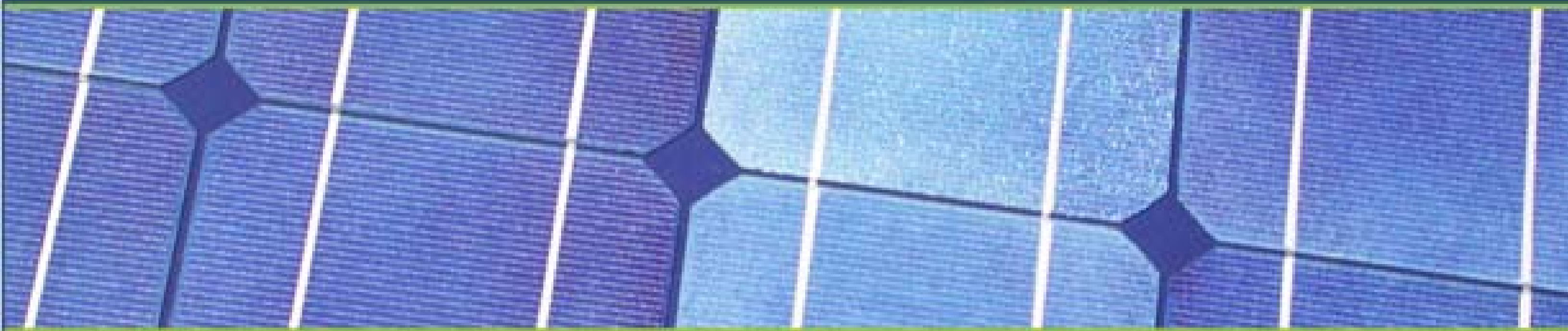

SOLAR ENERGY TECHNOLOGIES PROGRAM

Accelerated Aging Tests in Photovoltaics
Summary Report

Sponsored by:

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Solar Energy Technologies Program

Authors:

Dan Ton, U.S. Department of Energy
Joe Tillerson, Sandia National Laboratories
Thomas McMahon, National Renewable Energy Laboratory
Michael Quintana, Sandia National Laboratories
Kenneth Zweibel, National Renewable Energy Laboratory

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Executive Summary

The solar photovoltaic industry is expanding at rates that were only dreams a few years ago. Multiple new manufacturers (some with new PV technologies) are seeking to gain entry into the marketplace and existing manufacturers are aggressively expanding their manufacturing lines. Changes in processes and production rates, evaluating materials from new suppliers, and bringing new plants on line all offer significant challenges to product quality. Engineers in every plant are concerned with assuring the quality and reliability of their products. It is very understandable then that the desire for high quality, validated testing techniques is also at an all-time high. 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). They also 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 in this industry. Expanded understanding of accelerated aging testing technology will be pivotal in furthering the credibility of this growing industry.

Discussions with industry and observations by U.S. Department of Energy (DOE) and National Laboratory staff identified a growing interest in the problems and opportunities associated with accelerated aging tests in photovoltaics. As a result, a technical meeting was held near Baltimore, MD on February 22-23, 2006 to gather information that would help DOE in its research planning and prioritization by establishing:

- the current status of accelerated aging tests in photovoltaics – what tests and equipment are used, how they are applied, how the results are used, and the limitations of current methods;
- where accelerated aging tests need to be improved – methods, applications, understanding of results, capabilities, costs and other factors; and
- what the priorities should be for improvement

Nearly 70 of the nation's leading PV researchers, module manufacturers, systems integrators, and equipment manufacturers actively participated in the meeting. The industry representatives described the types of decisions that can and cannot be made today based on the current testing protocols. This information allows the R&D performed in the DOE Solar Energy Technologies program related to accelerated aging to be focused directly on the industry's highest priority needs.

This report documents the meeting. The meeting format, technical presentations, and the content of the breakout sessions in which industry representatives openly discussed and debated the status, needs and priorities for accelerated testing are described in the body of the report. The principal priorities resulting from the technical meeting are summarized below in Table 1. This is followed by summaries of the status, needs, and priorities established in separate breakout sessions held on photovoltaic systems, modules, and devices. The overwhelming conclusion drawn from the meeting is that results from current accelerated aging tests are much more than a research curiosity and are in daily use throughout the industry as a decision-making tool. With new technologies and larger-scale manufacturing processes continually being used, substantial expansion and extension of the techniques are needed now to assure even better, more reliable PV

energy systems. Additional, targeted technical meetings are planned for 2007 to evaluate specific test protocol improvements.

Table 1: Priorities for Accelerated Aging Test Improvements

Priorities for Accelerated Aging Test Improvements	
Crosscut	Crosscutting needs and priorities for accelerated aging testing: • Reliable correlation between Highly Accelerated Lifetime Testing (HALT) and actual performance in the field that will help HALT actually predict lifetime as well as performance • Understanding of true mechanisms and sources of failures and degradation and their relationship to what HALT measures • Open database that effectively deals with sensitivities surrounding information on equipment failure, HALT results, and proprietary information on materials and manufacturing processes • Get beyond pass/fail modes of testing – need to predict impact of changes • Evaluate real world deployments to quantify successes and failures • Test for multiple variable impacts, conditions more extreme than standard test conditions, and components as they exist in a system or subsystem
Systems	Development of systems-level predictive model that utilizes comprehensive component aging/lifetime data and yet-to-be-developed transfer functions to accurately predict system lifetime
	System test protocols, including field test protocol w/o acceleration
Modules	Establish correlation between time-to-failure in accelerated testing and time-to-failure in field observations for dominant failure mechanisms, e.g. corrosion and delamination in thin-film modules and corrosion and solder bonds in Si-type modules.
	Central clearinghouse (database) on accelerated testing and failure data is needed; should contain existing DOE and DoD data, test protocols, and dominant cause of failure (listed by applied stress or mechanism) with privacy maintained on data sources
Devices	Thin films, particularly CdTe and CIS, need an improved base of scientific knowledge (e.g. issues of water vapor, uniformity, encapsulation, etc.) to understand root causes of current issues.
	For established technologies, faster tests are needed for stability evaluations and problem identification, especially for assuring quality control during design and process changes.

Systems Breakout Summary

The Systems Accelerated Aging sessions had roughly 15 attendees representing industry, labs, universities, and DOE. Assessing the status of accelerated aging came quickly since there are no standard accelerated aging procedures for systems at this time. This may be attributed to the business model currently in practice in which each system is a “near one-of-a-kind” that is designed for the application and installed by an integrator/installer with components that meet design requirements. Definition of needs quickly addressed where effort should be focused. The industry needs models that integrate information on aging/lifetime prediction of components and a suite of transfer functions that will accurately predict system lifetime; thereby assisting in system design. These models need to incorporate information from accelerated aging, extreme climate exposure, and degradation studies in lab and field environments. Data needs to be a result of standardized test protocols in order to provide accuracy in the integration process. Additionally, the models need to address a variety of PV applications; from ground mounted systems, to trackers, to building integrated systems in environments such as high humidity, high wind, salt spray, and extreme cold conditions.

The priority proposed was to take a systems level approach to develop a predictive model. Comprehensive component lifetime data from standardized test protocols combined with yet-to-be-developed transfer functions forms the basis of the model that incorporates information from lab and field studies of components and systems that exemplify real world stresses. The following table summarizes the status, needs and priorities for systems accelerated aging tests discussed at the meeting.

Table 2: PV Systems Accelerated Aging Tests - Status, Needs, Priorities

	PV Systems Accelerated Aging Tests - Status, Needs, Priorities
Status	No standard accelerated aging tests exist for integrated PV systems – components and subsystems at best
	Lab-scale system testing is done under some controlled stress conditions
	Field-aging is done at nominal (local) operating conditions – no acceleration
	Inverters and Charge Controllers: Manufacturers standard testing includes HALT, thermal, UL1741, component qualification, efficiency, performance, humidity, salt/fog, moisture intrusion, HASS, and some field aging testing (unaccelerated),
	Mounting hardware: Manufacturers' standard tests include corrosion, static/dynamic loads, vibration, parts qualification, grounding (limited), building code compliance, fire codes, wind, tracking performance and controls, installer certification, shipping
	Wiring: Installer training and certification, manufacturer tests (e.g., code evaluations, connectors, terminal strips, wire splices, moisture intrusion)
	Switch gear: Manufacturer tests include meters, instrumentation, batteries, data acquisition, installation (code, installer tolerance)
	Software: Industry standard, UL1998, system performance, limited networking
Needs	Comprehensive accelerated aging on components; model data into a screening criteria for system lifetime prediction
	Protocols for testing systems; test matrix
	Performance testing of systems in extreme field conditions
	Operate systems that can be stressed and tested in field or lab to develop knowledge beyond nominal
	Transfer functions from testing to lifetime prediction—a predictive mechanism
	System simulations in controlled conditions or chambers to help validate transfer functions
	Study field-aged components and apply data to system models
	Extreme conditions system testing (hot, humid, dry, salt, windy, seismic, etc.) – several test facilities are available
	Procedures and protocols to detect small change- early intervention; preventive approach
	Test protocols for BIPV components for modular housing - specific to the application
	Accelerated aging test capabilities for BIPV prototypes
	Develop analysis framework for system integrators to predict system performance w/aging
	From paper analysis to operational analysis
	Accurate data/analysis of ~10kW building block size; larger systems will be scaleable

Priorities	Systems-level predictive model that utilizes comprehensive component aging/lifetime data and yet-to-be-developed transfer functions to accurately predict system lifetime • Approach to apply existing and new tests at a systems level • Test facilities for: UV, temperature, humidity, wind, ambient conditions • Field data collection in key climates (e.g., CA) and extreme climates • Extraction of field-aged actual samples to broaden existing database of aged systems • Model transfer function from accelerated aging tests to lifetime prediction • Applicable to utilities, commercial, residential, off-grid, and BIPV
	System test protocols, including field test protocol w/o acceleration • Identify external existing resources, facilities and protocols that PV industry can use • For components: standardized HALT protocols, test matrix, independent performance and certification testing
	Better tools for • gathering accurate data from field (faster, remote operations, accurate, portable) • communication (e.g. standard communication protocol for all inverters/systems) • systems certification to provide assurance of system quality (including results from models of aged system)

Modules Breakout Summary

The PV Modules Accelerated Aging breakout group had the largest number of attendees with representatives from industry, university, and government laboratories. Comments addressing the Status, Needs, and Priorities were freely expressed, recorded and summarized in the table below. The highest priority item was to establish a correlation between time-to-failure in accelerated testing and to time-to-failure in the field. In doing this we noted that the same mechanism must be tracked and field environmental conditions noted. A data base for different field failure mechanisms needs to be tabulated and perhaps DOE has a start on this. The most useful diagnostic measurements are listed as: I-V, IR camera, Hi-pot wet and dry, Visual inspection, Layer adhesion-peel and torque shear.

Of a general nature, we agreed that we should have continuing studies by members of this group to address the more commonly occurring mechanisms. Adhesion and corrosion were mentioned along with solder bond and interconnect issues. The goal would be to determine acceleration factors, i.e. establish correlation, for the dominant failure mechanisms. The table below summarizes the status, needs and priorities for module accelerated aging tests discussed at the meeting.

Table 3: PV Modules Accelerated Aging Tests - Status, Needs, Priorities

PV Modules Accelerated Aging Tests - Status, Needs, Priorities	
Status	Commonly used standardized tests include: Thermal cycle with and without current flow, Damp heat exposure, Humidity-freeze cycling, Hail impact, Surface cut, 45° cut (UL-1703) evaluation by wet hi-pot, Dynamic and static mechanical loading, and other elements of IEC 61215 or 61646 qualification test sequences
	Non-standard tests commonly used include: ASTM: G154 70°C, >1,000 hours; B117 5% salt solution, 35°C, 96 hr. cycle 48 hr wet, 48 hr. dry (salt/fog); D903 180° peel strength; D1002 shear test single-lap-joint
	Non-standardized tests for Flexible Modules include: Unique tests for flexible modules to capture coiling, flexing and forming characteristics, heat/humidity/sunlight/high voltage, delamination test TCOD 15, solder bond failure

	Non-standardized tests for Rigid Modules include: vibration tests for shipping, dynamic load testing, static load testing, non-uniform wind loading, dynamic testing in wind tunnels, exterior temperature testing, current based TC50 and HF10, voltage bias
Needs	Needs in test protocols and in correlating lab test results with field observations • Test capabilities/methodology validation: determination of what is an effective accelerated test, how accelerated can you go? Identifying changes or degradation, not just failure. Finite elements analysis. Combine and simulate multiple stresses, high and low levels of multiple variables. Ability to monitor panels in-situ as they are stressed. Ability to isolate stress concentrations. • Accelerated tests for reliable predictions – how to establish warranties • Correlation of accelerated tests to years in field. • Common failure modes established, i.e. corrosion, thermal cycle, breakage, etc. • Get to field to test/identify older modules to study for success/failure • Documented field conditions: develop standard field test protocols to gain consistent data;. What do they say about what to test – agreed conditions to warrant • Documented causes of most field failures • A meaningful test to predict end of life • Some improvement testing for manufacturing problems • Ability to apply voltage during humidity tests, UV
	Improvements needed specific to HALT and HASS testing: • HALT and real world tracking, correlation, testing • HALT outdoor capabilities – concentrating, light, heat etc. • HALT and HASS – are they only for new products? Apply more broadly to thermal cycling, freeze, ER, use for comparisons
	Needs in data collection and in accelerated aging data base development include: • Central clearinghouse/database for information, protocols, data • Documented module specifications, materials used, and characteristics • Detailed characteristics of material properties • Need to handle problems/failure anonymously • Collect data from manufacturers • Data on environment and installation conditions including product history • Data collection needs to be made in consistent, unbiased ways • Determine failures caused by damp heat and then vary to see what combination causes specific failures including corrosion -- do damp heat tests really show what happens in the field? • Access to existing data – OTF 1200 module testing for pass/fail, lessons already learned form JPL and past history on solder bonds, thin cells, lamination, interaction of layers, etc. • Energy output, other indicators like temperature, standardized ways of measuring in field, wind speed, kWh ratings and what they say for tests under different conditions
	New field tests: in different climates, exposure to conditions outside of standard tests, combinations of conditions, stress/deploy/test.
	Comprehensive tests for current and new materials and designs. Issues: alternatives to aluminum, unframed modules, frame alternatives, different glass/encapsulant, polymer aging and power delivery components like wire and connectors.
	Resources/Approaches: Money for equipment and expensive testing; access to multiple chambers and test runs; people to analyze and put information in useful form; work with new universities to tap their resources; new collaborative activities; approach to make module size samples uniform.

Priorities	Establish correlation between time-to-failure in accelerated testing and in field observations for dominant failure mechanisms, e.g. corrosion and delamination in thin-film modules and corrosion and solder bonds in Si-type modules. • Establish generic (most important for common module designs) problems/failure mechanisms; e.g. (1) adhesion, (2) cracks in cells (especially thinner cells of the future) and glass, (3) interconnect, (4) EVA • Assess protocols in detail to correlate to failure mechanism • Identify acceleration factors for dominant failure mechanisms Establish correlations of HALT to field results; Use of existing data, track the same failure mechanism.
	Central clearinghouse (database) on accelerated testing and failure data is needed; should contain existing DOE and DoD data, test protocols, and dominant cause of failure (listed by stress or mechanism) with privacy maintained on data sources • Create checklist of ALT procedures (standard actions before getting a sample) • Quantify total module production (# in field, # failed, modes) • Inventory and document control modules' characteristics • Document environmental characteristics: UV, irradiation, climatological, installation details • Protocol, determine stresses and sequence of stresses Most important diagnostic tests to acquire data for ALT, HALT and field returns: I-V, IR camera, hi-pot wet and dry, visual inspection, layer adhesion-peel, torque-shear tests
	Develop and assess testing protocols for emerging technologies

Devices Breakout Summary

Within the Device Testing group, we quickly realized that most device level issues fall into two areas:

1. Testing of new technologies
2. Testing of existing technologies during design and process changes; and periodically to assure quality control

Among the PV technologies, existing silicon and III-V technologies fall into the latter category; CIS and CdTe thin film technologies fall into the former *and may require the most emphasis*. If and when new technologies are evaluated to be promising for deployment, the same set of priorities should be extended to cover their needs.

The table below summarizes all of the status, needs and priorities discussed in the devices breakout session. The group that met to discuss accelerated tests of PV devices had no representatives outside thin film technologies so this portion of the report may not adequately cover other technologies.

Table 4: PV Devices Accelerated Aging Tests - Status, Needs, Priorities

PV Devices Accelerated Aging Tests - Status, Needs, Priorities	
Status	Evidence that III-V and X-Si are stable and rugged, except for a small light-induced loss in some higher efficiency x-Si cells (except for thinner cells which are showing a greater propensity for cracking).
	Evidence that all thin films have some device level instability issues (which can vary by device design and processing), and that CIS and CdTe have greater sensitivity to water vapor than silicon. Evidence that despite this, properly made and encapsulated devices may have adequate stability. Recognition that the challenge is to understand the mechanisms and map the range of process variables needed to assure stability.

	CdTe: 56-day light and heat exposure of CdTe at Voc (60-90 C), Electron beam induced current, laser soak (1-10 suns), monitor decay in photoluminesence intensity
	Optoelectronic analysis of pre- and post-stressed devices
	Uncertainty about gross- and micro-nonuniformity issues and impacts on degradation; initial papers and some experiments
	Early experiments with broadening the CdTe stress test to all thin films: temperature (<= 100°C), light (<2 suns), moisture, diurnal cycle, efficiency over time (capture degradation/stabilization)
	Uncertainty if there are slow or delayed degradation mechanisms that might occur in thin films after many years of apparent stability.
Needs	Recognition that thin films have the most existing and unknown problems, and among the thin films, a-Si is the most fully characterized at the device level, and most issues are well handled. Thus CdTe and CIS require the most attention at the device level.
	Both CIS and CdTe need greater scientific understanding (complexity of issues prevents understanding and fixing root causes)
	CIS and CdTe need faster, simpler, non-proprietary tests that are not misleading
	Cells must be tested enough to develop statistics; and in enough variety to span the range of processes and process variations.
	Correlation must be established between tests (e.g., the current 56-day test) with day/night cycling and other real world conditions
	A nonproprietary database should be developed to allow sharing. Issues of corporate sensitivity must be addressed.
	Small cells are not sufficient samples for establishing loss mechanisms: minimodule with interconnect features are needed to span gap from full module to cells. Both interconnects and area-nonuniformity are sources of loss mechanisms.
	Testing and stressing must be continued as cells progress through often-rapid process and design changes. New technologies and even established silicon and III-V devices may be vulnerable to such changes and need to be periodically analyzed.
	Some aspects of device testing require substantial investment in equipment and people; locating them at one location can allow for shared solutions
Priorities	Thin films, particularly CdTe and CIS, need an improved base of scientific knowledge (e.g. issues of water vapor, uniformity, encapsulation, etc.) to understand root causes of current issues. • Tests of CdTe and CIS devices are the highest priority; • CdTe and CIS need faster tests for stability and problem identification • Understanding of the greater sensitivity of CIS and CdTe to water vapor is needed: what are the areas most prone to losses? All thin films could use investigation of new water vapor barrier layers. • All thin films need understanding of the chemical impact of EVA and other encapsulation choices on devices • All thin films (but especially CIS and CdTe) need tests of mini-modules for uniformity and interconnect issues • CdTe and CIS need development and validation of specific protocols for long term performance assurance
	For established technologies, faster tests are needed for stability evaluations and problem identification, especially for assuring quality control during design and process changes. • Faster tests that correlate well with field observations of degradation are needed • All device technologies need periodic tests and tests after changes in design or processing.
	A nonproprietary database needs to be established, including device data (degradation, losses, analysis) and correlation with fielded arrays

Introduction

Discussions with industry and observations by DOE and National Laboratory personnel identified a growing interest in the problems and opportunities associated with accelerated aging tests in photovoltaics. The U.S. Department of Energy Solar Energy Technologies program engaged Joe Tillerson and Michael Quintana of Sandia National Laboratories with Tom McMahon and Ken Zweibel of the National Renewable Energy Laboratory, to explore the issues surrounding accelerated aging tests and define opportunities for more effective testing and application of the results. Working with Dan Ton from the DOE Solar program, this group organized a technical meeting with leading PV researchers, module manufacturers, systems integrators and equipment manufacturers to gather information that would help DOE in its research planning and prioritization by establishing:

- the current status of accelerated aging tests in photovoltaics – what tests and equipment are used, how they are applied, how the results are used, and the limitations of current methods;
- where accelerated aging tests need to be improved – methods, applications, understanding of results, capabilities, costs and other factors; and
- what the priorities should be for improvement

This report documents the technical meeting.

Background

The solar photovoltaic industry is expanding at rates that were only dreams a few years ago. News reports abound regarding important and positive industry happenings and predictions of even further growth, including:

- Venture capitalists "put more than $150 million into U.S.-based companies such as Advent Solar, Energy Innovations, Heliovolt, Miasole, Nanosolar, and PowerLight in 2005 -- double the investments in 2004." [1]
- "Solar companies accounted for the three largest technology IPOs last year, raising more than $800 million" [2]
- "To meet this strong demand, manufacturers are rapidly investing in production capacity" [3]
- "Given the rapid growth in new solar capacity, solar will likely make up some 5% of the total annual capacity additions worldwide by 2010" [4], and
- "Everything in the solar market is poised to explode: capacity, sales and competition."[5]

[1] Makower, Joel, Pernick, Ron, and Wilder, Clint. "Clean-Energy Trends 2006", CLEAN EDGE, p.4.
[2] Wong, Grace, "VC firms are seeing green in energy," CNNMoney.com, April 26, 2006.
[3] Stauffer, Nancy, "Solar Power Through 2015: Re-evaluating Its Potential", ESD Reports, Summer 2005.
[4] Stauffer, Nancy, "Solar Power Through 2015: Re-evaluating Its Potential", quotation of graduate student Michael Rogol, ESD Reports, Summer 2005.
[5] Roston, Eric, "A Web Vet Gives Solar a New Shine," TIME global business BONUS Section, December 4, 2005.

Multiple new manufacturers are seeking to gain entry into the marketplace and existing manufacturers are aggressively expanding their manufacturing lines. New processes are being validated to increase manufacturing capacity. New suppliers of component materials are coming on line. Product markets are growing at unprecedented rates with significant federal and state impacts. Emerging technologies are entering the marketplace. In this time of unparalleled growth, the pressure to produce products is intense and the industry cannot afford large numbers of failures that would cause a “black eye” for photovoltaic technology.

Changes in processes and production rates, evaluating materials from new suppliers, and bringing new plants on line all offer significant challenges to product quality. Engineers in every plant are concerned with assuring the quality and reliability of their products. It is very understandable then that the desire for high quality, validated testing techniques is also at an all-time high. 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). They also 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 in this industry. Expanded understanding of accelerated aging testing technology will be pivotal in furthering the credibility of this growing industry.

The DOE Solar Energy Technologies Program (SETP) has implemented a Systems-Driven Approach to program planning, prioritization, and evaluation. The approach is the basis for the DOE Solar Energy Technologies Program Multi-Year Program Plan[6] that was released in January 2006; the plan documents program goals, identifies applicable markets, evaluates reference PV systems that reflect where we are today, and quantifies where to work to best achieve our targets. The most important metrics seen in this effort are cost, performance, and reliability. It is reliability concerns that caused us to convene this meeting on Accelerated Aging Testing.

This technical meeting on accelerated aging tests was therefore needed by both the PV industry and the Department of Energy. By listening to the industry describe the types of decisions that can and cannot be made today based on the current testing protocols, the R&D performed in the DOE Solar Energy Technologies program related to accelerated aging can be focused directly on the industry’s highest priority needs.

Meeting Organization and Methodology

The approach taken to achieve the goals of the meeting was to listen to invited presentations by some of the technical experts in the audience and then to allow all of the meeting participants to participate fully in breakout sessions that were explicitly designed to capture the industry participants views as to the:

- status of accelerated testing today,
- additional industry needs for accelerating testing, and
- priorities for achieving the additional capabilities

[6] ”Solar Energy Technologies Program, Multi-Year Program Plan 2007-2011” U. S. Department of Energy, Energy Efficiency and Renewable Energy, January 2006.

To give the industry specialists the opportunity for maximum participation in their areas of expertise, concurrent breakout sessions were held. Focus was on testing issues and opportunities related to photovoltaic systems, modules, and devices.

The highly sensitive nature of reliability and failure mechanism evaluations was acknowledged in the opening remarks. The social dilemma that often surfaces between engineers (who see a tremendous need to share their technical struggles) and marketing/management staff (who often fear impacts of improper sharing of sensitive information) was also acknowledged. All participants were encouraged to share relevant information without violating the trust that their companies place in them.

Sixty nine people attended the technical meeting on February 22 and 23, 2006 near Baltimore, Maryland, representing systems integrators, module manufacturers (both thin-film and crystalline silicon), developers/manufacturers of devices and system components, and researchers, as shown in Figure 1. DOE and National Laboratory staff attended to hear first-hand from industry, universities and other institutions about their experience with accelerated aging testing and their interest in new accelerated aging test capabilities.

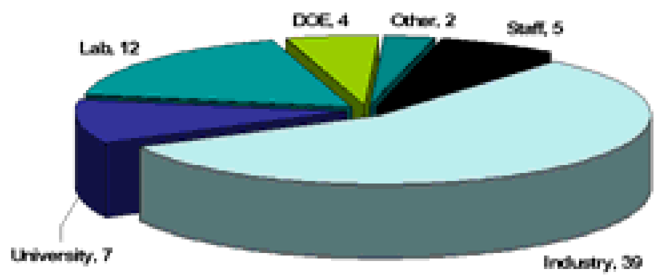


Figure 1: Attendee Affiliation

The technical meeting began with welcoming remarks and introductions from Dan Ton and Joe Tillerson, who explained DOE's interest in the topic and the goals of the technical meeting. The systems-driven approach being used in the DOE solar program was described briefly to the audience to establish the context for the meeting. This was followed by nine presentations from leading PV experts who were asked to explain their experience and perspective on accelerated aging testing in the PV industry, and their thoughts on key issues. These presentations gave the entire group a solid foundation of information on accelerated aging tests throughout the industry that the participants then used as a starting point for further defining the status, needs and priorities for future development. The presentations were:

- Accelerated Aging Tests – Types and Status Tom McMahon, NREL
- Accelerated Aging – Needs for Systems Design and Performance Issues Colleen O'Brien, PowerLight
- Highly Accelerated Lifetime Tests (HALT) and Highly Accelerated Stress Screening (HASS) – How Applicable to PV? Jim Loman, GE
- Using Accelerated Testing in the Development of New PV Products and Processes John Wohlgemuth, BP Solar
- BOS and System Component Requirements for Accelerated Testing Chuck Whitaker, BEW Engineering
- Devices, Interconnects and Module Design – Accelerated Testing Peter Meyers, First Solar

- Inverters and HALT Applications Ray Hudson/Harry McLean, Xantrex
- Quality Assurance – Accelerated Testing in Manufacturing Environment
  Alex Mikonowicz, Shell Solar
- Accelerated Testing Challenges for Flexible Modules,
  Arindam Banerjee, Uni-Solar

These technical presentations are summarized below.

