode effects analysis
x-Si crystalline silicon

Appendix E: Handout for Initial Breakout Groups

Reliability Consensus

– Textbook definition of 'reliability' as it might apply to our case: "a reliable PV module has a 'high probability' that it will perform its intended purpose adequately for 30 years, under the operating conditions encountered."
– A PV module fails to provide service if its power output decreases by more than 30% before 30 years, e.g., require a loss less than 1%/yr, in its use environment.
– A ' high probability' could mean that 95% of the modules in the field will achieve this success.
– 'Use environment,' we mean any and all use environments that the PV module will experience during service. Site meteorology, handling, and installation are included in use-environment considerations.

FMs: Modules General

Field returns and anticipated failures

- Front Sheet/Encap failure
- Cell/Encap failure
- Back Sheet/Encap failure
- Stress breakage of glass/glass laminate
- Glass edge damage/breakage
- Corrosion of grid lines
- R_{series}
- Poor solder joint(string ribbons and J-boxes)
- By-pass diode failure
- Frame/mounting failure
- Failure of electrical safety

FMs: Modules Technology Specific

Field returns and anticipated failures

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Wafer Si:

- Crack formation in thinner cells
- Solder joint degradation on cells
- Ribbon related open circuit or shunting

Thin Film:

- Flexible packaging interconnect failure
- Laser scribe interconnect failure
- De-adhesion of device layers, inc. CTOs and metal contacts
- Busbar adhesion and electrical contact
- Weak diode or shunt defects
- Decreasing ff (field collection or series resistance issues)
- Moisture ingress problems, esp. flexible with CIS
- Diffusion, esp. Cu in CdTe
- Staebler-Wronski, esp. single junction a-Si
- SnO_2 corrosion in superstrate cells

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FMs: Modules Technology Specific

Field returns and anticipated

CPV (both low X and high X):

- Degradation of optics (abrasion, corrosion of mirrors, yellowing, soiling, etc.) [either use this one or the next ones]
- Corrosion of mirrors
- High-flux damage to mirrors
- Abrasion of optics
- Voids or failures in solder bond between cell and heat sink
- Tracker mechanical breakdown

High-X CPV:

- Tracker pointing error
- Melting of or bubble formation in optical bond between cell and optic
- Cracking of optical bonding material
- Dopant or metal diffusion that affects electrical function
- Cracking of cells

FMs: Inverters and BOS

Field returns and anticipated failure

Inverters

- Failure due to improper torque on dc/ac terminal block
- Oxidation on improper/poor connections
- Breakage due to improper packaging (securing of heavy components e.g. transformers, capacitors, inductors)
- Failures due to tracking on PCB
- Failure of LCD display
- Mis-operation/failure of inverter integrated ac/dc disconnects
- Loss of communication
- Failure due to loss of active cooling component (s)

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FMs: Inverters and BOS

Field returns and anticipated failures

Inverters

- Loss of sensors
  - temperature
  - current
  - voltage
- Improper/loss of surge suppression devices
- Loss of control circuitry
- Failure of power supply (PCB)
- Failure of power electronic drive circuitry
- Failure of power electronic device/protection circuitry
- Failure of capacitors/inductors other filter components

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FMs: Inverters and BOS

Field returns and anticipated failures

BOS

- **Failure of string combiners (element intrusion)**
- **Fuse failures**
- **Conductor insulation breakdown**
- **Improper torque on connectors**
- **Improper connectors**
- **Failure of disconnects**
- **Failure of isolation transformers**
- **Loss of surge suppression devices**
- **Loss of GFI circuitry**
- **Loss of communications**

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AA Tests to Reveal Dominant Failure Modes

- Commonly agreed dominant failure modes and required testing :
  - Primary thin-film accelerated aging tests to reveal their dominant failure modes (device instability, corrosion, delamination, interconnects, and packaging integrity) are 1000h 85%rh/85°C, Thermal cycling with current bias, and 1000h light soak. Use I-V and IR imaging characterization.
  - Primary crystalline silicon accelerated aging tests to reveal their dominant failure modes (soldering, μ-cracks in thin-cells, and corrosion) are 1000h 85%rh/85°C, thermal cycling with current bias, and ???. Use I-V and IR imaging characterization.
- Less well understood failure modes and required testing :
  - Primary concentrating system accelerated aging tests to reveal their dominant failure modes (breakdown of electrical insulation, interconnect failures, corrosion, bypass diode failure, and misalignment of components) are Wet and dry insulation tests, thermal cycle tests of 500, 1000 or 2000 cycles at respective maximum temperatures of 110 C, 85 C or 65 C (depends on materials under test) with current bias, 85% humidity-freeze thermal cycling, bypass diode heat test, and off-axis beam damage test.(thanks Bob McConnell).
  - Service life prediction AA testing requires detailed knowledge of all the failure modes for each of the module types produced in all use environments; if change in parts, design or materials supplier occurs, a new SLP must be conducted!!! We instead propose establishing a test protocol for the dominant failure modes for the established technologies first, followed by the developing technologies next. This protocol will have predictive capability and be a major undertaking.

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