Technical Presentation Summaries

Accelerated Aging Tests – Types and Status, Tom McMahon, NREL

Tom McMahon reviewed five types of accelerated tests and what to expect. Definitions of failure, reliable PV, acceleration factor, types of stress, Arrhenius T and RH, and a response variable were given along with some examples. Criteria were given for dividing cell failure from module packaging related failure. Modes and mechanisms for thin-film modules were cited. An extensive list of 64 references was given.

The expectations for ideal accelerated testing are that they result in virtually no field/use failures, are quick, easy/inexpensive, and standardized to cover ALL module/component types.

There are problems applying “text book” accelerated testing to PV. The PV use environment is MUCH MORE SEVERE than for consumer products. Higher stress in field causes shorter time-to-failure and implies more field failures. Higher stress causes additional failure mechanisms. It is likely that accelerated testing doesn’t catch all of them and there are more field failures. The use times for PV are much longer, up to 30 years. There is a lack of large numbers of identical modules for accelerated testing and correlation with field deployed modules. Cost and efficiency pressures are greater -- changing a product requires re-validation of accelerated tests with field results. Diagnostic studies are complicated by the de-encapsulation process.

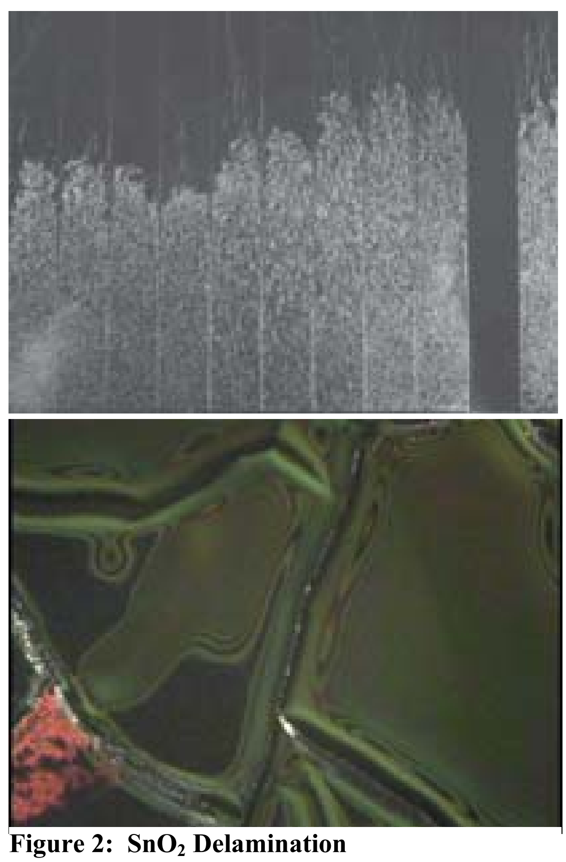


Figure 2: SnO_2 Delamination

Accelerated test decisions in the PV industry involve two main questions: What decisions can be made from accelerated testing? What decisions can’t we make now, but need to? Service life prediction is in this latter category. So are failures that have occurred in the field that weren’t caught with existing tests. These can be a result of known design/supplier changes, or unknown material or component changes. The images in Figure 2 show delamination first noted from field returns, caused by a glass supplier that changed the barrier layer, unbeknownst to the PV manufacturers using these glass supersrates, causing multiple problems.

There are five types of accelerated testing: Qualification tests (design flaws, fabrication error, etc.); UL tests (Safety) ; Screening (rank ordering); Service life prediction(time-to-failure, predicted energy output, etc.); Exploratory (to uncover new failure mechanisms, reveal new failure mechanisms found from field returns, HALT and HASS etc.)

Failure: When the PV product no longer meets the needs/requirements of the user/certifier. A nebulous statement such as this needs some numbers before it has any quantitative significance for engineering studies.

Reliable PV: A “reliable PV” module has a “high probability” that it will perform its intended purpose adequately for 30 years, under the operating conditions encountered. As an example (with numbers added): A PV module fails to provide service if its power output decreases by more than 30% before 30 years, i.e., 1%/yr, in its use environment. A "high probability" could mean that 95% of the modules in the field will achieve this success. By "use environment," we mean any and all use environments that the PV module will experience during service.

Acceleration Factor: How much indoor chamber stress testing accelerates the time-to-failure as compared to time in use environment. This depends on stress (use site) and mechanism being studied.

Types of Stress: Temperature (T), Relative Humidity (RH), I (cell-to-ground or cell bias), V (cell-to-ground or cell bias), T-cycling, H-freeze, UV,… applied singly, together, or serially; user induced stresses (incorrect wiring, improper module mounting or handling, etc.);

There is an exponential dependence for T and RH. T usually has a simple Arrhenius failure rate function. RH sometimes is given the same exponential dependence with 1 to 3% RH equated to 1 °C.[48] How do we develop tests and acceleration constants for other stresses or combinations of stress that are found in the field? Do we want isolated stress, simultaneous stresses, or sequential stresses?

Sensitive Parameter (Response Variable): Quantity derived from I-V (light and/or dark); Hi-Pot current; Visual area damaged; Individual cell shunt resistances. An example of “Area” used as a sensitive parameter is illustrated in Figure 2 shown earlier, involving SnO delamination[RP,56,57]. BP and EPV have developed accelerated tests to screen SnO glass[59]

Figures 3a through 3d illustrate IR Camera diagnostics. In Figure 4 individual cell shunt resistance using the two-terminal method is shown. Figure 5 is the Calculated Acceleration Factor “a”[15, RP] for Yearly Distribution of Module Temperatures at Three Sites. Figure 6 shows delamination failure.

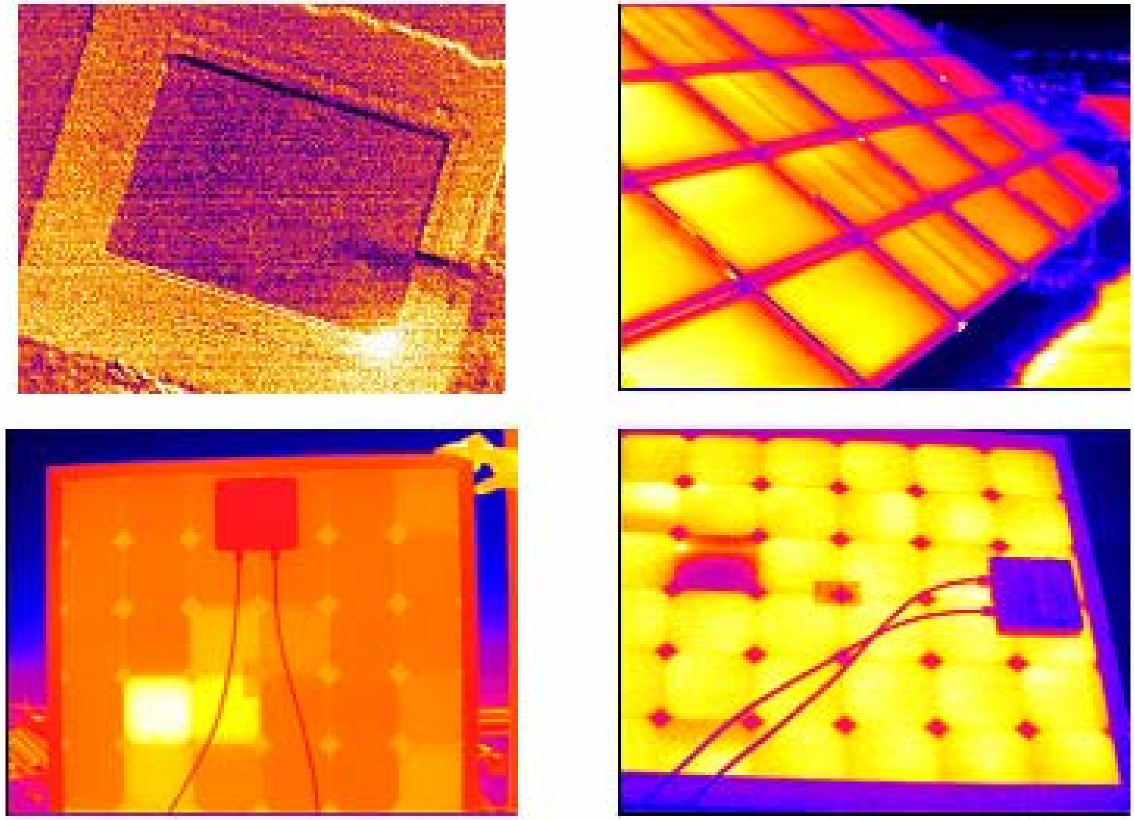


Figure 3 a-d: IR Camera Diagnostics -- Cells to Systems

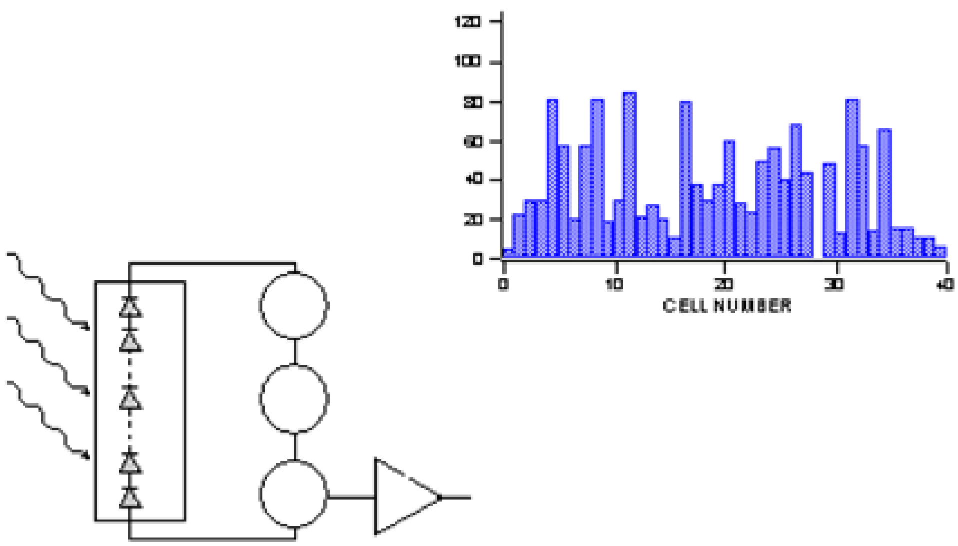


Figure 4: Individual Cell Shunt Resistance: Two Terminal Method

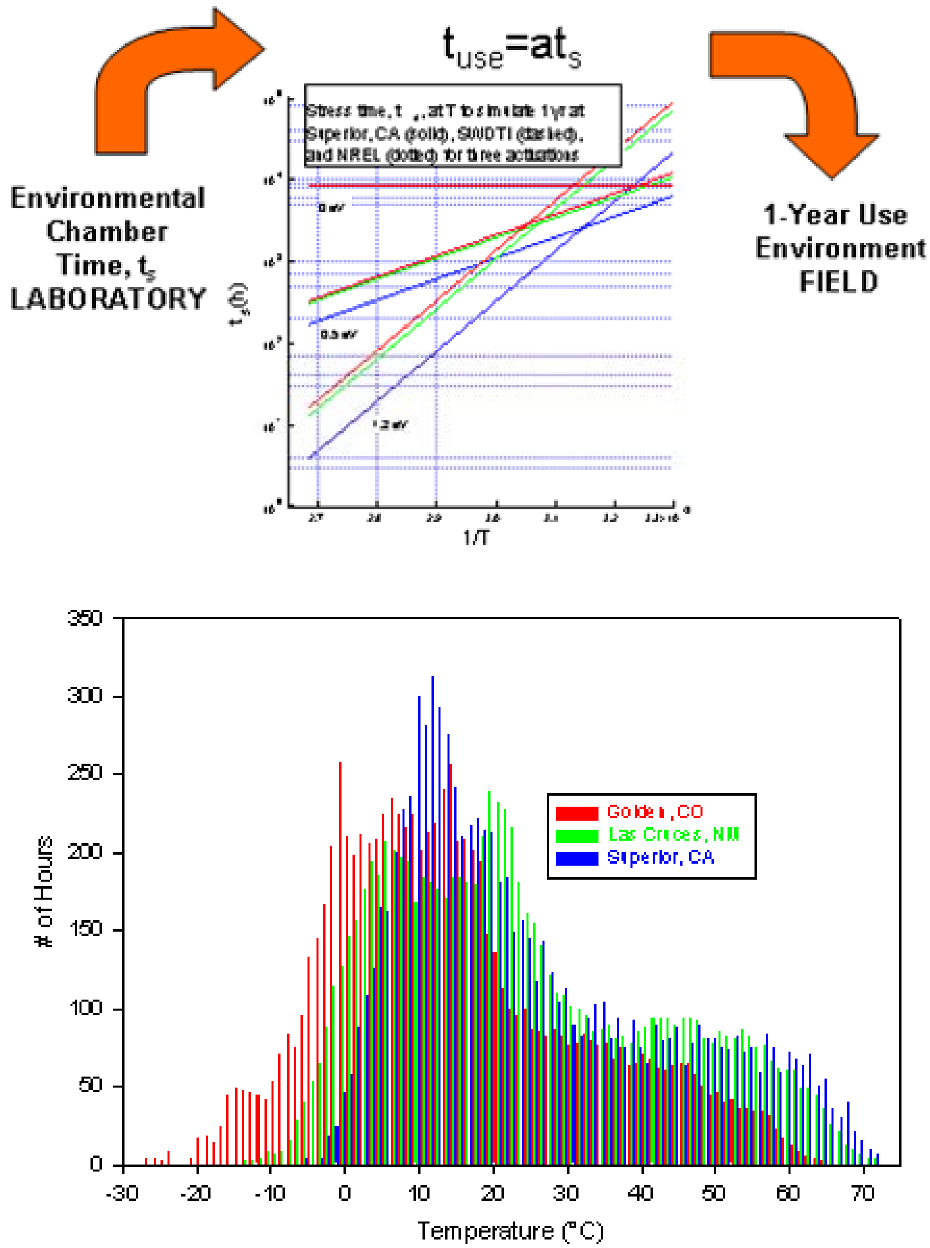


Figure 5: Calculated Acceleration Factor "a" [15,RP] **(top) and Yearly Distribution of Module Temperatures at 3 Sites (bottom)**

Figure 6: "Bubble" Type Delamination Failure

Table 5 below documents the potential failure modes and mechanisms of thin film PV cells[RP] (*Numbers refer to references provided in Appendix A)

Criteria for cell and module failure:[RP] Cell-related failures are a) caused by use-environment stress, such as temperature, that packaging cannot protect against; and b) cells must tolerate low levels of pollutant gases or water vapor. These levels will depend on technology and related device processing.

<u>Packaging-related failures</u> involve:
a) Pollutant gas (admitted from the outside or generated from within) or water vapor levels are elevated at the cell, cell interconnect, or bus-line interconnects to levels that induce damage that diminish module output power.
b) Loss of electrical isolation of cells from ground, loss of structural integrity, or visual defects that are unsatisfactory to the user.
c) Use of incompatible materials; thermal expansion mismatch, creep, loss of adhesion, galvanic corrosion, etc[7]

The following conclusions were offered

- Specific problems of applying text book accelerated testing to PV industry products were identified
- Field failures will continue to plague PV until those problems are resolved.
- Accelerated test terminology was presented. (Types of accelerated tests, failure, reliability, acceleration factor, types of stress, sensitive parameter)
- Failure modes and mechanisms for cells and modules were reviewed.
- Be aware of "pitfalls."
- Importance of field (use-condition) testing emphasized.

[7] See: "Pitfalls of Accelerated Testing," W.Q. Meeker and L.A. Escobar, IEEE Trans. on Reliability, vol. 47, No 2, June 1998

Table 5: Potential Failure Modes/Mechanisms for Thin Films

Failure Mode	Effect on I-V Curve	Possible Failure Mechanism
Main junction; increased recombination24	Loss in fill-factor, Isc, and Voc	Diffusion of dopants, impurities, etc.; electromigration
Back barrier; loss of ohmic contact (CdTe)	Roll-over, cross-over of dark and light I-V, Rseries increases	Diffusion of dopants, impurities, etc.; corrosion, oxidation, electromigration
Shunting26-28*	Rshunt decreases	Diffusion of metals, impurities, etc.
Series; ZnO23*, Al29*, Mo 23*	Rseries increases	Corrosion, diffusion
De-adhesion of SnO2 from soda-lime glass57,59*	Isc decreases and Rseries increases	Na-ion migration to SnO2/glass interface
De-adhesion of back metal contact	Isc decreases	Glass warp age, Lamination stresses
Failure Mode	Effect on I-V Curve	Possible Failure Mechanism
Interconnect Degradation		
a. Interconnect resistance; Zn:Al/Mo or Mo,23 Al interconnect49*	Rseries increases	Corrosion; electromigration
b. Shunting; Mo across isolation scribe23*	Rshunt decreases	Corrosion; electromigration
Busbar Degradation	Rseries increases or open circuit	Corrosion; electromigration
Solder Joint	Rseries increases or open circuit	Fatigue, coarsening (alloy segregation)
Encapsulation Failure		
a. Delamination36-38*	Loss in fill-factor, ISC, possible open circuit	Surface contamination, UV-degradation, hydrolysis of silane/glass bonds, glass warpage, cracking of glass edges, thermal expansion mismatch
b. Loss of hermetic seal		
c. Glass breakage		
d. Loss of high-potential isolation50,56,57*		

Accelerated Aging – Needs for Systems Design and Performance Issues, Colleen O'Brien, PowerLight

Colleen O'Brien, PowerLight, described accelerated life testing of PV modules and system accessories. She indicated that accelerated life testing is done on various components by PowerLight, component manufacturers and third-party testing groups to assure the reliability of their PV systems. Much more than just modules, systems reliability requires testing of structural components, wire, custom electrical components, inverters, and mounting materials (Styrofoam, mortar, adhesives, fasteners, etc.). Practical examples were provided of the importance of qualifying structural materials (e.g. anodized aluminum) and their mechanical loading (wind, seismic, etc.). Detailed testing has shown that some design code improvements are needed for better estimation of both wind and seismic loads.

Accelerated life testing was indicated to be important to the accuracy of energy predictions, to purchasing decisions, and to warranty considerations. Light-induced degradation issues were quantified. The importance of field observations was highlighted by the discussion of some field failures that can't generally be predicted by current accelerated life testing of modules; these include some design flaws, manufacturing defects, and installation errors. Connector failures, delamination, and solder bond failures were some of the most common failure modes observed to date in the field. Ms. O'Brien highlighted the loss of power resulting from solder-bond degradation as a potential risk for systems, especially those with long-term power purchase agreements. Numerous IR images were shown that emphasized the value of these observations in analyzing reliability issues.

Specific areas where test improvements would aid the PV industry are:

- Wind design guidelines specific to PV systems
- Mechanical integrity of PV modules, especially in non-uniform, dynamic loading
- Solder bond integrity in modules
- Understanding effects of 25 year exposure to thermal cycling
- Performance and longevity of modules in very hot environments
- Longevity of electrical components and connections

It was noted in closing remarks that improved testing techniques can significantly help the industry because enormous financial strain can occur if components fail while under warranty.

Highly Accelerated Lifetime Tests (HALT) and Highly Accelerated Stress Screening (HASS) – How Applicable to PV?, James Loman, General Electric

Dr. James Loman, General Electric, made a presentation on GE's approach to applying HALT testing to photovoltaics. Description of HALT as a technique put the entire audience on the same plane as far as understanding HALT and the objectives of applying it. GE is in a unique situation since they have a strong corporate history of applying HALT to product development and were able to apply rationale as well as procedural knowledge to their module testing. Dr. Loman described some results obtained in their conversion to lead-free solder, results related to QA/QC of vendor supplied materials, and results used to evaluate lifetime of encapsulant materials. Dr. Loman was the first of many attendees who proposed the need to develop transfer functions based on accelerated testing. The presentation began with a discussion of why GE is concerned with accelerated aging:

GE Warranty on PV Modules

- Workmanship for 5 years
- <10% Power Degradation at 10 years
- <20% Power Degradation at 25 years

Field Data

- Data on AstroPower PV modules with similar materials- 6 years to 10 years old
- Degradation is only a few % at 10 years- but data sets are small

Dr. Loman then provided a definition of HALT from GE's perspective:

- HALT is a test technique that uses extreme temperature, vibration, temperature change rates, and combinations of temperature and vibration step stresses (and other product specific stresses) to rapidly identify marginal design and manufacturing processes in a product.
- HALT quickly stresses a product from ambient to lower operating limit, to lower destruct limit, upper operating limit, upper destruct limit, vibration operating limit, vibration destruct limit, and finally with combined temp/vibe fast change rates.

- HALT should be used as part of the design process to rapidly expose design weaknesses by: combining a wide range of temperature (-100ºC to + 170ºC), rapid rate of temperature change (60ºC/min), multi-axis vibration (6 degrees of freedom, 2Hz-10KHz, up to 60Grms), power and frequency cycling, and other product specific extremes.

Figure 7 illustrates why GE performs HALT, in particular the relative importance of reliability processes/tests during the design phase. Examples of some of the key failure modes GE's HALT has helped them address include:

- improper component preparation and installation of axial parts (mfg)
- improper component installation; power resistors too low to surface (mfg)
- incorrect component lead spacing; broken transistor, resistor (design layout)
- incorrect power resistor pad design on the solder side (design layout)
- improper component installation; passive parts are installed too high (mfg)
- intermittent components during the vibration tests; relays (supplier)
- bad solder joints; developed early cracks
- failed component; Mylar cap mounted without lead-formed stress relief (mfg)
- flux contamination under the conformal coating (mfg)
- asymmetric solder joints on the IC which will lead to premature solder joint failure (mfg)

Relative Importance of the Reliability Processes during the ACTUAL DESIGN phase

Ranking Numbers: (9 = important; 3 = average; 1 = low)

CTQs (whats)	CTQ Weight	Halt	Hass/ Hasa	Relia/ Simulation	Fmea	Fracas	WCA	Growth Testing	RQT/ PRAT	Environ. Tests	Tolerance Analysis	Thermal Survey	Stress/ Derate	Reliability Allocation
Do early reliability estimates	5	3	1	9	3	1	1	1	1	1	1	1	3	9
Reliability improvements	4	9	9	3	3	9	3	9	3	3	3	3	9	1
Reduce failure risk	5	9	9	1	9	9	9	9	3	9	3	9	9	1
Cost-effective validation	5	9	9	1	1	1	1	3	3	3	1	3	1	1
Time-effective validation	5	9	9	1	1	1	1	1	1	3	1	3	1	1
Design trade study assistance	1	9	1	9	9	1	3	1	3	3	1	3	3	1
Vendor part selection	3	3	1	1	1	1	1	1	3	3	3	3	3	1
Safety	5	3	3	1	9	9	9	1	1	9	3	9	3	1
Vendor/Mfg Process Monitoring	5	1	9	1	1	9	1	1	3	3	1	1	1	1
Failure Mode Identification	5	9	9	1	9	9	3	9	3	9	9	9	3	1
Warranty / SCR reduction	3	9	9	3	3	9	3	9	3	3	3	3	9	1
Identifying CTQs	1	3	3	9	9	1	9	9	9	9	9	9	9	3
Unit cost reduction	3	3	3	9	1	1	1	1	3	3	9	3	3	1
Total Process Weight		308	324	144	210	266	164	204	126	236	162	226	198	92

Figure 7: Why Perform HALT?

Figures 8 through 12 illustrate the application and results of GE's HALT effort.

Conclusion

HALT testing uses high levels of stress to induce failure or degradation

Attempt to excite failure modes that could occur in the field and limit life

HALT testing and Physics of Failure analysis provide a valuable way to uncover failure modes and also to simulate 25 year life

Further investigation of transfer functions from HALT test to predicted life is needed

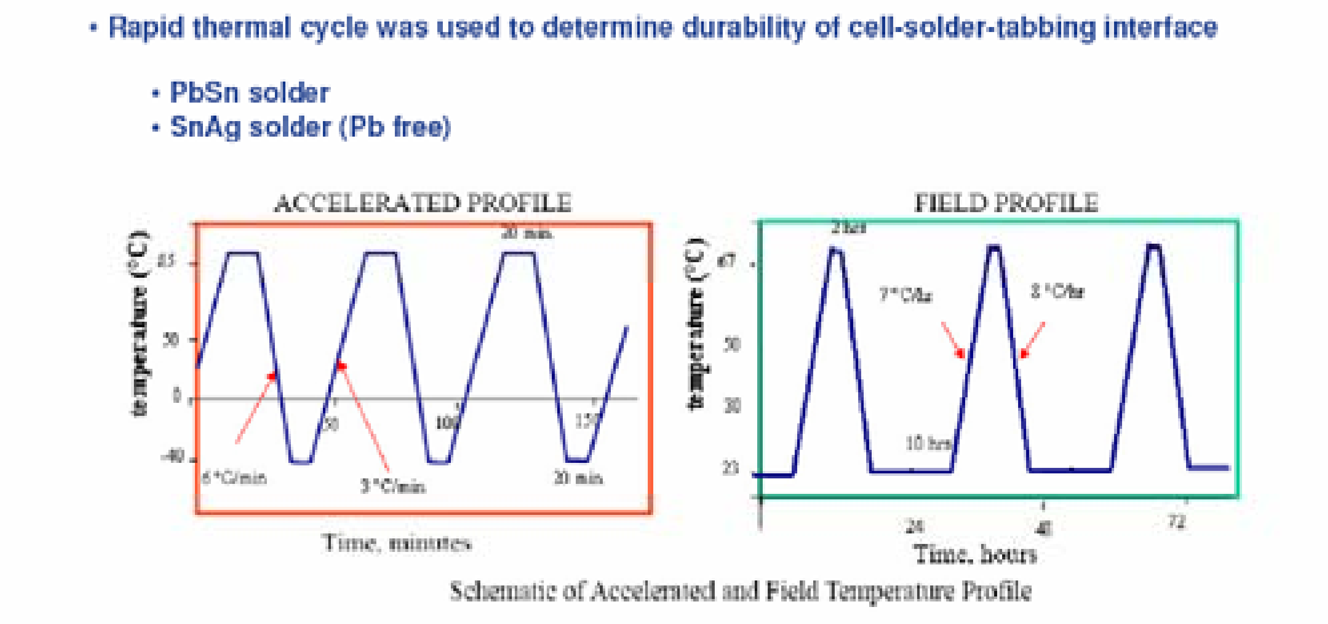


Figure 8: Rapid Thermal Cycling

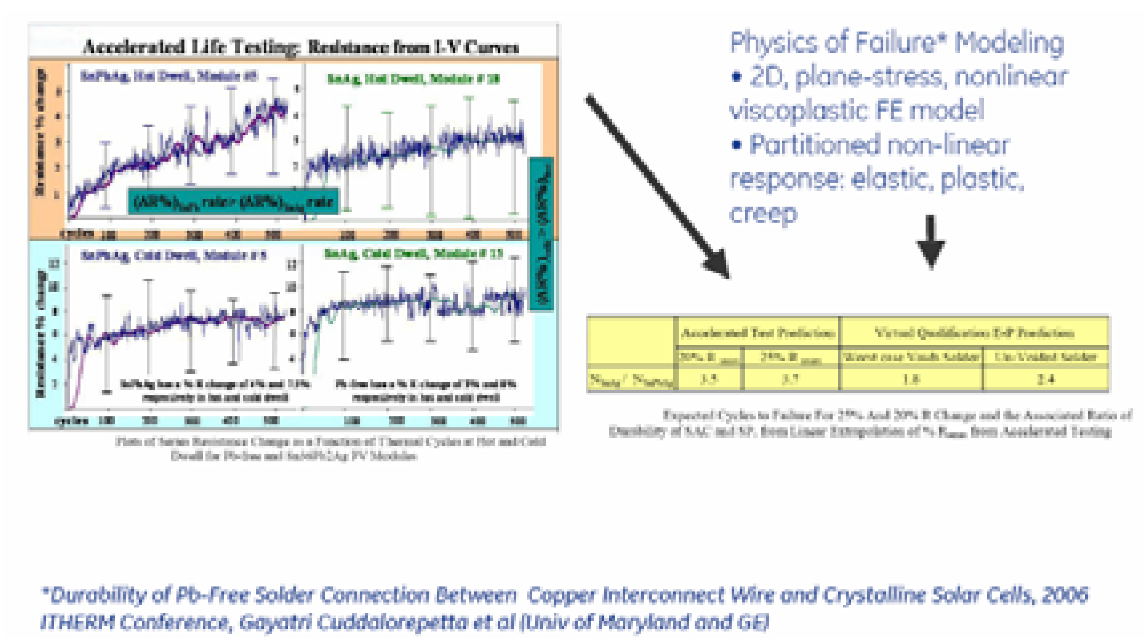


Figure 9: Physical Failure Modeling

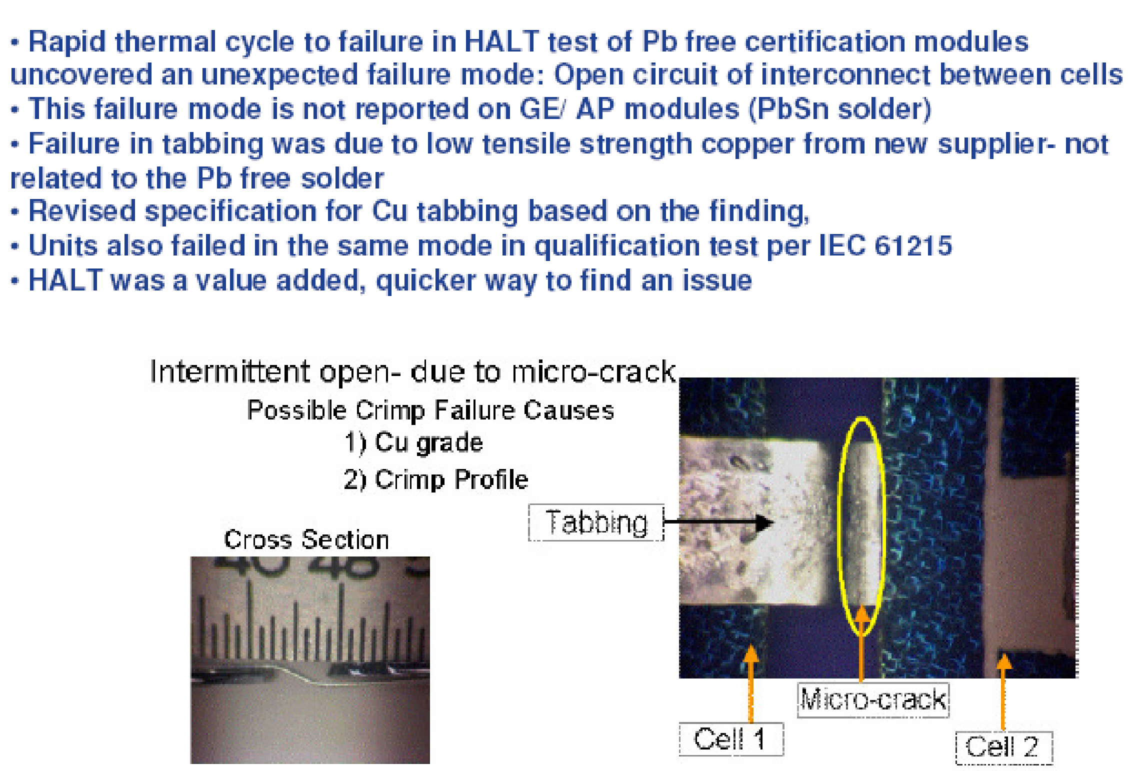


Figure 10: Unexpected Failure Mode Found by HALT

- Reliability tests as specified in IEC61215 are a form of HALT Test
- As an example, consider 1000 hours of damp heat
- Test conditions: 85°C Temperature, 85% RH
- Typical environmental condition (East Coast USA): -10 to +40° C, 10% to 100%RH
- DH- allows the ability to distinguish between different design approaches
    - De-lamination
    - AR coating fading
    - Bond strength- example follows
- Still being investigated: transfer function from DH test to field life

Figure 11: Damp Heat Applied to a PV Module

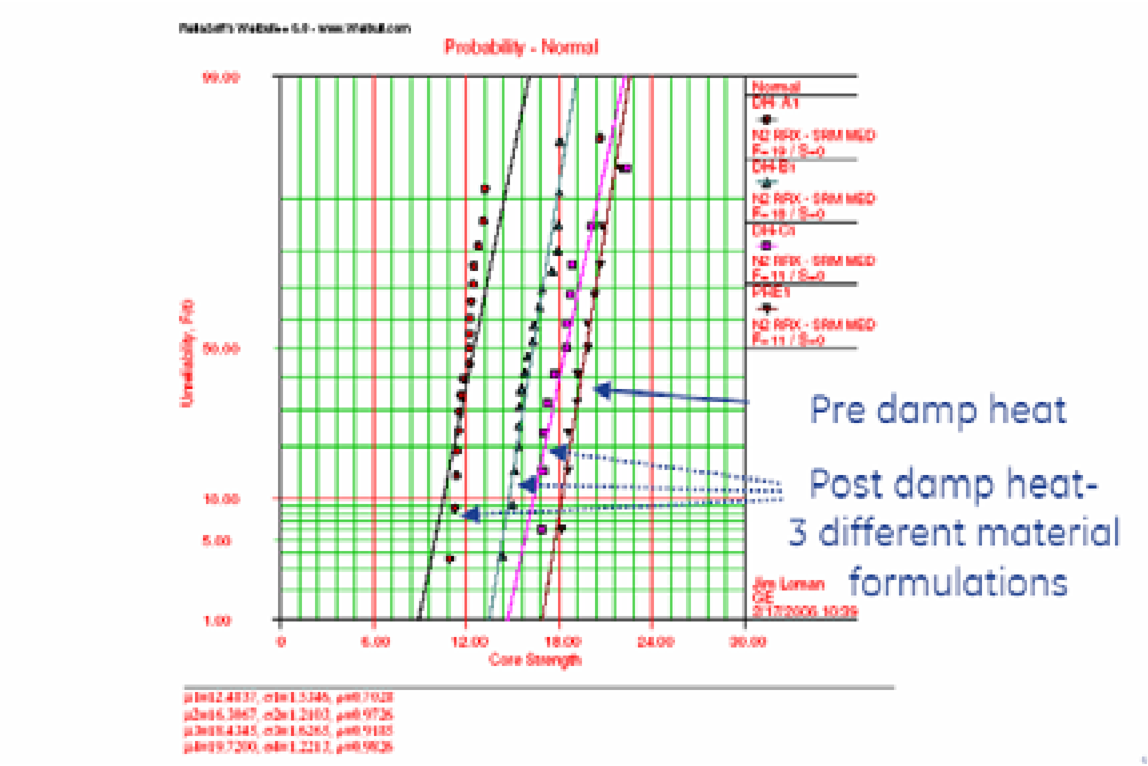


Figure 12: Pre- and Post- Damp Heat Data Example

Using Accelerated Testing in the Development of New PV Products and Processes, John Wohlgemuth, BP Solar

John Wohlgemuth explained how accelerated tests are used at BP Solar to verify product reliability with the goal of a 25-year lifetime. Dominant failure mechanisms are identified, usually from field experience, and accelerated tests are developed to screen for these. Although life prediction is desirable, it hasn't been done yet, but the rank ordering of the durability of materials/processing is accomplished with these tests.

He explained the diagnostic tools and how they are used. Three examples where accelerated tests were used as a screening tool were explained: 1) new interconnect equipment, 2) new backsheet materials, and 3) corrosion of the SnO superstrate glass.

Finally the importance of learning "the reaction rates for various failure mechanisms" was stressed. The presentation opened with a discussion of "How do we test the reliability, long term durability and even the safety of PV modules built using new materials or with new processes?" A key point is outdoor field testing is a must, but it takes much too long to be of much use. Wohlgemuth further indicated, "We can't wait 25 years to introduce a new product and therefore we must use accelerated tests to qualify new PV products and processes."

Next accelerated stress tests were discussed. First, failure mechanisms must be identified from outdoor exposure. Then stress tests are developed that accelerate the same failure mechanisms, and then these accelerated tests are applied to modules with new materials and processes with hope that the tests are still valid for studying the previously identified failure mechanisms. That is the ideal, but the last point was that this is not always the case.

Overall reliability efforts were discussed in terms of field experience, and accelerated stress tests. Field Experience includes analyzing commercial warranty returns, deploying and monitoring individual modules over long time periods, and monitoring the performance of PV systems over time. Then there are accelerated stress tests.

The accelerated stress tests used by BP solar include:

- Thermal cycle with current flow
- Damp heat exposure (Sometimes with applied voltage)
- Humidity-freeze cycling
- Dynamic and static mechanical loading
- UV plus heat

The condition and duration of testing is guided first by the qualification test sequence (IEC 61215 or 61646). BP Solar extended the thermal cycles to 500 and the damp heat to 1250 hours when it went to a 25 year warranty. These are the minimum test durations. Sometimes BP tests longer to build their understanding. Sometimes they change the conditions to understand the failure mechanisms and the acceleration rates.

- For UV BP tries to simulate 25 years of exposure. Typically they test through the glass for a long time (~26 weeks) and direct exposure for a short time (~ 3 weeks)
- Usually use qualification test protocol, but may deviate to better evaluate failure mechanisms.
- Not every accelerated test failure is going to cause a problem in the field!

The measurement tools BP uses include:

- PV Performance (I-V curve)
- Dry Hi-Pot
- Wet insulation resistance
- Visual inspection
- Discoloration
- Embrittlement
- Delamination
- Corrosion
- IR camera
- Adhesion of layers, boxes, frames, etc.

When analyzing test results, BP doesn't just go by pass-fail criteria. A module design that loses 4% of its power after 500 thermal cycles is not as robust as one that loses 1% of it power during the same test. BP uses other tools to understand why one set lost 4% and the other only 1%. This leads to a better understanding and ultimately to more robust products. BP also uses accelerated tests to qualify new products and processes, first by running their modified qualification sequence and reviewing the results carefully. Did the modified modules suffer any greater degradation than the standard product? If yes, then they must understand why and determine if this will lead to reliability, durability or safety issues. If there is a potential to degrade field performance the change is rejected.

Examples of where this is applied include new interconnect equipment, new back sheet material, and thin film corrosion

In the case of new interconnect equipment, it is evaluated using thermal cycling with current flow. In addition to power loss, BP utilizes IR to find broken interconnects or damaged solder bonds. In one example after 200 thermal cycles the power was down only 2%, but IR showed some interconnects were broken, as shown in the accompanying figure.

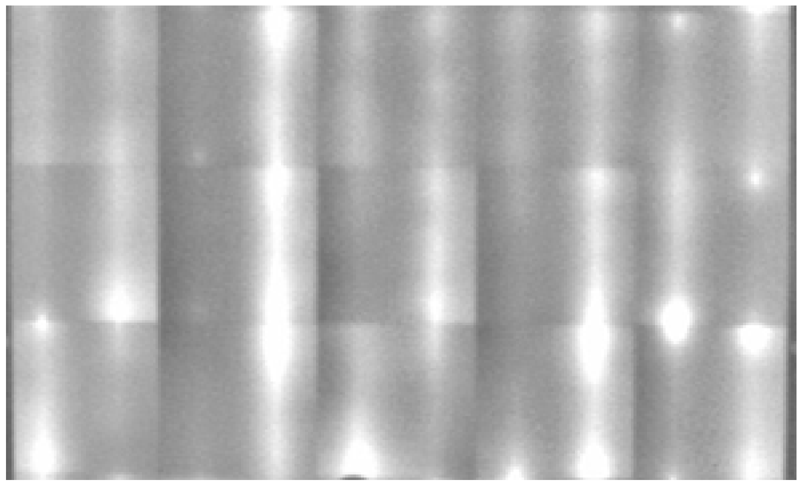


Figure 13: Example of Broken Interconnects Shown By IR

The module shown in the pictures was continuously cycled during the tests. After 400 cycles it was down ~ 4%, but more interconnects were broken. Some modules made with new equipment passed 500 TC with less than 5% power loss. However, others had 2 interconnects on the same cell break and so lost a large fraction of their power. (Determined by # of cells per diode). By making educated modifications to the new equipment and its process, we stopped the interconnect breakage. This equipment is now used to build quality products.

New backsheets were tested through the standard qualification sequence. The module tested performed very well especially in damp heat (85°C/85% RH) with no measurable power loss. However, during the course of the damp heat testing the adhesion between the EVA and the backsheet decreased as shown in Figure 14.

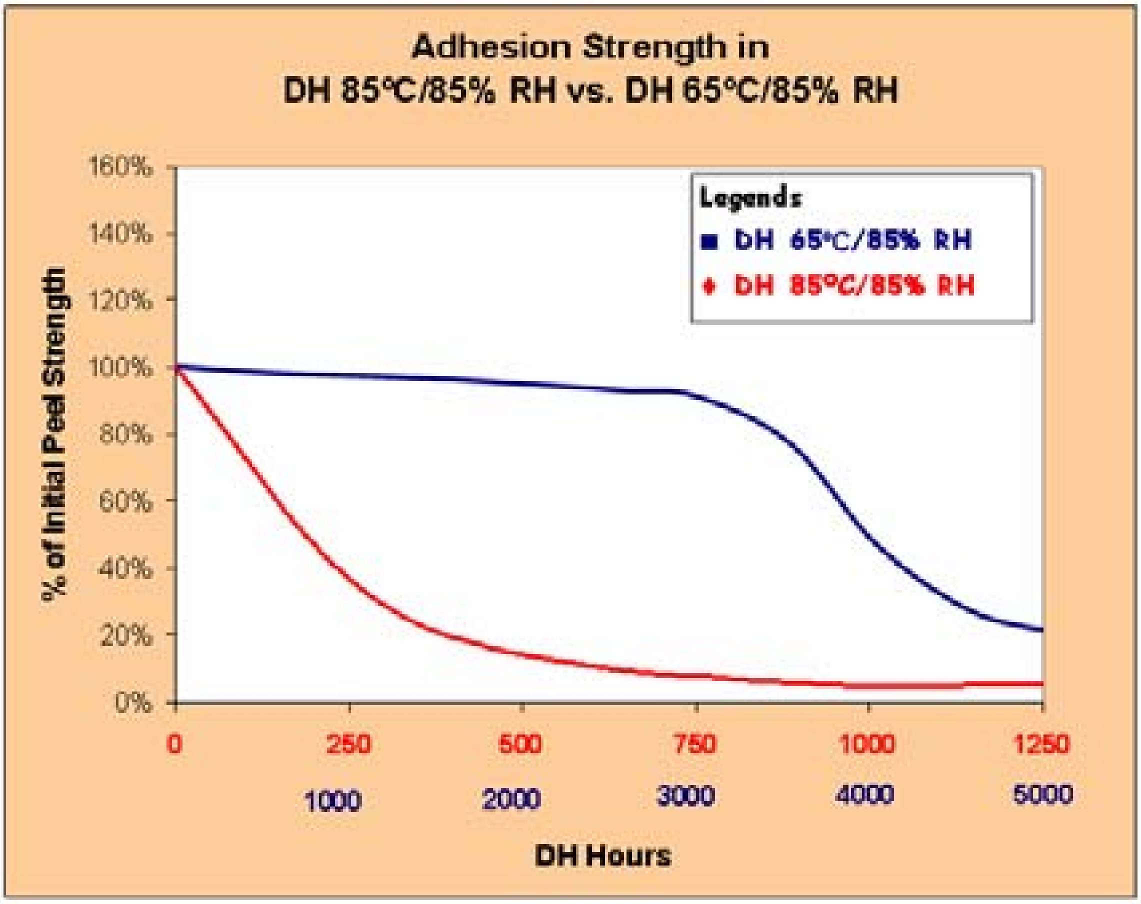


Figure 14: Curves Generated by Adhesion Strength Testing

Is this loss of adhesion a problem for the field? BP used a 1000 hour Damp Heat test based on JPL analysis of cell metallization corrosion and a rate constant that doubled for every 10^{o}C rise in Temperature. So BP performed the test at 65°C/85% RH for 4 times the duration. Theses results are also plotted on the chart. BP found that adhesion does not have the same behavior as corrosion: in this case the acceleration rate must be greater than a factor of 4. It turns out material undergoes a phase change just below 85°C so any test at 85°C or higher will be much more severe than at lower temperatures.

When BP Solar manufactured thin film modules, they were qualified through IEC 61646 including 1000 hours of damp heat. However, these modules experienced early field failures due to corrosion. BP tried performing the damp heat test with applied voltage and found it could duplicate the observed failure after only a few days of exposure. This led directly to development of a product that did not suffer from this corrosion mechanism.

Future protocols need to include the capability to evaluate the reaction rates for various failure mechanisms occurring during the damp heat test and equate them to long term field data to get a better prediction of module lifetime. How many years of operation in Miami does 1000 hours of damp heat exposure at 85° C/85% RH represent for each failure mechanism?

More data is needed in order to develop a model to equate performance in the thermal cycle test to outdoor performance in various climates. How many years of operation in Arizona does 500 thermal cycles from -40° C to +85° C represent?

In his conclusion, Wohlgemuth indicated that without accelerated aging tests it would be extremely difficult, if not impossible, to determine before implementation whether a proposed change in a module material or process would have a major impact on long term reliability and lifetime.

While accelerated aging tests can not tell you how long a particular module design will last, they can be used to determine whether changes are likely to improve the reliability and lifetime or to have a detrimental effect on the reliability and lifetime.

Accelerated aging tests also assist in identifying those failures observed in the field, and help to eliminate them. For new technologies accelerated aging and field exposure are both necessary in order to develop reliable, long lifetime modules.

BOS and System Component Requirements for Accelerated Testing, Chuck Whitaker, BEW Engineering

Chuck Whitaker, BEW Engineering, presented information on field stresses that need to be considered when accelerated aging of Balance of System components is configured. Initially, Whitaker described the BOS as everything but the modules and then broke out the components into the inverter, electrical (ac and dc), structure(s), site, and monitoring/control, detailed in the accompanying figure. This laid a foundation for things to come/consider in the systems breakout session. The presentation did an excellent job of identifying field stresses beyond the highly recognized temperature and humidity factors including high level insolation, wind, dirt, high voltage/current, transportation, animals, and vandalism. One of the really important stresses that is not often mentioned is utility caused transients. Existing electrical and structural tests were outlined as well as the shortcomings of some of these tests. Whitaker's summary made it a point to encourage the industry to "know the environment and never underestimate" these environmental factors in defining accelerated aging tests.

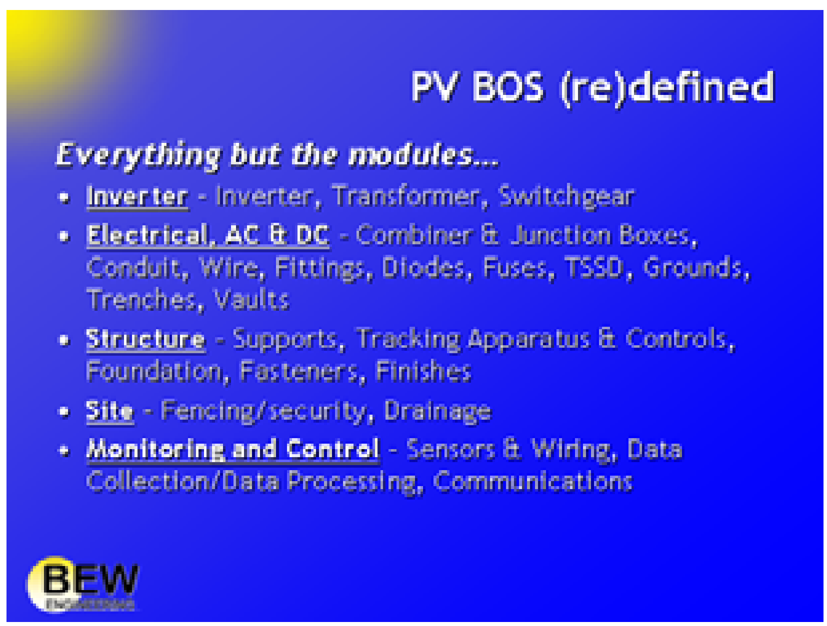


Figure 15: PV BOS (Re) Defined

The basic structure of the presentation was to define BOS, aging factors, existing tests, field observations, and present conclusions. The following figure presented an interesting perspective on accelerated testing in other industries:

Key aging factors include:

- Voltage
    - DC: currently 600/1000 nominal, 1200/2400 coming
    - AC: Low (≤600V) and Medium (≤60kV) Voltage
- Current
    - Hundreds of Amps
- Secondary Mechanisms
    - Soiling
    - Critters
    - Vegetation
    - Shipping, installation, operational damage
    - Vandalism

Existing inverter tests discussed during the presentation included:

- Inverter
    - Surge withstand, hi-pot testing in UL 1741
- Transformer & Switchgear
    - IEEE CPMT Technical Committee on Accelerated Stress Testing and Reliability (TC-ASTR)
    - <u>Thermal Endurance Testing:</u> **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*
    - <u>Electrical Endurance Testing:</u> **IEEE 1043** *IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils*
    - <u>Multifactor Stress Testing:</u> **IEC 60034-18-33** *Functional Evaluation of Insulation System-Multifactor Functional Evaluation*

Existing electrical tests discussed included:

- Combiners, junction boxes
    - NEMA 250 Enclosures for Electrical Equipment (1000 V Max)
    - IEC 60529 Degrees of Protection Provided by Enclosures
- Conduit, Wire, Fittings
    - Wire and cable are subjected to numerous mechanical, electrical, thermal, UV, and moisture tests
- Diodes, Fuses, Transient Surge Suppression Devices
    - Numerous IEEE C62.XX procedures related to surge devices (ac)
    - UL listing/recognized fuses & diodes
- Grounding

  - NEC specifies how to ground in multitude of situations, presumably this has come about through testing and field experience to see what holds up mechanically and electrically.

Existing structural tests discussed included:

- Supports
  - Standard mechanical/structural load and flexure certifications are customary for UL-listed products and for large custom systems.
  - Some engineers are performing wind tunnel testing
- Tracking Apparatus & Controls
  - None specific to PV

Next, field experiences applicable to accelerated aging tests for BOS were discussed for inverters, electrical and structural systems. For inverters experience includes early chalking of powder coats, pitting of unprotected metal, and UV degradation of displays and buttons/knobs. IGBT, Electrolytic Capacitor, wiring harness, connector, cooling system, failures have been reduced substantially, though not eliminated Utility steady state & transients voltage are underestimated—"they don't make 130V light bulbs for nutin'" Transformer field failures are related to improper sizing or installation errors. There are some field examples of failed switches, usually dc. Most ac switchgear issues appear to be related to sizing/installation errors.

For electrical systems, field data on combiners and junction boxes have shown failures caused by water intrusion and dc ground faults are more common than designers expected, which has led to modifications in NEMA selection, terminals, and fuses. Conduit, wire, and fittings experience is only compromised by workmanship, (with the exception of mislabeled non-UV wire) rarely by flaws attributable to a lack of adequate life cycle testing. For diodes, fuses, and transient surge suppression device experience it was noted that Siemens GmbH no longer uses array fuses unless required by module manufacturers. ***Aging and high voltage operation of TSS devices remain a source of concern*** In the case of grounding/transient protection, it is rare to get data on adequacy of grounds long after installation. NEC-compliant systems do not seem prone to premature grounding integrity failures.

Field experience with structures varies by component. For supports there are few field issues related to structure failure. Those that do occur are usually due to underestimating wind/snow load or overestimating roof deck strength. Tracking apparatus, including controls, were formerly PV's Achilles Heel. Many trackers failed in field service due to leaks, corrosion, mechanical damage, rodents, and electrical surges. Improvements have been incremental and mistakes have been repeated by some. For fasteners, existing non-PV testing is probably adequate. For finishes it is obvious that existing testing hasn't been adequate for PV, but all that might be needed is to raise the bar via more severe versions of existing tests.

The final conclusions from the presentation were:

- Know your environment: Don't underestimate the level of voltage, temperature, current; consider steady state and transients
- Assume installation errors will occur—minimize installation steps, test for errors

- Learn from the mistakes of others
- Don't try to hide your products short comings with a little paint…

Devices, Interconnects and Module Design – Accelerated Testing, Peter Meyers, First Solar

Peter Meyers of First Solar presented information on an attempt to find a faster stress test for their CdTe cells and modules. Although much faster than their 56-day light and temperature test, their new test did not correlate with module reliability in the field (see Figure, R_{sq} = 0%). Cells that degraded under the increased stress did not significantly degrade outdoors, since the stress test (by going to a much higher temperature) accessed a physical mechanism that does not occur in the field. This null result showed that simply raising the temperature of a stress test may not lead to a better, faster test; it may indeed lead to a test that shows degradation irrelevant to actual experience. Thus developing new, faster, simpler tests for thin films remains unresolved.

- **Sister plates from each of twelve conditions were stressed using ALT**
- **ALT results were compared to baseline field performance**
- **No correlation observed – for this specific ALT protocol**

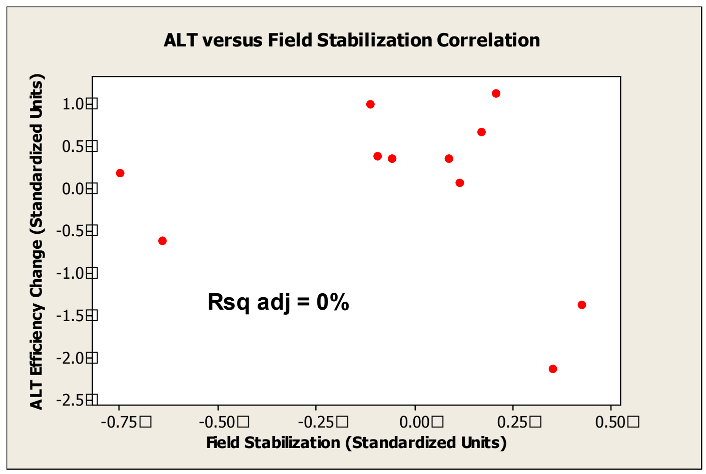


Figure 16: ALT versus Field Stabilization

Inverters and HALT Applications, Ray Hudson/Harry McLean, Xantrex

Harry McLean and Ray Hudson, both from Xantrex, teamed to present a well developed HALT application for inverter development. Xantrex has invested significant effort to develop their HALT application and their success was demonstrated as the presenters walked the audience through reliability techniques, application of these techniques to the manufacturing process, HALT fundamentals and benefits, and finally some of the issues and solutions that HALT testing have identified. Steps to integrate a dedicated reliability engineer into all development and manufacturing processes showed the depth of commitment necessary. Application of HALT to Xantrex product development is a true success story worthy of recognition in an industry segment that battled major reliability issues just a few years ago.

Both high and low volume manufacturing activities were shown to benefit from the Design for Reliability approach used by Xantrex. Goals for the reliability techniques are:

- Design in wide operating margins

- Make the product simple to build
- Analyze failure modes
- Verify assumptions through environmental and HALT testing
- Make key features easy to test
- Screen units as produced

The "Bathtub Curve" concept (see Figure 17) was introduced to show the significant impact of HALT. This curve indicated reductions in workmanship flaws early in production, minimization of failure rates during product lifetime, extension of product life, and less wearout failures are likely when using HALT. Seven other benefits of HALT were noted as:

1. Quickly determine design & process limitations.
2. Determine & increase design margins.
3. Dramatically reduce infant mortalities as well as dramatically improve long-term product reliability (both reduce field return rate).
4. Reduction of development time and cost.
5. Eliminate design problems before launch.
6. Obtain statistical information on margins for HASS/A.
7. Sustaining engineering tool to assess product changes.

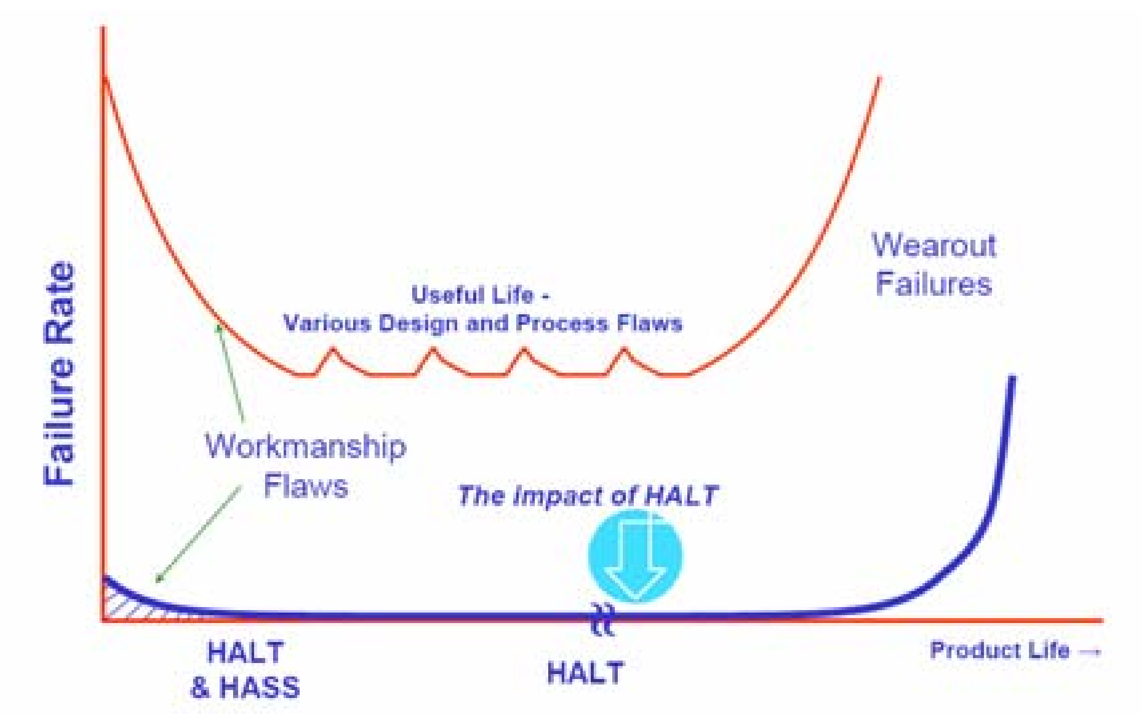


Figure 17: The Bath Tub Curve

Ways in which HALT differs from qualification testing were noted in that HALT is not a pass/fail test but rather a process of discovery and design optimization. The application of HALT plays a critical role in improving the inservice reliability of a product through better, more robust designs and manufacturing processes. Finally several examples of

HALT applications on Xantrex products were provided that clearly demonstrated product improvements made as a result of the testing.

Quality Assurance – Accelerated Testing in Manufacturing Environment, Alex Mikonowicz/Bob Weiting, Shell Solar

Three questions drove the focus of this presentation:

- Can accelerated testing in a manufacturing environment be useful?
- Can the costs be recouped?
- Do sales, distribution, resellers, installers, eventual customers care?

Each question was thoughtfully discussed and resoundingly answered "**YES!**" Three approaches were identified to accomplish this: to use portions (block 5) of IEC 61215, to continuously "sample" products from the production line, and to selectively increase test requirements (being careful not to destroy the product). Difficulties or 'realities" of adapting the existing test to a manufacturing environment were recognized. In particular, qualification of new materials and processes as well as material substitutions were noted as leading to conflicts in protecting the customer, warranty performance, and the sanity of the testers. Shell's approach is to conduct the majority of IEC 61215 on two modules of finished goods, to selectively test new materials to failure (or far beyond design requirements), and to "qualify" all processes and materials. Principal things that the industry does not have are:

- a meaningful test to predict end of life
- 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.

Finally, Dr. Mikonowicz offered advice on what the labs can do to support PV manufacturing as:

- suggesting tests that can be correlated to life expectancy of module performance
- operating long term site installations to measure performance over time and in several environments within the U.S.

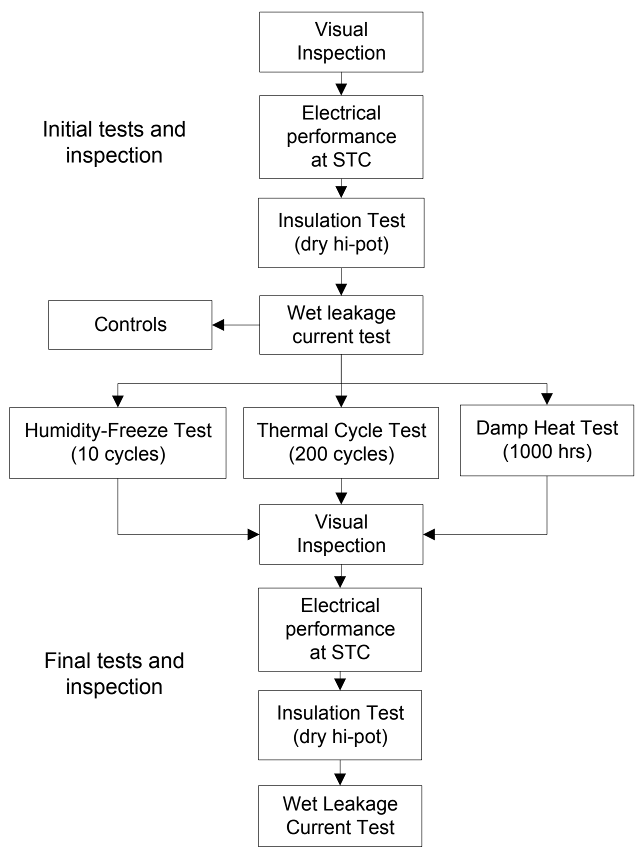


Figure 18: Testing Flow Diagram

Accelerated Testing Challenges for Flexible Modules, Arindam Banerjee, Uni-Solar

Arindam Banerjee presented the AT testing protocol in use at United Solar to screen and verify product reliability, His presentation was unique in that his product is a thin-film, flexible, and sold into the power market. As such it must pass all the IEC qualification tests as well as, in some cases, additional flex stress testing.

He explained the decision making process and important elements/properties being tested. In the conclusion he explained the importance of developing accelerated tests to catch failures that might occur in the field. Summaries or examples of some of his key viewgraphs follow.

United Solar Accelerated and Evaluation Tests for materials include:
- Material analysis: AES, SEM, IR, etc.
- Optical tests: transmission / reflection
- Peel test: 180° peel strength (ASTM D903)
- Shear test: single-lap-joint (ASTM D1002)

Module tests include Humidity-Freeze (HF) testing for 10-50+ cycles, -40°C to +85°C, 85%RH. Thermal Cycle testing includes 200+ cycles, -40°C to +90°C. Damp-Heat testing includes 1000+ hours, +85°C, 85% RH. Insulation testing goes up to 6 kV, wet or dry, and the Wet Leakage Current test is conducted up to 6 kV. A testing flow diagram is shown in the accompanying figure. Other accelerated/performance tests include UV Exposure: continuous UVA, >1000 hrs, 70°C (ASTM G154). Salt Fog testing : 5% salt solution, 35°C, 96 hr cycle 48 hr wet, 48 hr dry (ASTM B117). Surface Cut testing: 45°cut (UL-1703), evaluation by wet hi-pot. Hail Impact: 1” diameter, 23 m/s, 11 locations. Static Load: 50-90 lb/ft2, 1 hr application to each side, 2 cycles.

Examples of tests unique to flexible modules include the cyclic flex test. These are necessary because Uni-Solar modules are flexible. Some applications require coiling, flexing, or forming. The cyclic flex (fatigue) test is used to evaluate encapsulant, interconnect, and busbar integrity. Twist and Dynamic Mechanical Loading tests are not performed – they are more applicable to rigid flat-plate modules. In the cyclic flex tests modules are attached to a mandrel, 6-12 inches in diameter. Tension is applied to the module to ensure contact with the mandrel, and then the cycling is motor driven. In the accompanying figure, A identifies the mandrel and B the tension applied to the module. The module is coiled around the mandrel clockwise then counterclockwise (=1 cycle, ~0.2 Hz). Widthwise or lengthwise flexing is possible. The number of cycles can be one to thousands. The next figure shows the module coiled around the mandrel.

Figure 19: Cyclic Flex Test

The second example of a test unique to flexible modules is the Deposition Film Adhesion Test. In this test both tensile and compressive stress may be applied to the film. As shown in the accompanying figure, a 1" wide sample is formed around a conical mandrel resulting in a variable and increasing stress towards the top of cone (1-4%). The percent compressive and tensile strain is measured at film adhesion failure which is dependent on film thickness and cone diameter. This is faster and less subjective than tape test for thin, malleable substrates.

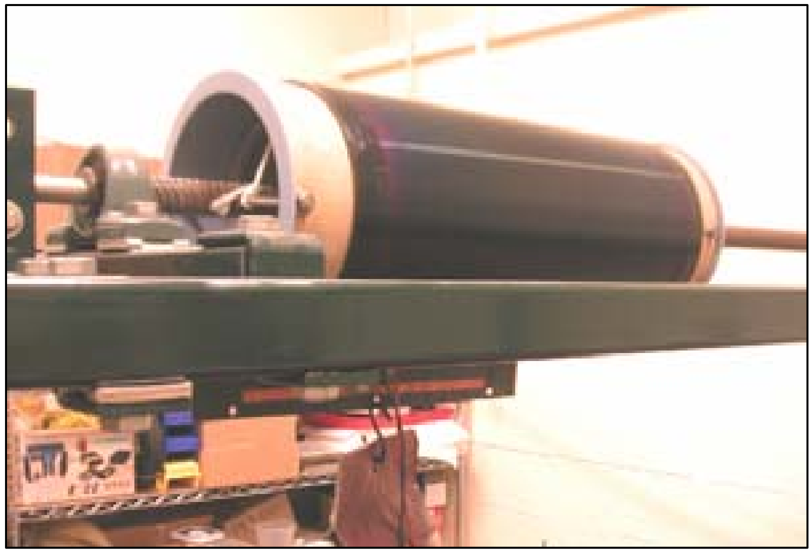


Figure 20: Cyclic Flex Test Apparatus with Flexible Module

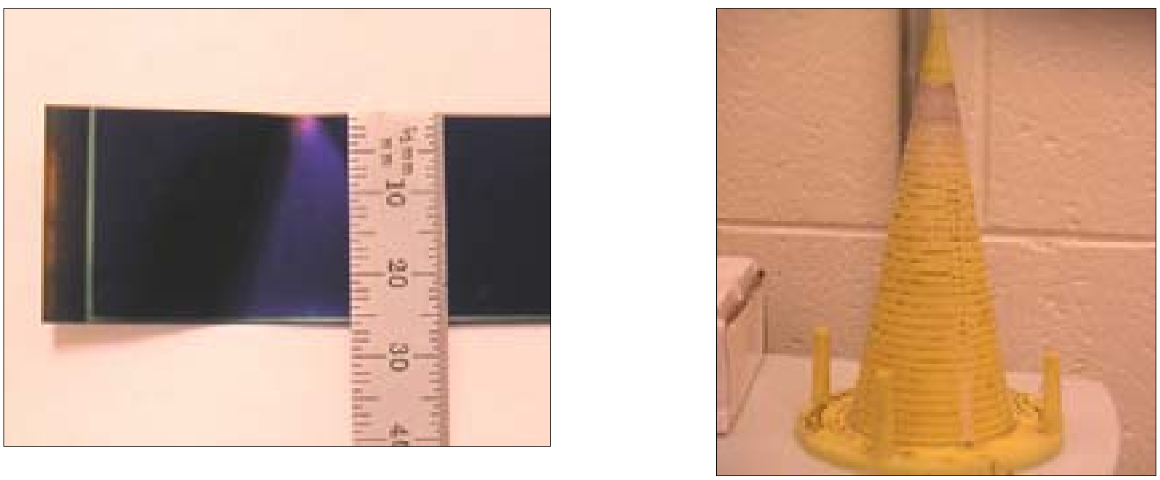


Figure 21: Deposition Film Adhesion Test

Specific tests and test plans are used for design evaluation and qualification of alternative materials; materials from alternative suppliers (supplier evaluation/ qualification); alternative product designs; alternative/improved production processes; performance of encapsulating materials such as interlayer adhesion, insulation, etc.; cell substrate and module backing plate corrosion resistance; interconnect design and material acceptance; and module/cell design electrical performance acceptance.

The following table summarizes important aspects of Uni-Solar accelerated testing.

Table 6: Uni-Solar Accelerated Testing

Accelerated Test	**Evaluation / Acceptance Test Examples (in addition to IEC 61646 and UL 1703 acceptance)**
Humidity-Freeze, Damp-Heat, and Thermal-Cycle Tests	Insulation test (wet hi-pot) - dielectric properties of encapsulating films at various temperatures. Very important immediately after exposure to HF and DH tests. Up to 6 kV totally immersed. Peel and shear tests at various temperatures - encapsulation adhesion and bonding at material interfaces. Surface cut test - outer encapsulation cut test followed by wet hi-pot, up to 6 kV totally immersed. Increasing cut force until failure.
HF or DH with voltage or current bias	Ion movement (electromigration) under high humidity, high temperature, and voltage bias
Cyclic Flex test	Interconnect and busbar fatigue, encapsulation integrity
Light Soak test	S-W degradation of new/improved deposition recipes, also used to help establish stabilized module power ratings
Salt fog test	Insulation test (as described earlier) Corrosion resistance of cell substrate, backing plate, terminals for coastal or marine applications

The following figure shows an example test plan for a copper busbar.

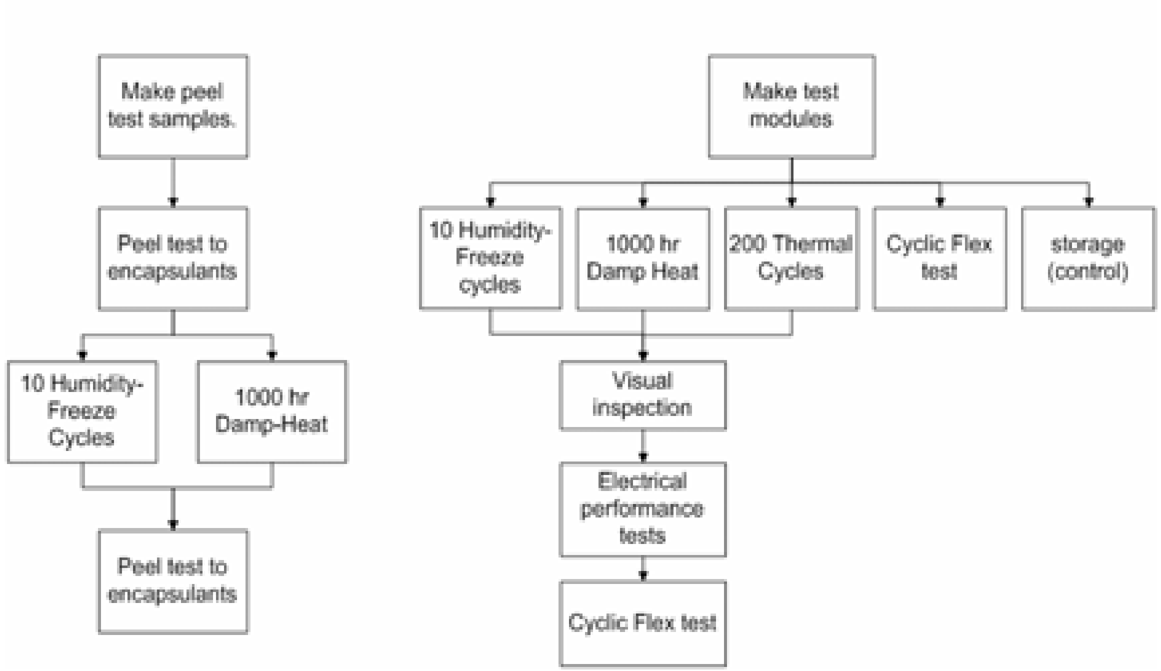
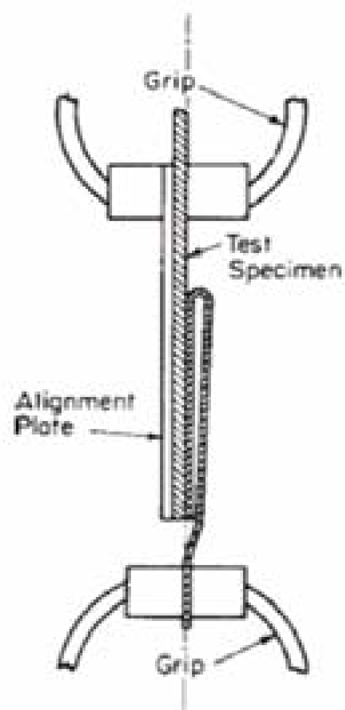


Figure 22: Example Test Plan for a Copper Busbar

In predicting field failures from accelerated testing, Uni-Solar has found that some accelerated tests are fairly accurate predictors of field behavior. For example, the Light Soak Test. This test is similar to IEC 61646 section 10.18 Light-Soaking test conducted for 1000 hours, cell held at NOCT. Indoor metal-halide illumination or another suitable light source, >800 W/m^2, is used. It was found that the electrical performance of United Solar products after the light-soak test correlated with field observations.

Another example of field failure correlation to accelerated testing is the Peel Test. HF and DH tests are used to evaluate adhesion properties of encapsulating films. The peel test is performed after HF or DH exposure (ASTM D903, 180° peel). The peel test has been used to confirm weak encapsulant adhesion. Subsequent root cause analysis identified a contaminant in supplied material. Figure 23 illustrates the peel test method.



Ref: ASTM D903-98 Standard Test Method for Peel or Stripping Strength of Adhesive Bonds

Figure 23: Peel or Stripping Test

Field observations and customer feedback are important sources of information regarding reliability. Field data helps to identify conditions for which to develop accelerated tests. For example, encapsulant delamination was discovered due to contamination which resulted in corrective action with the supplier. Information on copper busbar failures resulted in busbar design changes and verification by cyclic flex testing. Laminating film adhesive failures resulted in Uni-Solar moving to a new supplier. United Solar's testing protocol has contributed to a very low observed product return rate.

Future advancements in accelerated aging tests that Uni-Solar desires include more accurate prediction of module lifetime, electrical performance, integrity of encapsulation, bonding to roofing substrates. Faster test procedures for design evaluation and qualification testing are desired – Time is money! Can 50 HF test be substituted for 1000 hour DH test? An evaluation of the pros and cons of 50 HF cycle test versus 1000 hour DH test is needed. Can HALT/HASS be used to predict long-term field performance and module lifetime? Can HASS be used to quickly determine design weaknesses/flaws?

In conclusion, United Solar uses industry accepted accelerated tests as decision-making tools in the product development process. Flexible modules have unique properties that require unique tests. Several tests have been developed by United Solar to evaluate flexible module performance. Accelerated tests followed by appropriate evaluation tests have been shown to predict potential field failures. Field observations are a tool to evaluate and develop accelerated tests and associated acceptance test criteria. Faster and more reliable accelerated tests are needed to reduce cost and improve quality.

Accelerated Aging Breakout Groups

With the information from these presentations fresh in their minds, the participants were organized into three breakout groups to cover accelerated aging test issues for Devices, Modules, and Systems. When a company sent more than one person they were asked to divide up among the breakout groups, but the attendees were free to attend the breakout session they preferred. 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: Ken Zweibel for Devices, Tom McMahon for Modules, and Michael Quintana for Systems.

To help start the discussion, each breakout group was given a set of potential questions/issues to consider. 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. Over the two days each of the three groups was asked to focus first on defining the current status of accelerated aging testing for their topic area, then on defining needs, and finally prioritizing needs.

Personnel from the National Laboratories and DOE were asked to participate, but to let representatives from industry and universities take the lead in the discussions. 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.

In the final breakout session each group was asked to reach a group decision on the top priorities for advancing accelerated aging testing, rather than relying on votes. This approach was chosen to encourage the groups to organize and combine needs into broader categories, and focus on common interests. This wasn't a problem for any of the groups. At the end of the breakout sessions the meeting reconvened and each group presented its results. Many of the attendees stayed after the meeting to participate in an informal discussion of the meeting results that helped further define many of the needs and priorities developed by the breakout groups. There was a general interest in continuing to meet as a group as DOE works on HALT issues to help work out the details of what kinds of tests are needed, comment on protocols, help resolve issues with proprietary data, and generally work as a group to sustain progress. The group decided that it would be premature to start organizing meetings at this point, until there was some indication whether DOE would be able to dedicate the resources needed to really pursue improvements in HALT.

The results from these breakout sessions are summarized below.

Systems Breakout Sessions

The Systems Breakout Sessions at the Accelerated Aging Testing in Photovoltaics Technical Meeting were assembled to address accelerated aging for complete systems. These sessions drew participants from industry, utilities, universities, national labs and DOE. The sessions on day one and two were charged with identifying the status, needs and priorities for accelerated aging of photovoltaic systems. Given the nice cross-section of participants, the results reflected a global view of the work that has been done as well as future needs.

In the initial session the group was to define the status of accelerated aging for PV system. Immediately the participants defined a complete system as a combination of all components including modules. However, since there was a separate module session in this meeting the group thought it appropriate to exclude modules. This became a difficult proposition at times because there are potential system failure mechanisms associated with the modules that are not considered when discussing module stresses. A good example that was brought up is that the environment stresses the ground connections to module frames causing corrosion and consequently failing the ground. While the failure could be attributed to corrosion at the module frame, module manufactures currently do not address grounding continuity as a reliability aspect of the module.

Excluding modules, the group set off to understand the role of accelerated aging in systems including the inverter, meters, switchgear, wiring, instrumentation/data acquisition, mounting hardware (including trackers), installation (installer qualifications), packaging/transportation, software and in some cases batteries/charge controllers. *It should be noted that the author believes that the group missed PV system-specific hardware, such as distribution transformers, that is required under some utility* *jurisdictions that may not be required elsewhere.* A more concise description of a PV system may be generated by considering everything from the utility interconnect back to the system mounting points.

STATUS

Once the group defined the system, there was consensus that *there are no accelerated aging tests currently applied to complete systems.* Participants listed current tests that might become part of a comprehensive accelerated aging protocol. These tests ranged from the truly accelerated tests such as HALT, thermal cycling, salt spray, vibration, crush, and drop tests to tests that may be considered more like extreme environment tests. These might include the qualification tests, long term field aging (high UV, high bias voltage, grounding, humidity, temperature, etc), environment induced corrosion, wind loading, UL, code compliance (e.g. fire and building codes), and operation and safety tests.

Participants noted static and dynamic tests are performed sporadically but need to be comprehensive where environmental stresses oscillate. It was also acknowledged that many of the aging tests are performed by OEM manufacturers and the PV industry is dependent on procurement specifications to assure the component's ability to withstand the stresses. A good example is wiring. Wiring must withstand temperature, humidity, abrasion, UV, flexure, etc. and still maintain dielectric strength, conductivity, code compliance, etc. over thirty years service.

Additional discussion explored the status of controls, data acquisition, communication and software. Participants recognized that considerably more sophistication can be expected in these areas although there is little in the way of aging tests.

NEEDS

The second session focused on identifying the accelerated aging needs for PV systems applications. Some immediate barriers were recognized. Primarily the complete system is too large and cumbersome to be tested. Each system will be different as components will change. Most importantly, the participants felt that any attempt to apply accelerated aging to the system level has to have *standardized metrics and procedures that measure small changes in systems.*

Participants immediately identified an approach, i.e. comprehensively test components and model the pieces into screening criteria. This approach needs to have an analysis framework that assists the integrator in system design and is user friendly. An enhancement to this effort, a complete system simulator, was also suggested. An associated need that got very strong support is the development of transfer functions that allows the individual component data to be integrated into a model.

All other needs discussed supported the aforementioned model. Strong support was voiced for testing system in extreme climates. Hot, dry, humid, cold, windy, salt spray, UV, etc. extremes can be found in the continental US, providing potential data points. Another similar suggestion was to test operational systems in the lab or field by increasing stresses and observation of system interactions; e.g. high voltage bias tests. Support was voiced for development of test centers. Along with this approach came encouragement to extract components from fielded systems and study them in the laboratory.

Finally, there was recognition that PV has still one frontier that needs to be developed and will need significant accelerated aging information. Building integrated photovoltaics is still very much in its infancy. BIPV needs to be stressed to simulate the use environments, these can be very different from outdoor applications. Participants recognized that BIPV will have multiple functions. Some requirements may take precedence to the PV energy generation. A good example is that, in a high value installation, BIPV window application may place higher priority on sealing than energy generation; making accelerated aging of the seals much more important than something like corrosion of a connector.

PRIORITIES

Setting priorities for accelerated aging for systems was a fairly straight forward exercise. *Standardized accelerated testing protocols* for components are mandatory for the data to be of value. Once the data is available, *transfer functions* need to be developed to integrate the results into a *predictive model*. *Long term testing* is needed to compare to accelerated testing and for model validation. Finally, a feedback mechanism to assist manufacturers in assessing corrective measures and a continuous improvement process will produce highly reliable systems.

Table 7: PV Accelerated Aging Tests - Status, Needs, Priorities

PV Systems Accelerated Aging Tests - Status, Needs, Priorities	
Status	No standard accelerated aging tests exist for integrated PV systems – components and subsystems at best
	Lab-scale system testing is done under some controlled stress conditions
	Field-aging is done at nominal (local) operating conditions – no acceleration
	Inverters and Charge Controllers: Manufacturers standard testing includes HALT, thermal, UL1741, component qualification, efficiency, performance, humidity, salt/fog, moisture intrusion, HASS, and some field aging testing (unaccelerated),
	Mounting hardware: Manufacturers' standard tests include corrosion, static/dynamic loads, vibration, parts qualification, grounding (limited), building code compliance, fire codes, wind, tracking performance and controls, installer certification, shipping
	Wiring: Installer training and certification, manufacturer tests (e.g., code evaluations, connectors, terminal strips, wire splices, moisture intrusion)
	Switch gear: Manufacturer tests include meters, instrumentation, batteries, data acquisition, installation (code, installer tolerance)
	Software: Industry standard, UL1998, system performance, limited networking
Needs	Comprehensive accelerated aging on components; model data into a screening criteria for system lifetime prediction
	Protocols for testing systems; test matrix
	Performance testing of systems in extreme field conditions
	Operate systems that can be stressed and tested in field or lab to develop knowledge beyond nominal
	Transfer functions from testing to lifetime prediction—a predictive mechanism
	System simulations in controlled conditions or chambers to help validate transfer functions
	Study field-aged components and apply data to system models
	Extreme conditions system testing (hot, humid, dry, salt, windy, seismic, etc.) – several test facilities are available

	Procedures and protocols to detect small change- early intervention; preventive approach
	Test protocols for BIPV components for modular housing - specific to the application
	Accelerated aging test capabilities for BIPV prototypes
	Develop analysis framework for system integrators to predict system performance w/aging
	From paper analysis to operational analysis
	Accurate data/analysis of ~10kW building block size; larger systems will be scaleable
Priorities	Systems-level predictive model that utilizes comprehensive component aging/lifetime data and yet-to-be-developed transfer functions to accurately predict system lifetime • Approach to apply existing and new tests at a systems level • Test facilities for: UV, temperature, humidity, wind, ambient conditions • Field data collection in key climates (e.g., CA) and extreme climates • Extraction of field-aged actual samples to broaden existing database of aged systems • Model transfer function from accelerated aging tests to lifetime prediction • Applicable to utilities, commercial, residential, off-grid, and BIPV
	System test protocols, including field test protocol w/o acceleration • Identify external existing resources, facilities and protocols that PV industry can use • For components: standardized HALT protocols, test matrix, independent performance and certification testing
	Better tools for • gathering accurate data from field (faster, remote operations, accurate, portable) • communication (e.g. standard communication protocol for all inverters/systems) • systems certification to provide assurance of system quality (including results from models of aged system)

Modules Breakout Sessions

The PV Modules Accelerated Aging breakout group had the largest number of attendees with representatives from industry, university, and government laboratories. Member's interests and backgrounds were widely varied. Many were in the business of producing and selling PV modules with a minority of the expertise in the thin-film area. Others were users and buyers of PV modules. A common understanding of what constitutes a failure was developed. Comments addressing the Status, Needs, and Priorities were freely expressed, recorded and summarized in the table below. The highest priority item was to establish a correlation between time-to-failure in accelerated testing and to time-to-failure in the field. In doing this we noted that the same mechanism must be tracked and field environmental conditions noted. The failure mechanisms selected for correlation study should be dominant causing the shortest time-to-failure. This is in lieu of a generic 20- or 30-year lifetime predictive, accelerated aging test protocol By now we all understand that such a testing protocol is un-attainable.

Field experience for PV products, in general, and modules, in particular, was highly sought after. A data base for different field failure mechanisms needs to be tabulated and perhaps DOE or DOD has a start on this.

The most useful diagnostic measurements are listed as: I-V, IR camera, Hi-pot wet and dry, visual inspection, layer adhesion-peel and torque shear. It was pointed out by many that a sensitive parameter(observation) was of great value in detecting failure mechanisms long before degradation in power output. The value of the IR camera image was expressed by several.

Of a general nature, we agreed that we should have continuing studies by members of this group to address the more commonly occurring mechanisms. It was suggested that the best time for a follow-up meeting may be after the Solar America Initiative awards are made. Then participants will know what their support will be. We agreed that adhesion and corrosion along with soldier bond and interconnect related failure were most dominant and, therefore most worthy of study by this group. The goal would be to determine acceleration factors for these dominant failure mechanisms. The table below summarizes the status, needs and priorities for module accelerated aging tests discussed at the meeting.

Table 8: PV Modules Accelerated Aging Tests - Status, Needs, Priorities

PV Modules Accelerated Aging Tests - Status, Needs, Priorities	
Status	Commonly used standardized tests include: Thermal cycle with and without current flow, Damp heat exposure, Humidity-freeze cycling, Hail impact, Surface cut, 45° cut (UL-1703) evaluation by wet hi-pot, Dynamic and static mechanical loading, and other elements of IEC 61215 or 61646 qualification test sequences
	Non-standard tests commonly used include: ASTM: G154 70°C, >1,000 hours; B117 5% salt solution, 35°C, 96 hr. cycle 48 hr wet, 48 hr. dry (salt/fog); D903 180° peel strength; D1002 shear test single-lap-joint
	Non-standardized tests for Flexible Modules include: Unique tests for flexible modules to capture coiling, flexing and forming characteristics, heat/humidity/sunlight/high voltage, delamination test TCOD 15, solder bond failure
	Non-standardized tests for Rigid Modules include: vibration tests for shipping, dynamic load testing, static load testing, non-uniform wind loading, dynamic testing in wind tunnels, exterior temperature testing, current based TC50 and HF10, voltage bias
Needs	Needs in test protocols and in correlating lab test results with field observations • Test capabilities/methodology validation: determination of what is an effective accelerated test, how accelerated can you go? Identifying changes or degradation, not just failure. Finite elements analysis. Combine and simulate multiple stresses, high and low levels of multiple variables. Ability to monitor panels in-situ as they are stressed. Ability to isolate stress concentrations. • Accelerated tests for reliable predictions – how to establish warranties • Correlation of accelerated tests to years in field. • Common failure modes established, i.e. corrosion, thermal cycle, breakage, etc. • Get to field to test/identify older modules to study for success/failure • Documented field conditions: develop standard field test protocols to gain consistent data;. What do they say about what to test – agreed conditions to warrant • Documented causes of most field failures • A meaningful test to predict end of life • Some improvement testing for manufacturing problems • Ability to apply voltage during humidity tests, UV
	Improvements needed specific to HALT and HASS testing: • HALT and real world tracking, correlation, testing • HALT outdoor capabilities – concentrating, light, heat etc. • HALT and HASS – are they only for new products? Apply more broadly to thermal cycling, freeze, ER, use for comparisons
	Needs in data collection and in accelerated aging data base development include: • Central clearinghouse / database for information, protocols, data • Documented module specifications, materials used, and characteristics • Detailed characteristics of material properties • Need to handle problems/failure anonymously • Collect data from manufacturers • Data on environment and installation conditions including product history

	• Data collection needs to be made in consistent, unbiased ways • Determine failures caused by damp heat and then vary to see what combination causes specific failures including corrosion -- do damp heat tests really show what happens in the field? • Access to existing data – OTF 1200 module testing for pass/fail, lessons already learned form JPL and past history on solder bonds, thin cells, lamination, interaction of layers, etc. • Energy output, other indicators like temperature, standardized ways of measuring in field, wind speed, kWh ratings and what they say for tests under different conditions
	New field tests: in different climates, exposure to conditions outside of standard tests, combinations of conditions, stress/deploy/test.
	Comprehensive tests for current and new materials and designs. Issues: alternatives to aluminum, unframed modules, frame alternatives, different glass/encapsulant, polymer aging and power delivery components like wire and connectors.
	Resources/Approaches: Money for equipment and expensive testing; access to multiple chambers and test runs; people to analyze and put information in useful form; work with new universities to tap their resources; new collaborative activities; approach to make module size samples uniform.

Devices Breakout Sessions

Within the Device Testing breakout group, we quickly realized that most device level issues fall into two areas:

1. Testing of new technologies
2. Testing of existing technologies during design and process changes; and periodically to assure quality control

Among the PV technologies, existing silicon and III-V technologies fall into the latter category; CIS and CdTe thin film technologies fall into the former and require the most emphasis. If and when new technologies are evaluated to be promising for deployment, the same set of priorities should be extended to cover their needs.

We discussed the intrinsic stability and degradation mechanisms of PV cells in the Device Reliability group. The group meeting to discuss Device Reliability numbered about 25. However, there were no representatives outside thin films, and we felt our report may not adequately cover these topics. Thus although we felt that the issues in traditional wafer silicon and for III-Vs for concentrators were minimal, this was not a finding based on the stated views of experts in those areas. This could be an area for further understanding.

Within thin films, it was clearly expressed that reliability is a major issue, even to the point of sometimes transcending cost and efficiency. For example, severe intrinsic degradation mechanisms could prevent a technology from being competitive, either due to unacceptable annual losses, module failures, or a loss mechanism that only revealed itself in a long-term catastrophic manner. Each of these requires substantial understanding and possible improvements. For example, no known method exists for predicting 30-year lifetime, and as illustrated in the negative findings of the First Solar report (below), the effort to develop such tests is challenging or even impossible. As a pragmatic result, we may approach the problem through aggressive HALT tests in which individual degradation mechanisms are identified and addressed, even if we cannot be certain that the mechanisms will occur under actual (and milder) outdoor circumstances.

As an example of an attempt to develop a long-term test, Peter Meyers of First Solar presented information on a stress test for their CdTe cells and modules. Although much faster than their current (and partially validated) 56-day light and temperature test, it turned out that their new test did not correlate with module reliability in the field (see Figure 24, $R_{sq} = 0\%$). Cells that degraded under the increased stress did not degrade outdoors, since the stress test (by going to a much higher temperature) accessed a physical mechanism that has not been observed in the field. This null result showed that simply raising the temperature of a stress test may not lead to a better, faster test; it may indeed lead to a test that shows degradation irrelevant to actual experience. Thus developing new, faster, simpler tests for First Solar CdTe remains unresolved.

There is one existing protocol for a known loss mechanism in thin films: the 50° C, 1000

- **Sister plates from each of twelve conditions were stressed using ALT**
- **ALT results were compared to baseline field performance**
- **No correlation observed – for this specific ALT protocol (Rsq adj = 0)**

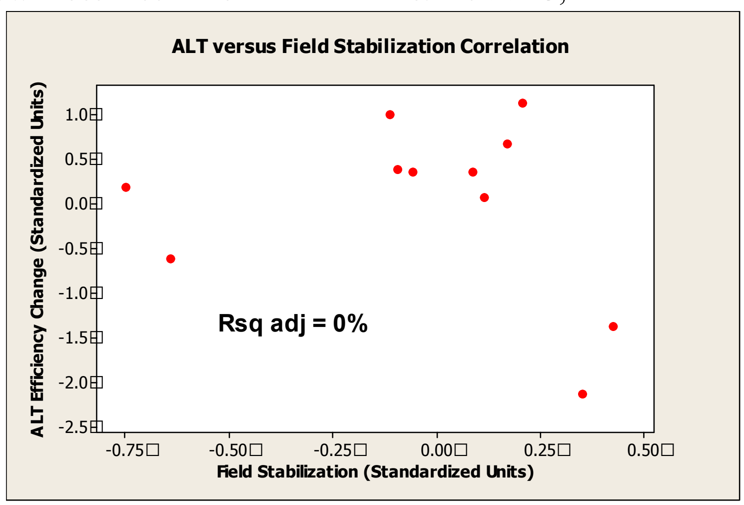


Figure 24: ALT and Field Stabilization Correlation

hours light soak test for amorphous silicon devices. This test shows the advantages and problems with such protocols. Although it cannot establish degradation in specific solar locations (since temperatures and spectrum vary), the test can give a sense of the expected range of degradation of amorphous silicon devices. This is about 20% for contemporary devices. More importantly, this same test showed that after the initial degradation, the devices stabilize. This stabilization was essential to the survival of amorphous silicon PV.

Because thin films have not been in the field to the same degree that x-Si has, there is little publicly available, long-term module reliability data, and what there is shows the usual mixed pattern of early deployments in any PV technology. Thus the status of the reliability of thin films is not only an open question, it remains a key question for potential buyers. This question has both intrinsic device level components and encapsulation issues. At the device level, there are also questions of area uniformity, are-related defects, and monolithic cell interconnection.

We identified the following testing needs and priorities:

1. CdTe and CIS need an improved base of scientific knowledge to understand root causes of losses.
2. CdTe and CIS need faster tests for stability and problem identification. Other technologies do not express the need for these tests because they believe that fielded systems show that long-term device reliability already exists.
3. All device technologies need periodic tests and tests after changes in design or processing. Thus even existing technologies need re-testing.
4. Understanding of the greater sensitivity of CIS and CdTe to water vapor is needed: what are the areas most prone to losses? All thin films could use investigation of new water vapor barrier layers.
5. All thin films (but especially CIS and CdTe) need tests of mini-modules for uniformity and interconnect issues.
6. All thin films need understanding of the chemical impact of EVA and other encapsulation choices on devices.
7. A nonproprietary database needs to be established, including device data (degradation, losses, analysis) and correlation with fielded arrays.
8. CdTe and CIS need development and validation of specific protocols for long term performance assurance.

Although these issues seem almost universally associated with thin films, that was (1) a function of the attendees and (2) may understate the needs of the other technologies. This latter is not just because the technologies were not represented (which was both because of a lack of the right mix of attendees and also because the issue was not perceived as serious enough to warrant attendance) but because when changes are made in devices, they can become newly vulnerable.

Clearly, the vulnerability of thin films to degradation mechanisms is a high priority. Fielded systems are not old enough to show clear trends, and problems must be caught as soon as possible. Thus understanding, fixing, and validating degradation mechanisms in thin films are high priorities. Another important priority is to continue vigilant testing of existing technologies as they are changed and improved.

Table 9: PV Devices Accelerated Aging Tests - Status, Needs, Priorities

PV Devices Accelerated Aging Tests - Status, Needs, Priorities	
Status	Evidence that III-V and X-Si are stable and rugged, except for a small light-induced loss in some higher efficiency x-Si cells (except for thinner cells which are showing a greater propensity for cracking).
	Evidence that all thin films have some device level instability issues (which can vary by device design and processing), and that CIS and CdTe have greater sensitivity to water vapor than silicon. Evidence that despite this, properly made and encapsulated devices may have adequate stability. Recognition that the challenge is to understand the mechanisms and map the range of process variables needed to assure stability.
	CdTe: 56-day light and heat exposure of CdTe at Voc (60-90 C), Electron beam induced current, laser soak (1-10 suns), monitor decay in photoluminescence intensity
	Optoelectronic analysis of pre- and post-stressed devices
	Uncertainty about gross- and micro-nonuniformity issues and impacts on degradation; initial papers and some experiments

	Early experiments with broadening the CdTe stress test to all thin films: temperature (<= 100°C), light (<2 suns), moisture, diurnal cycle, efficiency over time (capture degradation / stabilization)
	Uncertainty if there are slow or delayed degradation mechanisms that might occur in thin films after many years of apparent stability.
Needs	Recognition that thin films have the most existing and unknown problems, and among the thin films, a-Si is the most fully characterized at the device level, and most issues are well handled. Thus CdTe and CIS require the most attention at the device level.
	Both CIS and CdTe need greater scientific understanding (complexity of issues prevents understanding and fixing root causes)
	CIS and CdTe need faster, simpler, non-proprietary tests that are not misleading
	Cells must be tested enough to develop statistics; and in enough variety to span the range of processes and process variations.
	Correlation must be established between tests (e.g., the current 56-day test) with day/night cycling and other real world conditions
	A nonproprietary database should be developed to allow sharing. Issues of corporate sensitivity must be addressed.
	Small cells are not sufficient samples for establishing loss mechanisms: minimodule with interconnect features are needed to span gap from full module to cells. Both interconnects and area-nonuniformity are sources of loss mechanisms.
	Testing and stressing must be continued as cells progress through often-rapid process and design changes. New technologies and even established silicon and III-V devices may be vulnerable to such changes and need to be periodically analyzed.
	Some aspects of device testing require substantial investment in equipment and people; locating them at one location can allow for shared solutions
Priorities	Thin films, particularly CdTe and CIS, need an improved base of scientific knowledge (e.g. issues of water vapor, uniformity, encapsulation, etc.) to understand root causes of current issues. • Tests of CdTe and CIS devices are the highest priority; • CdTe and CIS need faster tests for stability and problem identification • Understanding of the greater sensitivity of CIS and CdTe to water vapor is needed: what are the areas most prone to losses? All thin films could use investigation of new water vapor barrier layers. • All thin films need understanding of the chemical impact of EVA and other encapsulation choices on devices • All thin films (but especially CIS and CdTe) need tests of mini-modules for uniformity and interconnect issues • CdTe and CIS need development and validation of specific protocols for long term performance assurance
	For established technologies, faster tests are needed for stability evaluations and problem identification, especially for assuring quality control during design and process changes. • Faster tests that correlate well with field observations of degradation are needed • All device technologies need periodic tests and tests after changes in design or processing.
	A nonproprietary database needs to be established, including device data (degradation, losses, analysis) and correlation with fielded arrays

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Appendix B: Participants

Last	First	Company
Albin	Dave	National Renewable Energy Laboratory
Barikmo	Howard O.	Sunset Technology, Inc.
Borden	Peter	Applied Materials
Bordonaro	Chris	Evergreen Solar Inc.
Bulawka	Alec	DOE Office of Solar Energy Technologies
Capps	Philip	Nanosolar, Inc.
Cromer	Charlie	Florida Solar Energy Center
Cunningham	Daniel	BP Solar International
Davidson	Joel	Solar Integrated Technologies
Davis	Michael	Texas A&M University System
DeBergalis	Mike	DuPont Photovoltaic Solutions
Delahoy	Alan E.	Energy Photovoltaics, Inc.
Dhere	Neelkanth	Florida Solar Energy Center
Enzenroth	Al	Colorado State University
Hanoka	Jack I.	Evergreen Solar
Hassett	Robert	DOE Office of Solar Energy Technologies
Hegedus	Steve	SSH
Jansen	Kai	Energy Photovoltaics, Inc.
Ji	Liang	Underwriters Laboratories Inc.
Jorgensen	Gary	NREL
Kalejs	Juris	JPK Consulting
Kanto	Eric	Global Solar Energy, Inc.
Karpov	Victor G.	The University of Toledo
Kempe	Michael	NREL
Kuitche	Joseph M	Arizona State University - Polytechnic Campus
Margolis	Robert M.	National Renewable Energy Laboratory
Mazer	Jeffrey	DOE Office of Solar Energy Technologies
Meakin	David	Advent Solar
Meck	Robert	EMCORE Corporation
Nguyen	Andy	BP Solar International
Osterwald	Carl	National Renewable Energy Laboratory
Palomino	Ernie	Salt River Project
Placer	Neil	BP Solar International
Roedern	Bolko von	NREL-NCPV
Rosenthal	Andrew	Southwest Technology Development Institute
Ross	Mike	First Solar, LLC
Rudin	Arthur	SHARP Electronics Corporation
Schuyler	Terry	DayStar Technologies
Shreve	Kevin	GE Energy Solar Technologies
Shvydka	Diana	
Sites	James R.	Colorado State University
Strzegowski	Luke	Specialized Technology Resources
Sullivan	Jeff	Applied Materials
Surek	Tom	NREL
TamizhMani	Mani	Photovoltaic Testing Laboratory Arizona State University
Tang	Tony	GE Energy Solar Technologies

Tarbell	Ben	Miasolé
Terao	Akira	SunPower Corporation
Ton	Dan	Department of Energy Solar Energy Technologies Program
Tucker	Ryan	Specialized Technology Resources
Ullal	Harin S.	NCPV/NREL
Xavier	Grace	Schott Solar

Presenters

Banerjee	Arindam	Uni-Solar
Hudson	Ray	Xantrex
Loman	Jim	GE Energy Solar Technologies
McLean	Harry	Xantrex
McMahon	Tom	NREL
Mikonowicz	Alex	Shell
Myers	Peter	First Solar
O'Brien	Colleen	PowerLight
Whittaker	Chuck	BEW Engineering
Wohlgemuth	John	BP Solar International

Facilitators

Quintana	Michael	SNL
Tillerson	Joe	SNL
Zweibel	Ken	NREL
Degroat	Kevin	McNeil Technologies
Mulligan	Conrad	McNeil Technologies
Whittier	Jack	McNeil Technologies
Eisemann	Douglas	McNeil Technologies
Davis	Euniesha	McNeil Technologies

Appendix C: Final Agenda

Accelerated Aging Tests in Photovoltaics
(Research Curiosity or Decision-Making Tool?)

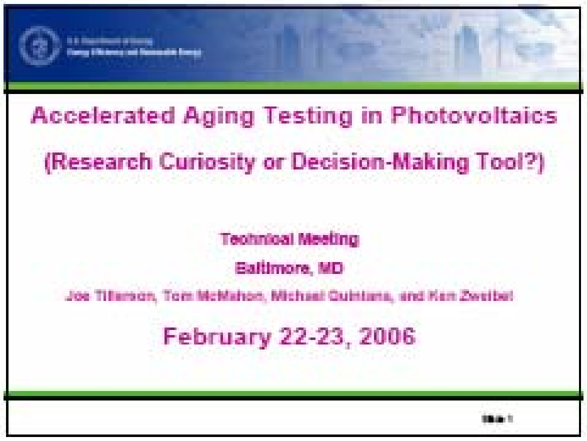
Wednesday, February 22, 2006

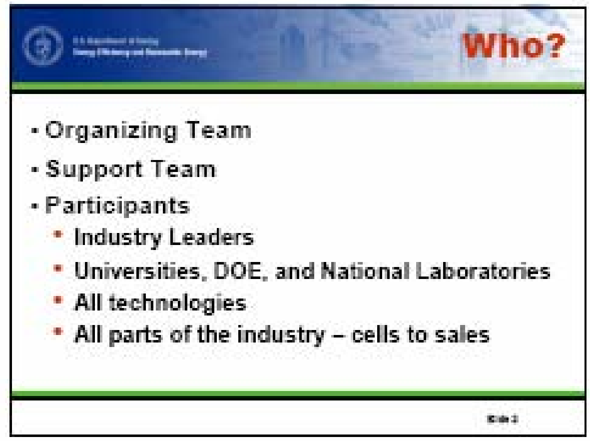
8:30 Welcome – Ray Sutula
8:40 Introductions and Meeting Goals – Joe Tillerson
8:50 Session 1 – Three, 25-minute presentations
Accelerated Aging Tests – Types and Status -- Tom McMahon, NREL
Accelerated Aging – Needs for Systems Design
and Performance Issues -- Colleen O'Brien, PowerLight
Highly Accelerated Lifetime Tests (HALT) and Highly Accelerated Stress
Screening (HASS) – How Applicable to PV? -- Jim Loman, GE
10: 05 Break
10: 25 Session 2 – Three, 25-minute presentations
Using Accelerated Testing in the Development of New PV Products
and Processes -- John Wohlgemuth, BP Solar
BOS and System Component Requirements for Accelerated Testing --
Chuck Whitaker, BEW Engineering
Devices, Interconnects and Module Design – Accelerated Testing --
Peter Meyers, First Solar
11:40 Lunch
1:15 Session 3 – Three, 25-minute presentations
Inverters and HALT Applications -- Ray Hudson/Harry McLean, Xantrex
Quality Assurance – Accelerated Testing in Manufacturing Environment --
Alex Mikonowicz, Shell Solar
Accelerated Testing Challenges for Flexible Modules -- Arindam Banerjee, Uni-Solar
2:30 Breakout Group Assignments: Devices, Modules, or Systems
2:50 Break
3:10 Breakout Session 1 Focus: Current Status or Capability
4:45 Adjourn
6:30 Reception

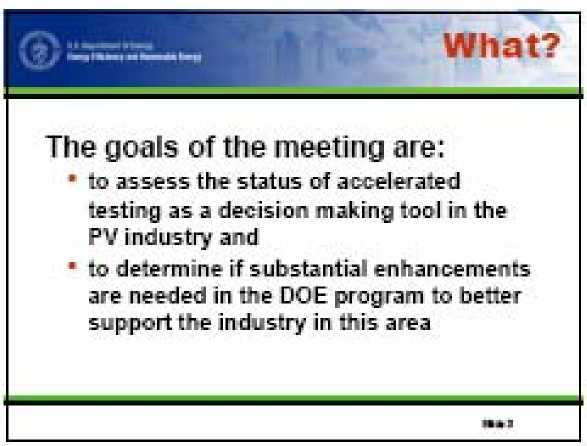
Thursday, February 23, 2006

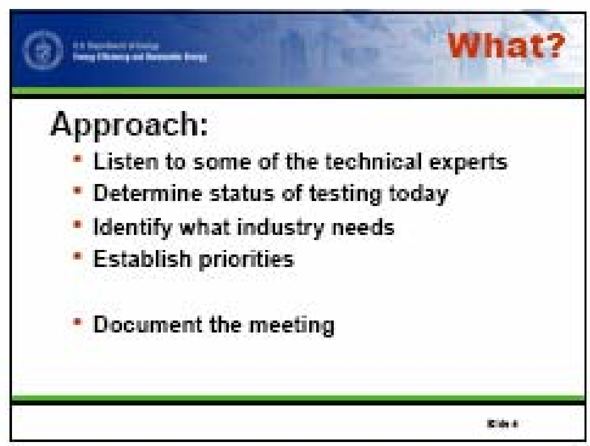
8:00 Breakout Session Assignments
8:15 Breakout Session 2 Focus: Industry Needs for Decision Support
9:45 Break
10:05 Breakout Session 3 Focus: Priority of Advanced Testing Needs
11:05 Summary Reports from Breakout Groups
12:30 Adjourn

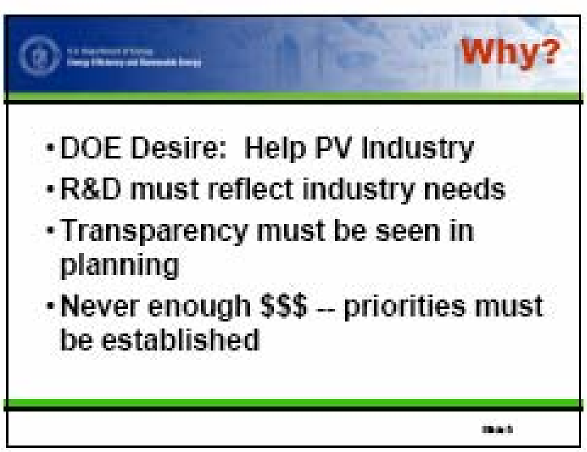
Appendix D: Presentations

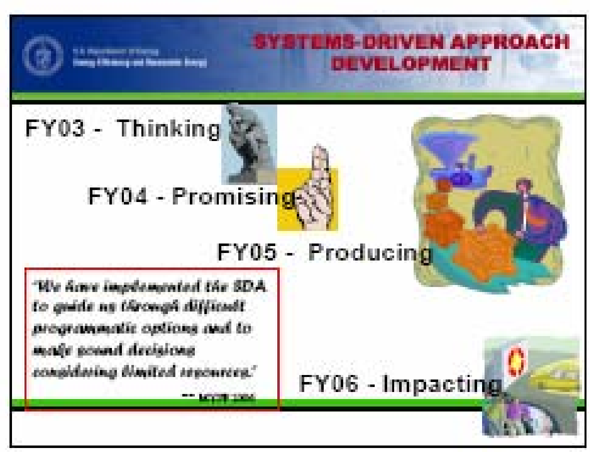












SDA

- Basis for Multi-Year Program Plan
- Reference Systems reflect where we are today
- Targets show where we need to be
- Analyses quantify where to work to best achieve targets
- Most important metrics are cost, performance, and reliability
- Reliability is why we are here today

NOW is the Time

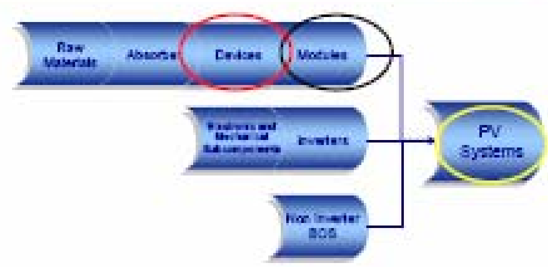
- Rapidly changing manufacturing capacity
- Process being changed to reduce cost
- New technologies being introduced
- Markets growing – federal & state impacts
- Pressure to produce products is immense
- Industry cannot afford a "black eye"

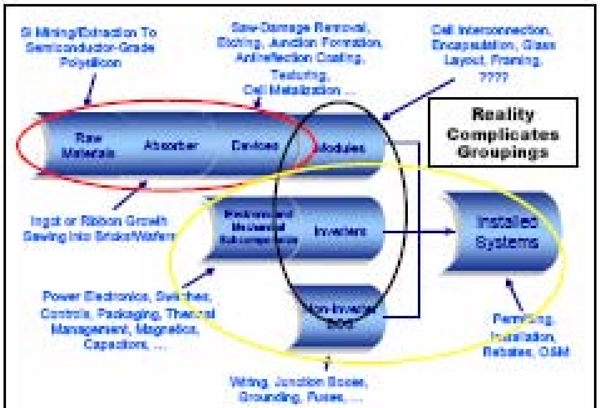
Sensitivity

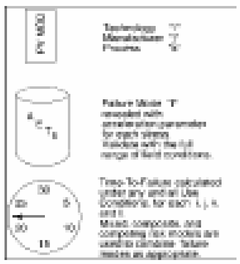
Elephant in the Living Room –

- Reliability and Failure Mechanisms are understandably sensitive information
- Engineers see tremendous need to share struggles
- CEOs and Marketing fear impacts of improper sharing
- Thanks to all for sharing what you can without violating trust

PV Systems & Breakout Groups







Accelerated Aging Tests - Types & Status

Tom McMahon

NREL, Golden CO

Expectations for Ideal Accelerated Testing (AT)

1. Virtually no field/use failures,
2. Quick,
3. Easy/inexpensive,
4. Standardized to cover ALL module/component types.

Problems applying text book AT to PV

1. PV use environment MUCH MORE SEVERE than for consumer products.
2. Higher stress in field causes shorter time-to-failure > more field failures
3. Higher stress causes additional failure mechanisms > AT doesn't catch all > more field failures.
4. Use times much longer, up to 30 years.
5. Lack of large numbers of identical modules for AT and correlation with field deployed modules.
6. Cost and efficiency pressures > a changing product and consequent re-validation of AT with field results.
7. Diagnostic studies complicated by de-encapsulation process

AT-Decisions in the PV industry

What decisions can be made from accelerated testing?

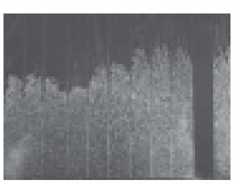
What decisions can't we make now, but need to?

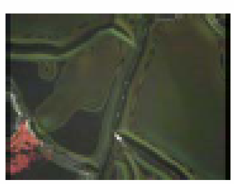
Service life prediction is in this category. [3]

Failures that have occurred in the field that weren't caught with existing tests. Can be a result of known design/supplier changes or unknown material or component changes.

SnO delamination[RP,56,57]

first noted from field returns.





Glass supplier changes barrier layer unbeknownst to superstrate PV manufacturers raising all kinds of problems.

Five types of testing AT

1. Qualification tests (design flaws, fabrication error, etc.)
2. UL tests (Safety)
3. Screening (rank ordering)
4. Service life prediction(time-to-failure, predicted energy output, etc.)
5. Exploratory (to uncover new failure mechanisms, reveal new failure mechanisms found from field returns, HALT and HASS etc.)

Failure

When the PV product no longer meets the needs/requirements of the user/certifier.

A nebulous statement such as this needs some numbers before it has any quantitative significance for engineering studies.

Reliable PV

A "reliable PV" module has a "high probability" that it will perform its intended purpose adequately for 30 years, under the operating conditions encountered.

Example with numbers added:
A PV module fails to provide service if its power output decreases by more than 30% before 30 years, i.e., 1%/yr, in its use environment.

A "high probability" could mean that 95% of the modules in the field will achieve this success.

By "use environment," we mean any and all use environments that the PV module will experience during service.

Acceleration Factor

How much indoor chamber stress testing accelerates the time-to-failure as compared to time in use environment.

Depends on stress(use site) and mechanism being studied.

Types of Stress

T, RH, I (cell-to-ground or cell bias), V (cell-to-ground or cell bias), T-cycling, H-freeze, UV,… applied singly, together, or serially.

User induced stresses (incorrect wiring, improper module mounting or handling, etc.)

Exponential dependence for T and RH

T usually has a simple Arrhenius failure rate function. RH sometimes is given the same exponential dependence with 1 to 3% RH equated to 1 °C.[48]

How do we develop tests and acceleration constants for other stresses or combinations of stress that are found in the field?

Do we want isolated stress, simultaneous stresses, or sequential stresses?

Sensitive Parameter (Response Variable)

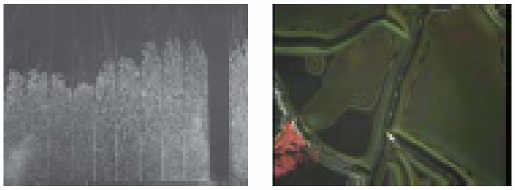
Quantity derived from I-V (light and/or dark),

Hi-Pot current,

Visual area damaged,

Individual cell shunt resistances,

Example of "Area" used as a sensitive parameter

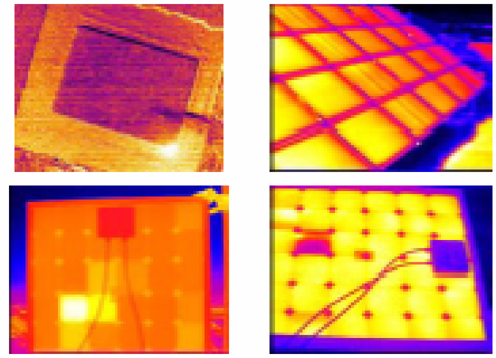


SnO delamination[?, 15, 17]

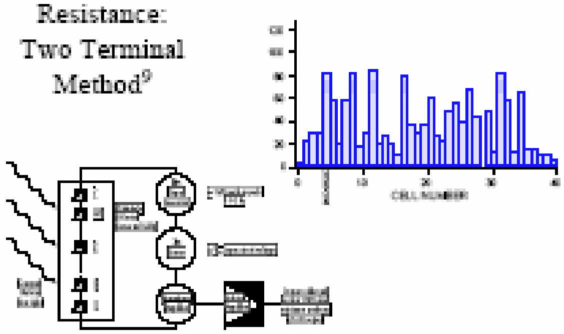
Accelerated tests developed by BP and EPV to screen SnO glass[18]

IR Camera Diagnostics

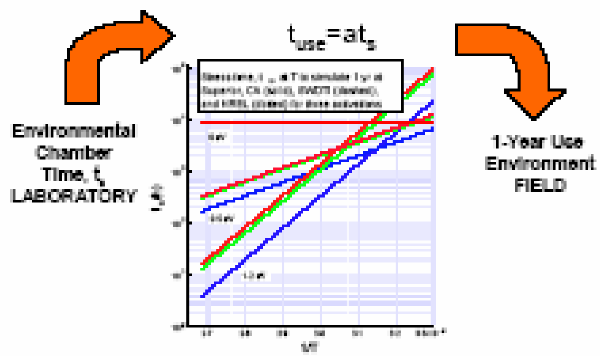
Cells to Systems, 0.2 to 50 °C



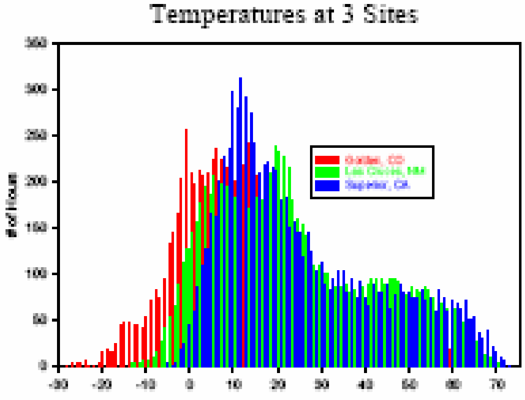
Individual Cell Shunt Resistance: Two Terminal Method[9]



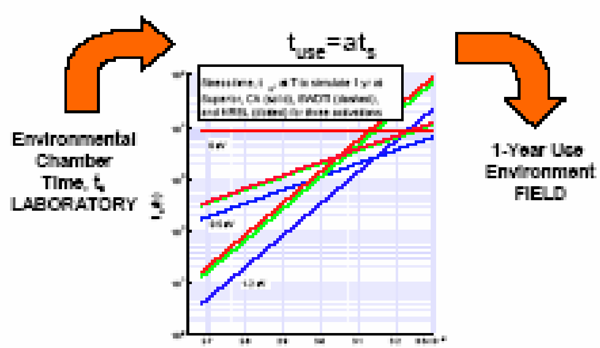
Calculated Acceleration Factor "a"[15, RF]



Yearly Distribution of Module Temperatures at 3 Sites



Calculated Acceleration Factor "a"[15, RF]



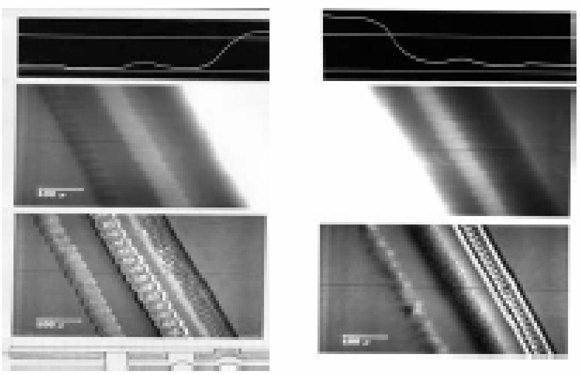
Potential Failure Modes and Mechanisms of Thin Film PV Cells[RP]

Failure Mode	Effect on I-V Curve	Possible Failure Mechanism
Main junction; increased recombination[24]	Loss in fill-factor, I_{sc}, and V_{oc}	Diffusion of dopants, impurities, etc.; electromigration
Back barrier; loss of ohmic contact (CdTe)	Roll-over, cross-over of dark and light I-V, R_{series} increases	Diffusion of dopants, impurities, etc.; corrosion, oxidation, electromigration
Shunting[26-28]	R_{shunt} decreases	Diffusion of metals, impurities, etc.
Series; ZnO[27], Al[28], Mo [33]	R_{series} increases	Corrosion, diffusion
De-adhesion of SnO_2 from soda-lime glass[27,30]	I_{sc} decreases and R_{series} increases	Na-ion migration to SnO_2/glass interface
De-adhesion of back metal contact	I_{sc} decreases	Glass warp age, Lamination stresses

Modes and Mechanisms of Thin Film PV Modules[RP]

Failure Mode	Effect on I-V Curve	Possible Failure Mechanism
Interconnect Degradation		
a. Interconnect resistance; Zn:Al/Mo or Mo,[27] Al interconnect[49]	R_{series} increases	Corrosion; electromigration
b. Shunting; Mo across isolation scribe[33]	R_{shunt} decreases	Corrosion; electromigration
Busbar Degradation	R_{series} increases or open circuit	Corrosion; electromigration
Solder Joint	R_{series} increases or open circuit	Fatigue, coarsening (alloy segregation)
Encapsulation Failure		
a. Delamination[26-31]	Loss in fill-factor, I_{SC}, possible open circuit	Surface contamination, UV-degradation, hydrolysis of silane/glass bonds, glass warpage, cracking of glass edges, thermal expansion mismatch
b. Loss of hermetic seal		
c. Glass breakage		
d. Loss of high-potential isolation[10,30,37]		

The Laser Scribe Line delineates between Cell and Module failure?



Criteria for cell and module failure:[RP]

Cell-related failures

a) Caused by use-environment stress, such as temperature, that packaging cannot protect against.
b) Cells must tolerate low levels of pollutant gases or water vapor. These levels will depend on technology and related device processing.

Packaging-related failures

a) Pollutant gas (admitted from the outside or generated from within) or water vapor levels are elevated at the cell, cell interconnect, or bus-line interconnects to levels that induce damage that diminish module output power.
b) Loss of electrical isolation of cells from ground, loss of structural integrity, or visual defects that are unsatisfactory to the user.
c) Use of incompatible materials; thermal expansion mismatch, creep, loss of adhesion, galvanic corrosion, etc

AT Pitfalls:

"Pitfalls of Accelerated Testing," W.Q. Meeker and L.A. Escobar, IEEE Trans. on Reliability, vol. 47, NO 2, June 1998

Conclusions:

The problems of applying text book accelerated testing(AT) to PV industry products was discussed.

Field failures will continue to plague PV until those problems are resolved.

AT terminology presented. (Types of AT, failure, reliability, acceleration factor, types of stress, sensitive parameter)

Failure modes and mechanisms for cells and modules reviewed.

Be aware of "pitfalls."

Importance of field(use-condition) testing emphasized.

HALT Testing: How Applicable to PV?

Presented by: Dr. James Loman, GE Energy
Co-authors: Kevin Shreve, Jerome Moyer, Todd Tolliver, Scott Sealing

February 22, 2006

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Why Are We Concerned With Accelerated Aging?

GE Warranty on PV Modules
- Workmanship for 5 years
- <10% Power Degradation at 10 years
- <20% Power Degradation at 25 years

Field Data
- Data on AstroPower PV modules with similar materials- 6 years to 10 years old
- Degradation is only a few % at 10 years- but data sets are small

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What is HALT?

HALT is a test technique that uses extreme temperature, vibration, temperature change rates, and combinations of temperature and vibration step stresses (and other product specific stresses) to rapidly identify marginal design and manufacturing processes in a product.

HALT quickly stresses a product from ambient to lower operating limit, to lower destruct limit, upper operating limit, upper destruct limit, vibration operating limit, vibration destruct limit, and finally with combined temp/vibe fast change rates.

HALT should be used as part of the design process to rapidly expose design weaknesses by: combining a wide range of temperature (-100°C to + 170°C), rapid rate of temperature change (60°C/min), multi-axis vibration (6 degrees of freedom, 2Hz-10KHz, up to 60Grms), power and frequency cycling, and other *product specific* extremes.

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Why Perform HALT?

Relative Importance of the Reliability Processes during the ACTUAL DESIGN phase

Ranking Numbers: (9 = important, 3 = average, 1 = low)

CTQs (whats)	CTQ Weight	Halt	Hass	Reliab. Simulation	FMEA	FRACAS	WCA	Growth Testing	RDT/PRAT	Environ. Tests	Tolerance Analysis	Thermal Survey	Stress Derate	Reliability Allocation
Do early reliability estimates	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Reliability Improvements	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Reduce failure risk	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cost-effective validation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Time-effective validation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Design trade study assistance	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vendor/part selection	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Safety	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vendor/Mfg Process Monitoring	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Failure Mode Identification	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Warranty / DOR reduction	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Identifying CTQs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Unit cost reduction	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total Process Weight		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Relative Ranking		2	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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Examples of Failure Modes Uncovered in HALT

Example of failure modes uncovered in HALT on Appliance Electronic Boards
- improper component preparation and installation of axial parts (mfg)
- improper component installation; power resistors too low to surface (mfg)
- incorrect component lead spacing; broken transistor, resistor (design layout)
- incorrect power resistor pad design on the solder side (design layout)
- improper component installation; passive parts are installed too high (mfg)
- intermittent components during the vibration tests; relays (supplier)
- bad solder joints; developed early cracks
- failed component; Mylar cap mounted without lead-formed stress relief (mfg)
- flux contamination under the conformal coating (mfg)
- asymmetric solder joints on the IC which will lead to premature solder joint failure (mfg)

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Examples of HALT Chamber @ GE

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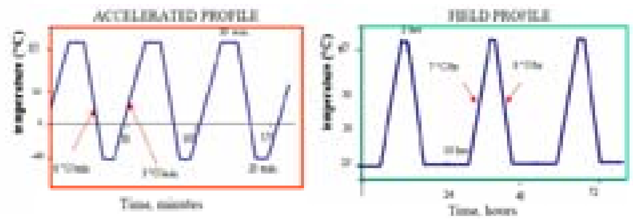
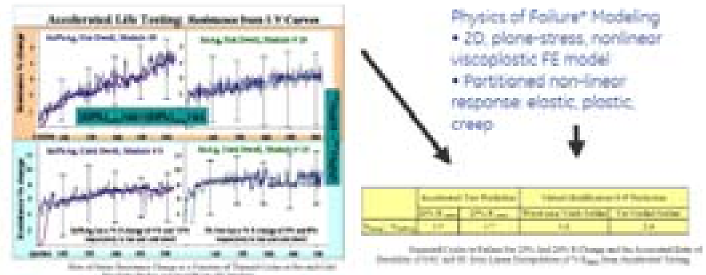
HALT Applied to Photovoltaic Module

- Rapid thermal cycle was used to determine durability of cell-solder-tabbing interface
  - PbSn solder
  - SnAg solder (Pb free)



Schematic of Accelerated and Field Temperature Profile

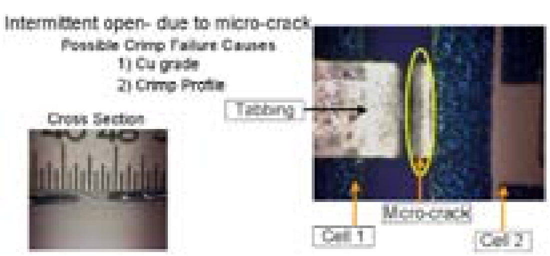
HALT Applied to Photovoltaic Module



*Durability of Pb-Free Solder Connection Between Copper Interconnect Wire and Crystalline Solar Cells, 2006 ITHERM Conference, Gayatri Cuddalorepatta et al Univ of Maryland and GE

HALT Applied to Photovoltaic Module

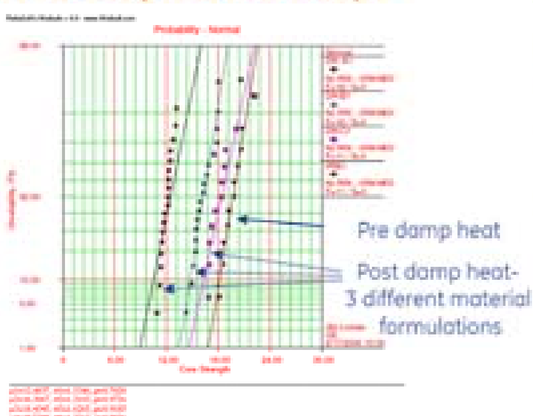
- Rapid thermal cycle to failure in HALT test of Pb free certification modules uncovered an unexpected failure mode: Open circuit of interconnect between cells
- This failure mode is not reported on GE/ AP modules (PbSn solder)
- Failure in tabbing was due to low tensile strength copper from new supplier- not related to the Pb free solder
- Revised specification for Cu tabbing based on the finding.
- Units also failed in the same mode in qualification test per IEC 61215
- HALT was a value added, quicker way to find an issue



Damp Heat is a HALT Applied to PV Module

- Reliability tests as specified in IEC61215 are a form of HALT Test
- As an example, consider 1000 hours of damp heat
- Test conditions: 85°C Temperature, 85% RH
- Typical environmental condition (East Coast USA): -10 to +40° C, 10% to 100%RH
- DH- allows the ability to distinguish between different design approaches
  - De-lamination
  - AR coating fading
  - Bond strength- example follows
- Still being investigated: transfer function from DH test to field life

Pre- and Post- Damp Heat Data Example



Conclusion

HALT testing uses high levels of stress to induce failure or degradation

Attempt to excite failure modes that could occur in the field and limit life

HALT testing and Physics of Failure analysis provide a valuable way to Uncover failure modes and also to simulate 25 year life

Further investigation of transfer functions from HALT test to predicted life is needed

Using Accelerated Testing in the Development of New PV Products and Processes

J. Wohlgemuth
BP Solar International

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INTRODUCTION

- How do we test the reliability, long term durability and even the safety of PV modules built using new materials or with new processes?
- Outdoor field testing is a must, but it takes much too long to be of much use. (We can't wait 25 years to introduce a new product.)
- Therefore we must use accelerated tests to qualify new PV products and processes.

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ACCELERATED STRESS TESTS

- We can't wait 20 or 25 years to see if a change will impact reliability or lifetime.
- Must identify failure mechanisms from outdoor exposure.
- Then develop stress tests that accelerate the same failure mechanisms.
- Then apply these accelerated tests to modules with new materials and processes with hope that the tests are still valid for studying the previously identified failure mechanisms.
- (This is not always the case.)

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Overall Reliability Efforts

- Field Experience
  - Analyzing commercial warranty returns
  - Deploying and monitoring individual modules over long time periods
  - Monitoring the performance of PV systems over time.
- Accelerated stress tests

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Which Accelerated Stress Tests do we use?

- Thermal cycle with current flow
- Damp heat exposure (Sometimes with applied voltage)
- Humidity-freeze cycling
- Dynamic and static mechanical loading
- UV plus heat

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How do we select the conditions and duration?

- First guideline is the qualification test sequence (IEC 61215 or 61646)
- BP Solar extended the thermal cycles to 500 and the damp heat to 1250 hours when we went to 25 year warranty.
- These are the minimum test durations. Sometimes we test longer to build our understanding.
- Sometimes we change the conditions to understand the failure mechanisms and the acceleration rates.
- For UV we try to simulate 25 years of exposure. Typically we test through the glass for a long time (~26 weeks) and direct exposure for a short time (~ 3 weeks)
- Usually use qualification test protocol, but may deviate to better evaluate failure mechanisms.
- Not every accelerated test failure is going to cause a problem in the field!

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Measurements Tools

- **PV Performance (I-V curve)**
- **Dry Hi-Pot**
- **Wet insulation resistance**
- **Visual inspection**
  - **Discoloration**
  - **Embrittlement**
  - **Delamination**
  - **Corrosion**
- **IR camera**
- **Adhesion of layers, boxes, frames, etc.**

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Analysis

- Don't just go by pass-fail criteria.
- A module design that loses 4% of its power after 500 thermal cycles is not as robust as one that loses 1% of it power during the same test.
- Use other tools to understand why one set lost 4% and the other only 1%.
- This will lead you to a better understanding and ultimately to more robust products.

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How do we use accelerated tests to qualify new products and processes?

- First step is to run our modified qualification sequence.
- Review results carefully.
- Did the modified modules suffer any greater degradation than the standard product?
- If yes, then must understand why and determine if this will lead to reliability, durability or safety issues.
- If there is a potential to degrade field performance the change is rejected.

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Examples

- New interconnect equipment
- New back sheet material
- Thin film corrosion

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NEW INTERCONNECT EQUIPMENT

- **Evaluated using thermal cycling with current flow.**
- **In addition to power loss, utilize IR to find broken interconnects or damaged solder bonds.**
- **In one example after 200 thermal cycles the power was down only 2%, but IR showed some interconnects were broken.**

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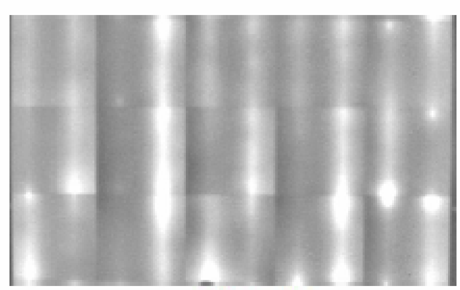
IR Scan showing broken interconnects



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Continued Testing of New Interconnect Equipment

- Continued cycling the module in picture.
- After 400 cycles it was down ~ 4%, but more interconnects were broken.
- Some modules made with new equipment passed 500 TC with less than 5% power loss.
- However others had 2 interconnects on same cell break and so lost a large fraction of their power. (Determined by # of cells per diode)
- By making educated modifications to the new equipment and its process, we stopped the interconnect breakage.
- This equipment is now used to build quality products.

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NEW BACK SHEET

- Tested through standard qualification sequence.
- Module performed very well especially in damp heat (85°C/85% RH) with no measurable power loss.
- However, during the course of the damp heat testing the adhesion between the EVA and the backsheet decreased as shown in the next slide.
- Is this loss of adhesion a problem for the field?
- 1000 hour Damp Heat test was based on JPL analysis of cell metallization corrosion and was based on a rate constant that doubled for every 10 C rise in Temperature.
- So performed the test at 65°C/85% RH for 4 times the duration.
- Results also plotted on chart.
- Adhesion does not have same behavior as corrosion, in this case the acceleration rate must be greater than a factor of 4.
- Turns out material undergoes a phase change just below 85°C so any test at 85°C or higher will be much more severe than at lower temperatures.

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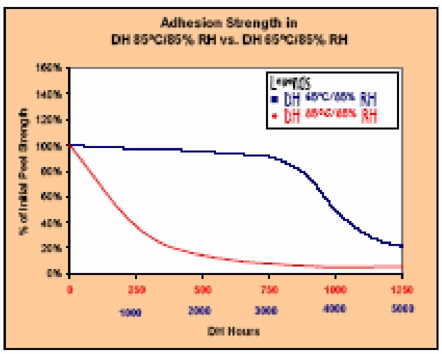

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THIN FILM CORROSION

- BP Solar used to produce a-Si modules.
- These modules were qualified through IEC 61646 including 1000 hours of damp heat.
- However, these modules experienced early field failures due to corrosion.
- Tried performing the damp heat test with applied voltage and found it could duplicate the observed failure after only a few days of exposure.
- We used damp heat with applied voltage to determine the corrosion mechanism.
- This lead directly to development of a product that did not suffer from this corrosion mechanism.

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FUTURE NEEDS

- Evaluate the reaction rates for various failure mechanisms occurring during the damp heat test. Equate to long term field data to get a better prediction of module lifetime.
  - How many years of operation in Miami does 1000 hours of damp heat exposure at 85° C/85% RH represent for each failure mechanism?
- More data is needed in order to develop a model to equate performance in the thermal cycle test to outdoor performance in various climates.
  - How many years of operation in Arizona does 500 thermal cycles from -40° C to +85° C represent?

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CONCLUSIONS

- Without accelerated aging tests it would be extremely difficult, if not impossible, to determine before implementation whether a proposed change in a module material or process would have a major impact on long term reliability and lifetime.
- While accelerated aging tests can not tell you how long a particular module design will last, they can be used to determine whether changes are likely to improve the reliability and lifetime or to have a detrimental effect on the reliability and lifetime.
- Accelerated aging tests also assist in identifying those failures observed in the field helping you to eliminate them.
- For new technologies accelerated aging and field exposure are both necessary in order to develop reliable, long lifetime modules.

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Accelerated Aging Testing for PV Balance-of-System Components

Chuck Whitaker, Tim Townsend
Behnke, Erdman, & Whitaker Engineering, Inc

Accelerated Aging Testing in Photovoltaics Conference
Baltimore, MD February 22, 2006

BEW

Introduction

- Try to give a "systems" perspective on accelerated testing needs for the rest of the system:
  - Define BOS
  - Aging Factors
  - Existing Tests
  - Field Observations
  - Conclusions

BEW

Accelerated Tests in Other Industries

BEW

PV BOS (re)defined

Everything but the modules…

- Inverter - Inverter, Transformer, Switchgear
- Electrical, AC & DC - Combiner & Junction Boxes, Conduit, Wire, Fittings, Diodes, Fuses, TSSD, Grounds, Trenches, Vaults
- Structure - Supports, Tracking Apparatus & Controls, Foundation, Fasteners, Finishes
- Site - Fencing/security, Drainage
- Monitoring and Control - Sensors & Wiring, Data Collection/Data Processing, Communications

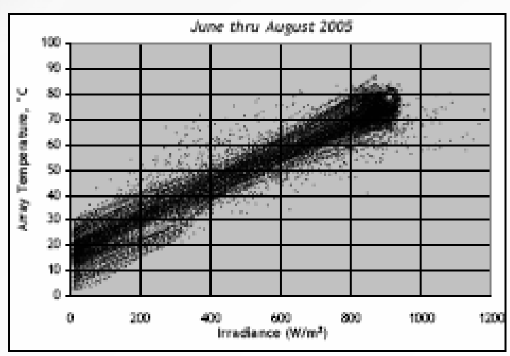
BEW

Aging Factors

- Sunlight
  - 1200+W/m² steady state, 1500W/m² transient
- Temperature
  - Ambient - 50°C and higher (Death Valley or sun exposed, wind protected side yard)
  - Module - 90°C or more (direct roof mounted)
  - And don't forget cold temperature
- UV
- Humidity/moisture
- Wind

BEW

How Hot is Too Hot?



BEW

How the NEC Sees it...

Table 310.17 Allowable Ampacities of Single-Insulated Conductors Rated 0 Through 2000 Volts in Free Air, Based on Ambient Air Temperature of 30°C (86°F)

Ambient Temp. (°C)	Temperature Rating of Conductor (See Table 310.13.)		
	60°C (140°F)	75°C (167°F)	90°C (194°F)
21-25	1.08	1.05	1.04
26-30	1.00	1.00	1.00
...snip...			
51-55	0.41	0.67	0.76
56-60	–	0.58	0.71
61-70	–	0.33	0.58
71-80	–	–	0.41

BEW

Aging Factors

- Voltage
  - DC: currently 600/1000 nominal, 1200/2400 coming
  - AC: Low (≤600V) and Medium (≤60kV) Voltage
- Current
  - Hundreds of Amps
- Secondary Mechanisms
  - Soiling
  - Critters
  - Vegetation
  - Shipping, installation, operational damage
  - Vandalism

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Existing Tests - Inverter

- Inverter
  - Surge withstand, hi-pot testing in UL 1741
- Transformer & Switchgear
  - IEEE CPMT Technical Committee on Accelerated Stress Testing and Reliability (TC-ASTR)
  - Thermal Endurance Testing: 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*
  - Electrical Endurance Testing: IEEE 1043 *IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils*
  - Multifactor Stress Testing: IEC 60034-18-33 *Functional Evaluation of Insulation System-Multifactor Functional Evaluation*

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Existing tests - Electrical

- Combiners, junction boxes
  - NEMA 250 Enclosures for Electrical Equipment (1000 V Max)
  - IEC 60529 Degrees of Protection Provided by Enclosures
- Conduit, Wire, Fittings
  - Wire and cable are subjected to numerous mechanical, electrical, thermal, UV, and moisture tests
- Diodes, Fuses, Transient Surge Suppression Devices
  - Numerous IEEE C62.XX procedures related to surge devices (ac)
  - UL listing/recognized fuses & diodes
- Grounding
  - NEC specifies how to ground in multitude of situations, presumably this has come about through testing and field experience to see what holds up mechanically and electrically.

BEW

Existing Tests - Structure

- Supports
  - Standard mechanical/structural load and flexure certifications are customary for UL-listed products and for large custom systems.
  - Some Mfgs are performing wind tunnel testing
- Tracking Apparatus & Controls
  - None specific to PV

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Field experience applicable to accelerated aging tests for BOS

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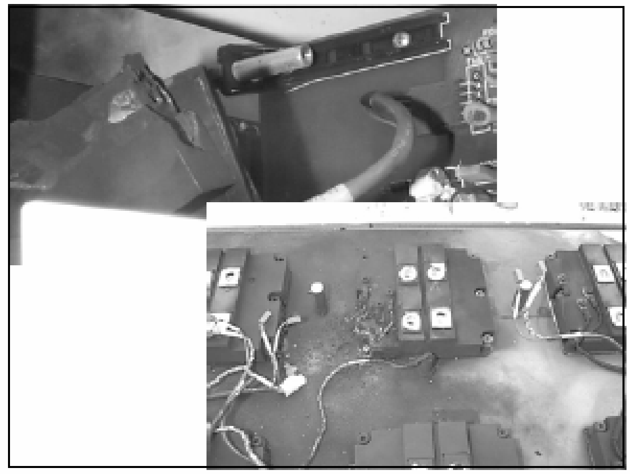
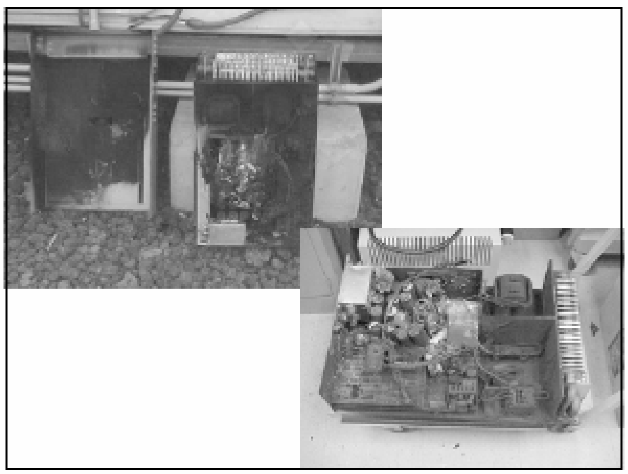
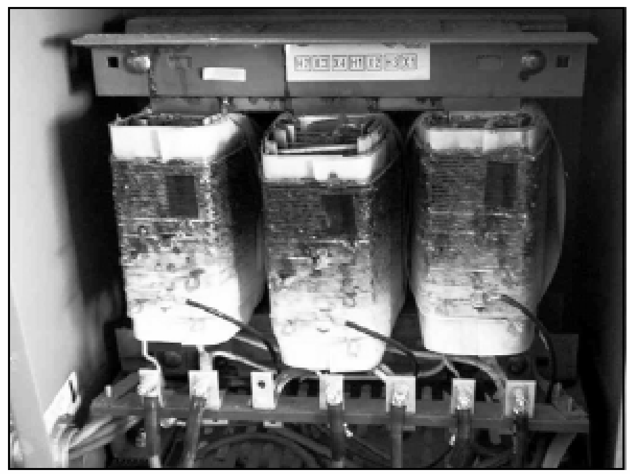
Inverter

- Inverter
  - Early chalking of powder coats, pitting of unprotected metal, and UV degradation of displays and buttons/knobs.
  - IGBT, Electrolytic Capacitor, wiring harness, connector, cooling system, failures have reduced substantially, though not eliminated
  - Utility steady state & transients voltage are underestimated—they don't make 130V light bulbs for nutin'
- Transformer
  - Field failures are related to improper sizing or installation errors
- Switchgear
  - Some field examples of failed switches, usually dc. Most ac switchgear issues appear to be related to sizing/installation errors

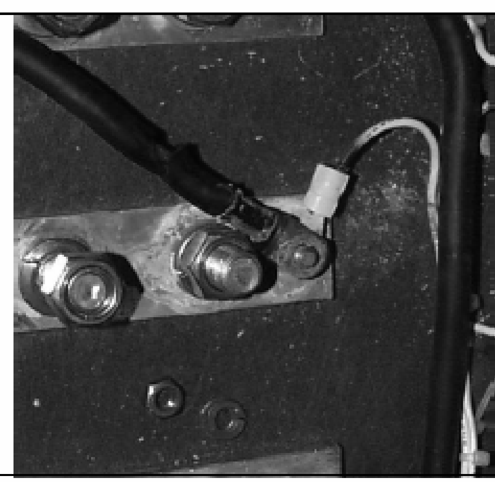


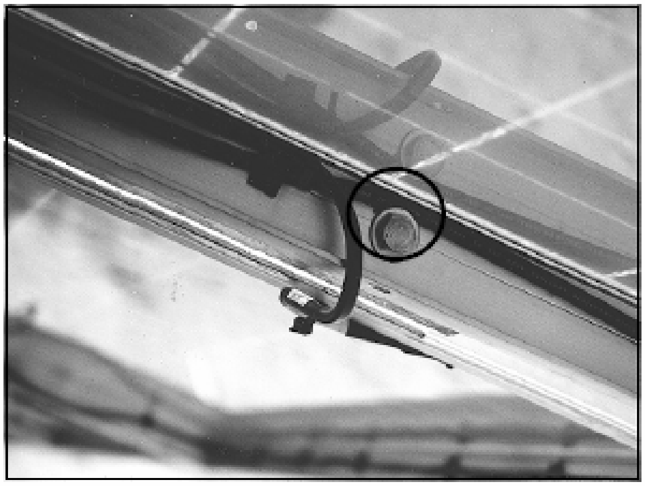


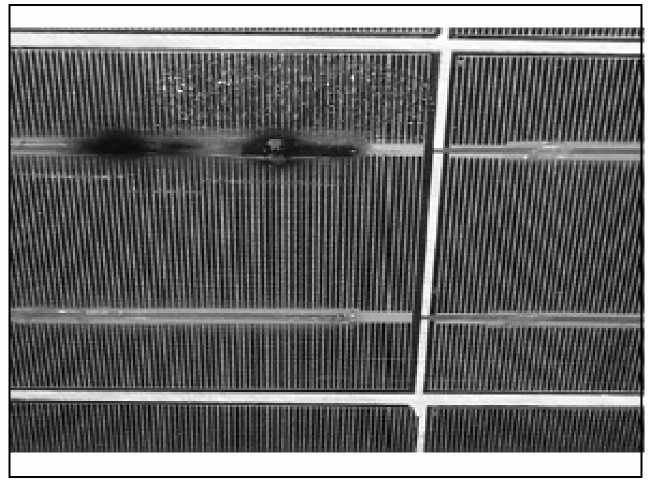


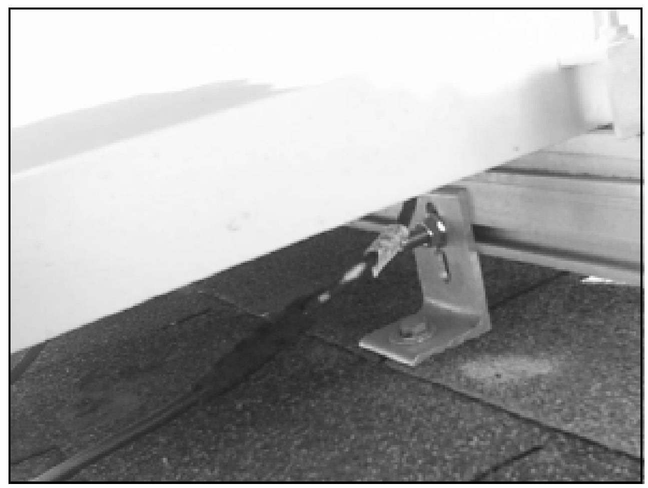
Electrical

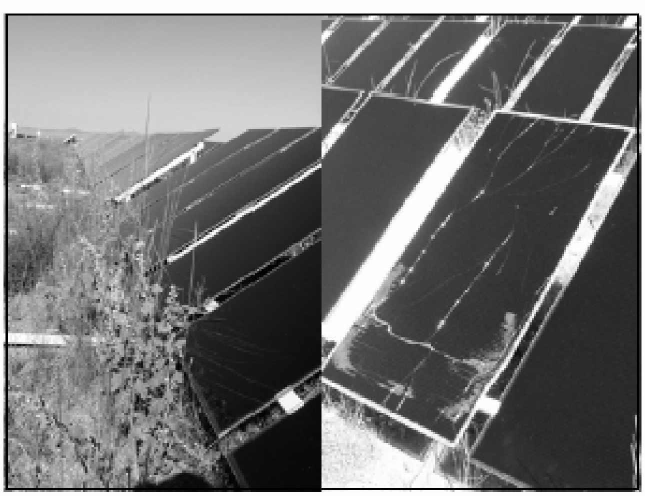
- Combiners, junction boxes
  - field data have shown failures caused by water intrusion and dc ground faults are more common than designer expected, which has led to modifications in NEMA selection, terminals, and fuses.
- Conduit, Wire, fittings
  - With the exception of mislabeled non-UV wire, field experience is only compromised by workmanship, rarely by flaws attributable to a lack of adequate life cycle testing.
- Diodes, Fuses, Transient Surge Suppression Devices
  - Siemens GmbH no longer uses array fuses unless required by module mfg
  - *Aging and high voltage operation of TSS devices remain a source of concern*
- Grounding/transient protection
  - Rare to get data on adequacy of grounds long after installation. NEC-compliant systems do not seem prone to premature grounding integrity failures.









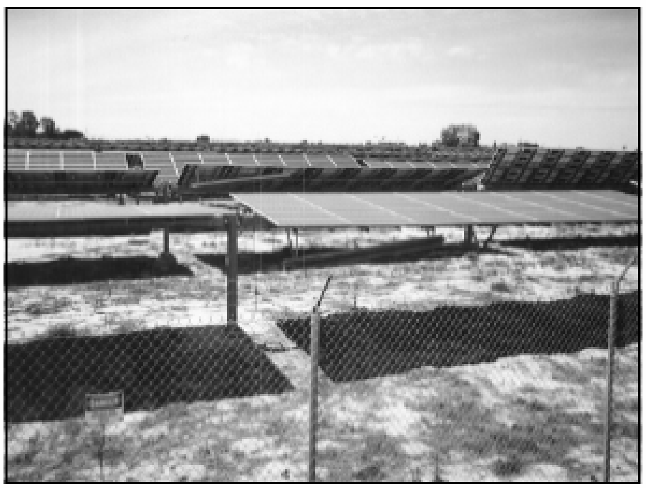



DO NOT
ENTER
WRONG
WAY

Structure

- Supports
  - Few field issues related to structure failure; usually due to underestimating wind/snow load, overestimating roof deck strength.
- Tracking apparatus including controls
  - PV's former Achilles Heel. Many trackers failed in field service due to leaks, corrosion, mechanical damage, rodents, and electrical surges. Improvements have been incremental and mistakes have been repeated by some.
- Fasteners
  - Existing non-PV testing is probably adequate.
- Finishes
  - Obviously, existing testing hasn't been adequate for PV, but all that might be needed is to raise the bar via more severe versions of existing tests.

BEW



Conclusions

- Know your environment: Don't underestimate the level of voltage, temperature, current; consider steady state and transients
- Assume installation errors will occur—minimize installation steps, test for errors
- Learn from the mistakes of others
- Don't try to hide your products short comings with a little paint…

BEW

ALT
Predicting Baseline Field Performance - a work in progress

Peter Meyers and Mike Ross
First Solar, LLC

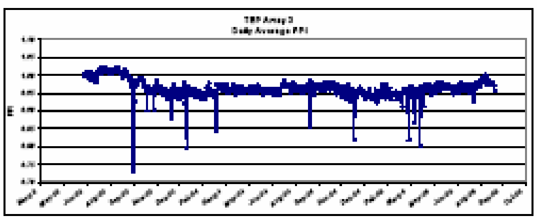
Background and Motivation for ALT Development Program

- Nameplate Performance of First Solar modules is based upon extensive field testing data and continuous in-house stress testing of current product
- Present qualification procedures work well and our customers report that First Solar modules perform at or above expectations
- However, even a good program can be improved
- Today's presentation describes preliminary efforts to develop an ALT protocol that is a) faster and b) more precise than current procedures
- Although these initial attempts at ALT protocol development were not successful, the general approach seems promising and work continues

First Solar Array Performance

TEP Array 3 – Tucson Electric Power - Springerville, Arizona

- Longest running, commercial First Solar array (operational May 2003)
- After initial 3% drop, array has maintained a stabilized performance with degradation rate <0.5%/year, after adjusting for seasonal variation.



Premises of Approach to ALT Development

- Stable baseline performance is achieved after an initial stabilization period
- Changes in module performance can be separated into a) device-related and b) packaging-related
- Changes observed during stabilization period are device-related
- Changes in device performance during the stabilization period are characterized by changes in IV curve parameters that can be described by one or more "stabilization modes"
- Stabilization modes reflect fundamental mechanisms that depend on material properties and device structure (not addressed here)
- Impact of specific stabilization modes depends on fabrication process
- Ideal ALT predicts baseline performance
- In order to predict baseline performance ALT must stimulate same mechanisms responsible for field stabilization
- More than one ALT may be required (It is not necessary to employ a single ALT protocol)

ALT Development Program Approach

- Produce modules using a Designed Experiment (L_{12})
- Monitor module performance in field to determine baseline performance
- Analyze data for
  - Stabilization modes
  - Dependence of stabilization modes on process variation
- Correlate ALT results with field baseline performance

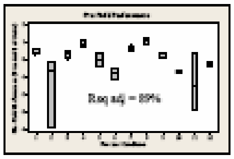
Layout of Designed Experiment

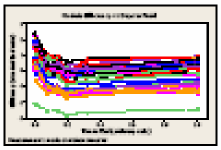
- L_{12} Design
  - 11 process variables
  - 12 "conditions" - specific process variations
  - "stretch but don't break" production line process values
  - Two levels per variable – upper and lower process control limits
  - 36 modules installed in the field array with max power point tracker
  - Nominally 3 modules per condition, some breakage and replacement
- "Sister plates" pulled for ALT testing

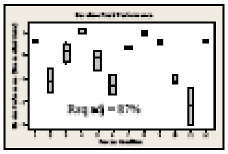
Condition #	Process Variables - high and low values										
	A	B	C	D	E	F	G	H	I	J	K
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Data was relatively "well behaved"

- Initial module performance displayed good separation by process condition
- Modules were periodically removed from field, measured on indoor simulator, and replaced in field
- Baseline performance was achieved relatively quickly
- Baseline performance displayed good separation by process variable







Search for Modes

- Approach – keep it simple; look at IV curves

$$\eta_0 = Jsc_0 * Voc_0 * Jmpsc_0 * Vmpoc_0$$

where Jmpsc = Jmp/Jsc; Vmpoc=Vmp/Voc (and Jmpsc*Vmpoc=FF)

- Efficiency changes as a function of stress, s

$$\eta(s) = \eta_0 * \left(1 - \frac{\Delta Jsc(s)}{Jsc_0}\right) * \left(1 - \frac{\Delta Voc(s)}{Voc_0}\right) * \left(1 - \frac{\Delta Jmpsc(s)}{Jmpsc_0}\right) * \left(1 - \frac{\Delta Vmpoc(s)}{Vmpoc_0}\right)$$

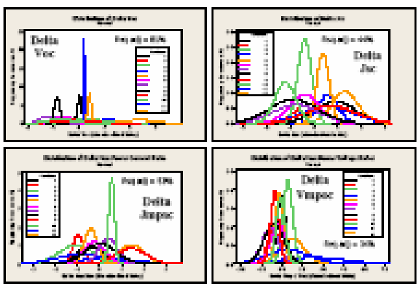
- Change in Efficiency with stress is then approximated by

$$\Delta\eta(s) \approx \eta_0 * \frac{\Delta Jsc(s)}{Jsc_0} + \eta_0 * \frac{\Delta Voc(s)}{Voc_0} + \eta_0 * \frac{\Delta Jmpsc(s)}{Jmpsc_0} + \eta_0 * \frac{\Delta Vmpoc(s)}{Vmpoc_0}$$

plus higher order terms…

- Treat each term as a separate Stabilization Mode

Stabilization Modes separate by condition



- Less mode variation is explained by condition than is efficiency variation

Quantifying Results

- Experimental dependence of Del Efficiency on stabilization modes can be obtained from regression analysis

$$Del\eta = A_{oc} * DelVoc + A_{sc} * DelJsc + A_{jmp} * DelJmpsc + A_{vmp} * DelVmpoc$$

- Analysis of Variance (ANOVA) for each Mode is quantized by sum of squares (SSq) [Rsq adj > 98%]
- Results for All Data:

All Data					
Regression Coefficients		Aoc	Asc	Ajmp	Avmp
		0.388	0.223	0.582	0.448
	Del Eff	Del Voc	Del Jsc	Del Jmpsc	Del Vmpoc
Mean Values	0	0	0	0	0
SSq	34.7	24.1	0.3	6.2	4.1
Percent SSq		69%	1%	18%	12%

Results of Analyses by Process Variable

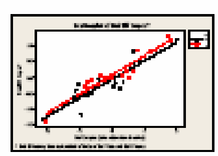
Process Variable B = -1					
Regression Coefficients		Aoc	Asc	Ajmp	Avmp
		0.421	0.250	0.548	0.452
	Del Eff	Del Voc	Del Jsc	Del Jmpsc	Del Vmpoc
Mean Values	-0.428	-0.392	-0.158	-0.0985	-0.336
SSq	10.5	4.8	1.4	3.3	0.9
Percent SSq		47%	13%	32%	8%

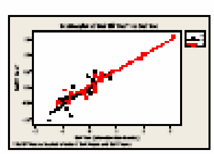
Process Variable B = +1					
Regression Coefficients		Aoc	Asc	Ajmp	Avmp
		0.368	0.200	0.597	0.450
	Del Eff	Del Voc	Del Jsc	Del Jmpsc	Del Vmpoc
Mean Values	0.478	0.438	0.177	0.11	0.375
SSq	24.2	19.4	0.4	1.4	2.9
Percent SSq		82%	2%	6%	12%

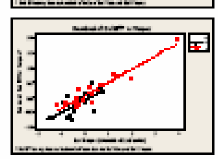
- Differences are statistically significant, but are they real?

Example: Effect of Process Variable "B"

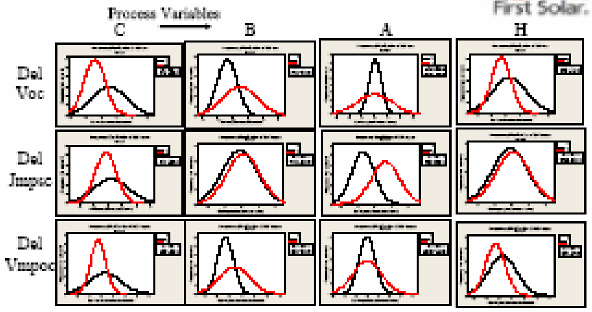
- Experimental variation of slope (regression coefficient) of Del Efficiency on Stabilization Mode
- Note that variation by process variable expected to depend only weakly on process variation







More significant – magnitude of stabilization modes depends on process variables



Conclusion: Field data is analyzable in terms of stabilization modes

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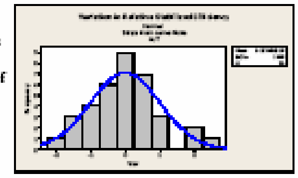
Preliminary ALT Protocol

- Initial ALT protocol involved stressing with illumination, bias and elevated temperature
- Devices under test were strips of cells cut from submodules – no lamination
- Device performance measured real time in situ
- ALT performance projected using curve fitting
- Demonstrated reproducibility using strips from same plates



Variation of relative baseline performance as predicted by curve-fitting for strips from the same plate that were stressed at elevated temperature. Variation is defined as 100 X (P-Pavg)/Pavg, where P is the predicted value and Pavg is the average of P on one plate.

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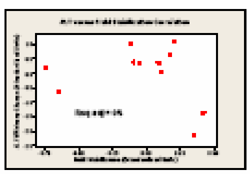
Comparison ALT to Baseline Performance

- Sister plates from each of twelve conditions were stressed using ALT
- ALT results were compared to baseline field performance
- No correlation observed – for this specific ALT protocol



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Summary

- First Solar continues to rely on its current, effective field and in-house module testing program
- Progress on development of an improved ALT has been demonstrated in several areas:
  - Baseline field performance can be predicted (and optimized) based on fabrication process and device architecture
  - Initial choice of stabilization modes works
- Hypotheses – suggest objectives for future work
  - Other protocols may be more effective - although this initial ALT protocol was not useful predictor there are many possible variations
  - More than one ALT protocol may be required
  - Additional stabilization modes may be discovered that improve ALT accuracy and sensitivity
- First Solar has retained sister plates from sets of modules that have been in the field for up to 5 years
  - Sister plates can be used to develop ALT protocols
  - "Correct" ALT results are known from field data
- Basic approach described here may be capable of providing timely, quantitative prediction of baseline performance

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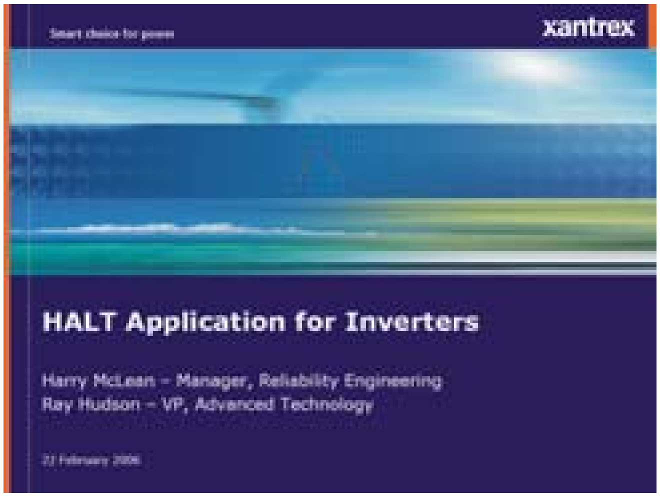
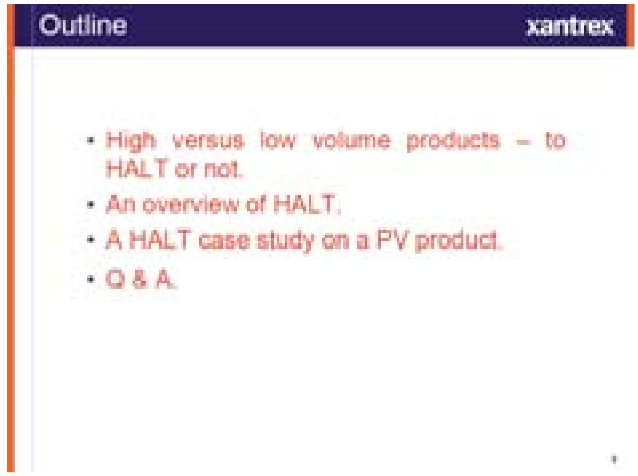
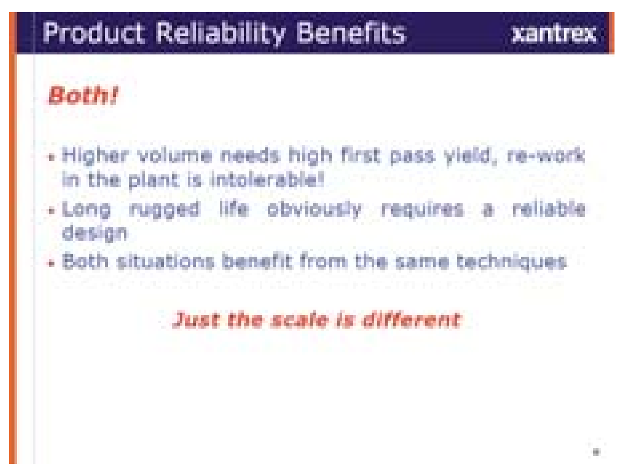

Smart choice for power
xantrex
HALT Application for Inverters
Harry McLean – Manager, Reliability Engineering
Ray Hudson – VP, Advanced Technology


Outline
xantrex
• High versus low volume products – to HALT or not.
• An overview of HALT.
• A HALT case study on a PV product.
• Q & A.


Large PV Installations
xantrex
References:
More than 500 inverters in commercial applications


Residential PV Installation
xantrex


Design for Reliability
xantrex
• Residential Products
• 1,000's per year
• 5 year warranty
• Avg list price $2,500
• Industrial Products
• 100's per year
• 5 year warranty
• Avg list price $50,000
Which product benefits more from using design for reliability techniques?


Product Reliability Benefits
xantrex
Both!
• Higher volume needs high first pass yield, re-work in the plant is intolerable!
• Long rugged life obviously requires a reliable design
• Both situations benefit from the same techniques
Just the scale is different

Design for Reliability

xantrex

- Residential products are simpler
  - Fewer parts
  - Well understood previously used designs
  - Wide operating margins to ensure yield and operation over wide range of conditions and during product life
  - Reliability testing validates any incremental changes
- Industrial products are much more complex
  - Must understand new designs very well!
  - Wide operating margins to ensure operation over wide range of conditions and during product life
  - Reliability testing to validate entire design

The Reliability Techniques

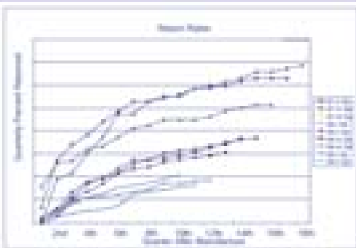
xantrex

- Goals are the same…
  - Design in wide operating margins
  - Make the product simple to build
  - Analyze failure modes
  - Verify assumptions through environmental and HALT testing


  - Make key features easy to test
  - Screen units as produced

An Older Xantrex Product

xantrex



- Product met its qualification tests.
- At intro the product had a very high failure rate (top line).
- Over time with corrective action the failure rate decreased.
- It's "best" level is unacceptable.
- Customer dissatisfaction is high throughout.
- Something different needed to be done.

The Bathtub Curve

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A Proven Reliability Process

xantrex

- Reliability Engineer assigned to every project
  - Perform baseline MTBF calculations
  - Coordinate DFMECA effort
  - Assist designers in focusing on reliability issues
  - Select other appropriate stress tests
  - Later in product development, reassess MTBF
  - Owns reliability process cradle-to-grave
- HALT assemblies as needed – mature each assembly
- Meet a few weeks prior to HALT with designer(s)
- Schedule and execute the HALT
- Assure Must Meet levels are achieved
- Designer participation when issues arise in HALT
- Log issues into Problem Tracker
- Repeat HALT on corrective actions
- Once launched, perform periodic verification HALTs
- Once in production the use of HASS and or HASA

MTBF Report

xantrex

- MTBF at three temperatures and duty cycles
- Components that could compromise MTBF
  - Parts which have an elevated failure history
  - Presented in tabular and graphic formats
- Premature end of life analysis
  - Usually capacitors – based on Arrhenius model
  - Components stressed beyond derating limits
- Estimates at different statistical confidences

The Benefits of HALT

xantrex

- Quickly determine design & process limitations.
- Determine & increase design margins.
- Dramatically reduce infant mortalities as well as to dramatically improve long-term product reliability (both reduce field return rate).
- Reduction of development time and cost.
- Eliminate design problems before launch.
- Obtain statistical information on margins for HASS/A.
- Sustaining engineering tool to assess product changes.

HALT is a design process ruggedization tool for the designers.

HALT Fundamentals

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- HALT is not a test you pass or fail, it is a process improvement tool for the design engineers.
- There are no "pre-established" limits - the product determines the limits.
- Stress to failure.
- Product monitoring during stressing.

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The application of HALT plays a critical role in improving the in-service reliability of a product through better, more robust designs, and manufacturing processes.

Goal: - Better Products and Accelerate Time to Market

HALT Chamber

xantrex

- **Liquid nitrogen cooled**
  - ➔Rapid thermal transitions. Up to 60°C/min on the product.
  - ➔-100°C to +200°C operating range
- **Repetitive shock vibration**
  - ➔6 degrees of freedom
  - ➔3 axis & 3 rotations simultaneously
  - ➔Broad frequency band (2-10,000Hz)

- **Combined environment**
  - ➔Thermal and vibration
- **Low ambient noise**

HALT Test Setup

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HALT Process

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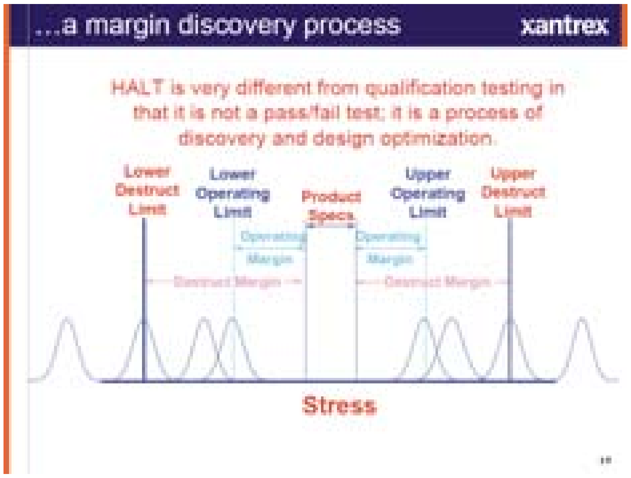
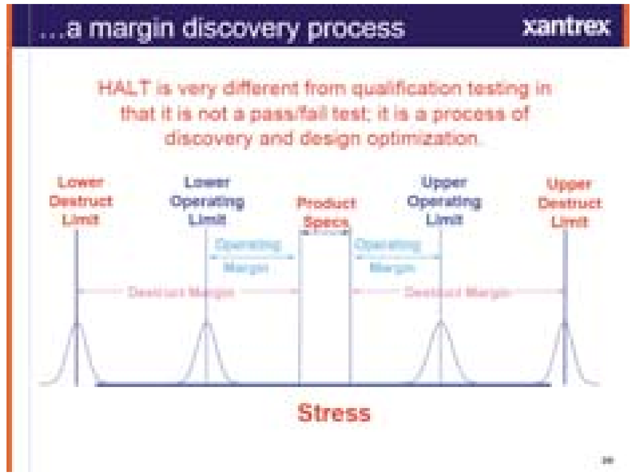
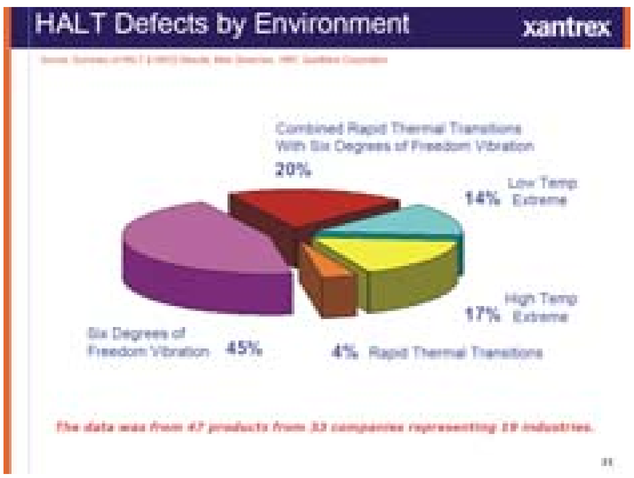
- Thermal Step Stress
  - Cold Step Stress
  - Hot Step Stress (stop at 140°C)
- Rapid Thermal Transitions
- Vibration Step Stress (stop at 50Grms)
- Combined Environments

Each step above will include:
- Power cycling
- Four corner characterization
- High and low input voltages
- Others as needed







Following the HALT Process Results in…

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- Mature design & assembly processes at launch
- Possible earlier product launch
- Much higher overall MTBF levels
- Reduction in total engineering costs
- Reduction in production & warranty costs

Delighted Customers!

Inverter HALT Results – A Historical

xantrex

Model	When	MTBF	# Issues	# Units	Hot, °C	Cold, °C	Vib, Grms
Thruhole	Mar-04	27	17	1	[illegible]	[illegible]	13
Thruhole	Mar-04	27	N/A	1	100	-60	14
SWT-1	Nov-04	27	29	2	80	-40	13
SWT-2	Jun-05	22	7	2	110	-60	21
Production	Aug-05	28	16	2	110	-65	17
Production	[illegible]	N/A	11	2	110	-65	11
SWT-2	Oct-05	22	2	2	110	-70	N/A

- All of our Distributed Outdoor products Must Meet specs from -60°C to +110°C and 15Grms. Thermal ramp rates ≥60°C/minute.
- All stresses are measured on the product.
- All products must operate from -70°C to +120°C.
- MTBF (in years) using Telcordia SR-332, Issue 1, Parts Stress Method.
- # Issues include all problems encountered. The first HALT was a single unit.
- A default sample size is four for HALT.
- PFMECA & DFMECA completed – no Undesirable issues.

HALT Product Issues

xantrex

- An inverter:
  - Problem – Units don't regulate (caps blow up) at -50°C. On another at +20°C.
  - Fix – Added a 10K resistor to stabilize the regulator circuitry.
  - Note – We have had units with blown caps during testing.
- An inverter:
  - Problem – White LCD display failed during rapid thermal -50°C to +80°C.
  - Fix – Changed to a green LCD; could not get to fail in HALT.
  - Note – The green LCD has not failed in the field.
- An inverter:
  - Problem – LCD backlight dims vs temperature (-30°C). Happens on the test bench.
  - Fix – Change backlight drive circuitry.
  - Note – All eight units on the bench test failed over time.
- An inverter/charger :
  - Original design – +10°C to +80°C; now -40 to +92°C.
  - Fix – Part value changes – no cost.
  - Note – This design would have failed in the field.
- An inverter/charger:
  - Problem – Unit won't start at -30°C; now -50°C.
  - Fix – Change to lower ESR cap.
  - Cost – $0.12.

Conclusions

xantrex

- A proven reliability process is very important for inverters.
- HALT is the cornerstone of the process.
- HALT should be used regardless of the volumes.

Accelerated Testing in a Mfg. Environment

Alex Mikonowicz
February 22-23-2006

Accelerated Testing in a Mfg. Environment

- Questions to be asked
  - Can accelerated testing in a mfg. Environment be useful?
  - Can the costs be recouped?
  - Does the sales, distribution, resellers, installers, eventual customer care?
- And the Answer is?
  - YES!!!

Accelerated Testing in a Mfg. Environment

- How to accomplish?
  - Some possibilities:
    - Use portions of IEC 61215 (block 5)
    - Continuously "sample" product of the line
    - Selectively increase test requirements (being careful not to destroy the product)

Accelerated Testing in a Mfg. Environment

- The "realities"
  - IEC 61215 (block 5) is a minimum design standard for a flat plate photovoltaic module
  - Most accelerated testing exceeds the rather narrow window of materials used in module construction

Accelerated Testing in a Mfg. Environment

- The conflict
  - Qualification of "new materials"
  - Qualification of "new processes"
  - Substitution of form, fit, or function materials
- Do these in a rapid controlled manor
  - and protect the customer
  - and protect the warranty performance
  - and keep your sanity

Accelerated Testing in a Mfg. Environment

Accelerated Testing in a Mfg. Environment

- What we do
  - Buy a sample of two modules out of finish goods & conduct the majority of IEC 61215
  - Selectively test new materials to failure or far beyond the design requirements
  - "Qualify" all processes and materials

Accelerated Testing in a Mfg. Environment

- 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.

Accelerated Testing in a Mfg. Environment

- What can the labs do for the mfg.'s
  - 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

Accelerated Testing in a Mfg. Environment

- Thanks for Listening.

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ACCELERATED AGING TESTING –
Research Curiosity or Decision Making Tool

DOE, Maritime Institute, Maryland
(February 22-23, 2006)

Accelerated Testing Challenges for Flexible Modules

J. Call, M. Walters, and S. Guha

United Solar Ovonic Corporation
3800 Lapeer Road, Auburn Hills, MI 48326

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Advantages of *UNI-SOLAR* Products

- Unbreakable and flexible
- Superior performance under cloudy conditions and in hot weather – more kWh/kW
- Lightweight
- Aesthetically pleasing
- Not affected by worldwide shortage of silicon
- Low material and processing cost
- Triple-junction, spectrum splitting device
- High yield
- Environmentally safe
- Roll to roll technology
- Applications: Building-integrated, utility power, remote stand-alone, battery charging, marine/RV
- More than 65 U.S. patents, many more worldwide

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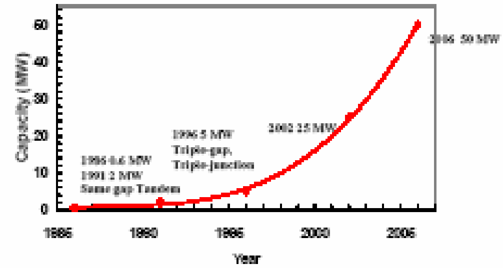
CAPACITY EXPANSION



"I am very proud that the Department of Energy has been able to partner with Uni-Solar and that the results have been so outstanding."
— Secretary Bodman's letter dated July 22 2005

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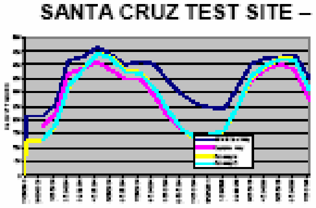
kWh/kW

Customers do not buy efficiency or power; they buy electricity – cents/kWh is the most important parameter

⇒ Our modules produce more kWh/kW

⇒ Less cents/kWh

SANTA CRUZ TEST SITE – ENERGY PRODUCTION



Over a period of two years, the Uni-Solar array has produced 22% more electricity than the crystalline silicon array for the same 2.5 kW power rating (Santa Cruz, CA site).

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WASH MACHINE
↓
BACK REFLECTOR DEPOSITION MACHINE
↓
AMORPHOUS SILICON ALLOY DEPOSITION MACHINE
↓
ANTI-REFLECTION COATING DEPOSITION MACHINE

Front End Roll-To-Roll Deposition

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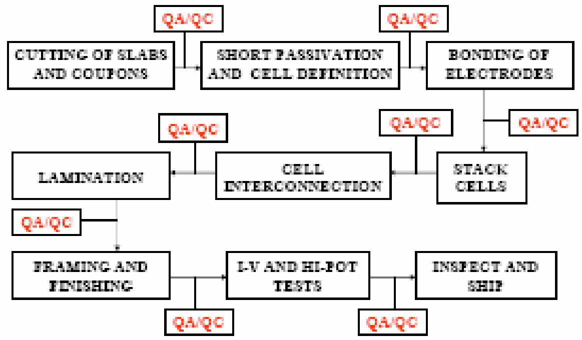

Back End Module Assembly Operation

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Accelerated Test Standards

Accelerated test standards followed by United Solar:

- **IEC 61646 –** Thin-Film Terrestrial Photovoltaic (PV) Modules- Design Qualification and Type Approval.
- **ASTM** standards, such as
  - G154 Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials
  - B117 Standard Practice for Operating Salt Fog Apparatus
- **UL-1703 –** Safety Standard for Flat Plate Modules

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United-Solar Accelerated and Evaluation Tests

Material Tests

- Material analysis: AES, SEM, IR, etc.
- Optical tests: transmission / reflection
- Peel test: 180° peel strength (ASTM D903)
- Shear test: single-lap-joint (ASTM D1002)

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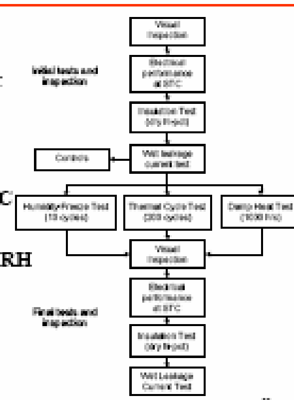
Module Tests

- **Humidity-Freeze (HF) Test**
  10-50+ cycles,
  -40°C to +85°C, 85%RH
- **Thermal Cycle Test**
  200+ cycles, -40°C to +90°C
- **Damp-Heat Test**
  1000+ hours, +85°C, 85% RH
- **Insulation Test**
  Up to 6 kV, wet or dry
- **Wet leakage current test**
  Up to 6 kV



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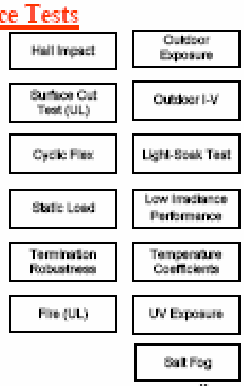
Other Accelerated / Performance Tests

- **UV Exposure: continuous UVA, >1000 hrs, 70°C (ASTM G154)**
- **Salt Fog: 5% salt solution, 35°C, 96 hr cycle 48 hr wet, 48 hr dry (ASTM B117)**
- **Surface Cut: 45°cut (UL-1703), evaluation by wet hi-pot**
- **Hail Impact: 1" diameter, 23 m/s, 11 locations**
- **Static Load: 50-90 lb/ft2, 1 hr application to each side, 2 cycles**



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United Solar Flexible Modules

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Examples of Tests Unique to Flexible Modules

Example 1: Cyclic Flex Test

Why?

- **Modules are flexible. Some applications require coiling, flexing, forming.**
- **Cyclic flex (fatigue) test used to evaluate encapsulant, interconnect, and bus bar integrity.**
- **Twist and Dynamic Mechanical Loading tests are not performed – More applicable to rigid flat-plate modules**

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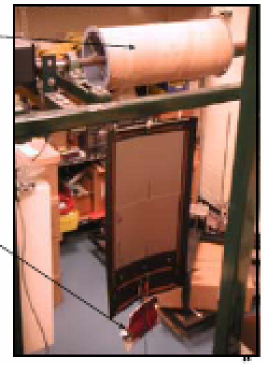
Cyclic Flex Test

- Test module is attached to mandrel, 6"-12" diameter
- Cycling is motor-driven
- Tension is applied to the module to ensure contact with the mandrel.



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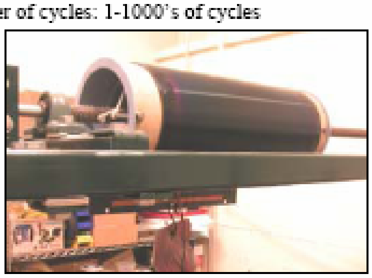
Cyclic Flex Test (cont….)

- Module is coiled around the mandrel clockwise then counter-clockwise (= 1 cycle, ~0.2 Hz)
- Widthwise or lengthwise flexing is possible
- Number of cycles: 1-1000's of cycles



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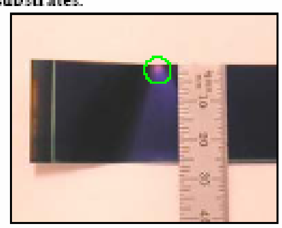
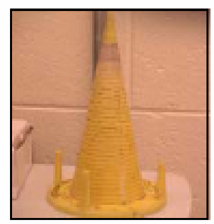
Example 2: Deposition Film Adhesion Test

- **Both tensile and compressive stress may be applied to the film.**
- **A 1" wide sample is formed around a conical mandrel resulting in a variable and increasing stress towards the top of cone (1-4%).**
- **% compressive and tensile strain is measured at film adhesion failure which is dependent on film thickness and cone diameter.**
- **Faster and less subjective than tape test for thin, malleable substrates.**





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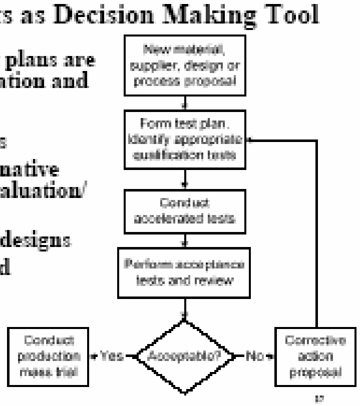
Accelerated Tests as Decision Making Tool

Specific tests and test plans are used for design evaluation and qualification of:

- **Alternative materials**
- **Materials from alternative suppliers (supplier evaluation/ qualification)**
- **Alternative product designs**
- **Alternative/improved production processes**



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Accelerated Tests as Decision Making Tool (cont…)

Accelerated environmental tests are used for material, design, and process evaluation. Examples:

- **Performance of encapsulating materials such as interlayer adhesion, insulation, etc.**
- **Cell substrate and module backing plate corrosion resistance**
- **Interconnect design and material acceptance**
- **Module/cell design electrical performance acceptance**

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Accelerated Test	Evaluation / Acceptance Test Examples (in addition to IEC 61646 and UL 1703 acceptance)
Humidity-Freeze, Damp-Heat, and Thermal-Cycle Tests	Insulation test (wet hi-pot) - dielectric properties of encapsulating films at various temperatures. Very important immediately after exposure to HF and DH tests. Up to 6 kV totally immersed. Peel and shear tests at various temperatures - encapsulation adhesion and bonding at material interfaces. Surface cut test - outer encapsulation cut test followed by wet hi-pot, up to 6 kV totally immersed. Increasing cut force until failure.
HF or DH with voltage or current bias	Ion movement (electromigration) under high humidity, high temperature, and voltage bias

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Accelerated Test	Evaluation / Acceptance Test Examples (in addition to IEC 61646 and UL 1703 acceptance)
Cyclic Flex test	Interconnect and busbar fatigue, encapsulation integrity
Light Soak test	S-W degradation of new/improved deposition recipes, also used to help establish stabilized module power ratings
Salt fog test	Insulation test (as described earlier) Corrosion resistance of cell substrate, backing plate, terminals for coastal or marine applications

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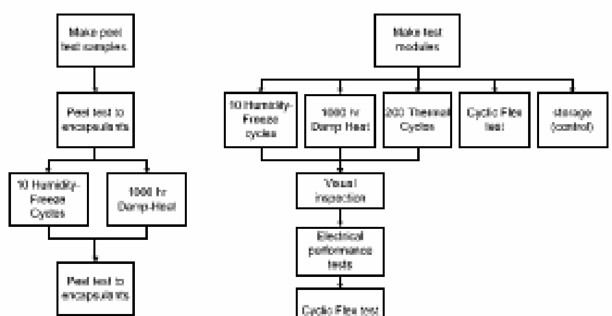
Example Test Plan: Copper Busbar



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Predicting Field Failures from Accelerated Testing

Some accelerated tests are fairly accurate predictors of field behavior.

Example #1: Light Soak Test

- similar to IEC 61646 section 10.18 Light-Soaking test
- 1000 hours, cell held at NOCT
- indoor metal-halide illumination or other suitable light source, >800 W/m^2
- Electrical performance of United Solar product after the light-soak test correlate with field observations.

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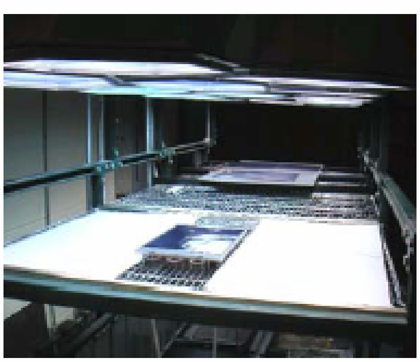
United Solar Indoor Light-Soak Test Station



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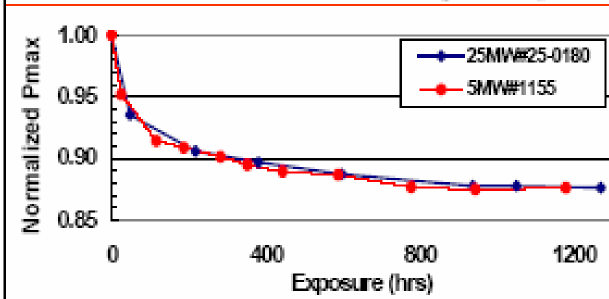

Plot showing typical S-W degradation due to light soaking at NOCT for United Solar product

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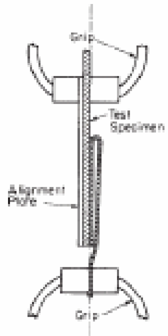
Example #2: Peel Test

- HF and DH tests are used to evaluate adhesion properties of encapsulating films.
- Peel test is performed after HF or DH exposure (ASTM D903, 180° peel)
- Prediction example: The peel test has been used to confirm weak encapsulant adhesion. Subsequent root cause analysis identified a contaminant in supplied material.



Ref: ASTM D903-98 Standard Test Method for Peel or Stripping Strength of Adhesive Bonds

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Role of Field Observations

- Field observations and customer feedback are important sources of information regarding reliability
- Field data helps to identify conditions for which to develop accelerated tests
- For example:
  - Encapsulant delamination due to contamination: resulted in supplier corrective action
  - Copper bus bar failure: resulted in bus bar design change and verification by cyclic flex test
  - Laminating film adhesive failure: resulted in new supplier
- United Solar's testing protocol has contributed to very low observed product return rate.

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Future Advancements in Accelerated Aging Tests?

- Desire for more accurate prediction of module lifetime, electrical performance, integrity of encapsulation, bonding to roofing substrates.
- Faster test procedures for design evaluation and qualification testing are desired – Time is money!
- Can 50 HF test be substituted for 1000 hour DH test? Evaluation of the pros and cons of 50 HF cycle test versus 1000 hour DH test.
- Can HALT/HASS be used to predict long-term field performance and module lifetime?
- Can HASS be used to quickly determine design weaknesses/flaws?

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Conclusions

- United Solar uses industry accepted accelerated tests as decision-making tools in the product development process.
- Flexible modules have unique properties that require unique tests. Several tests have been developed by United Solar to evaluate flexible module performance.
- Accelerated tests followed by appropriate evaluation tests have been shown to predict potential field failures.
- Field observations are a tool to evaluate and develop accelerated tests and associated acceptance test criteria.
- Faster and more reliable accelerated tests are needed to reduce cost and improve quality.

Appendix E: 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
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
FSEC Florida Solar Energy Center
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 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
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
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
NEC National Electrical Code
NEMA 250 National Electrical Manufacturers Association standard 250 for Enclosures for Electrical Equipment (1000 V Max)
NFPA National Fire Protection Association
NOCT nominal operating cell temperature
NRC National Research Council
NREL National Renewable Energy Laboratory
O&M operations and maintenance
ORNL Oak Ridge National Laboratory
PCU power control unit
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
RH relative humidity
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
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
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
x-Si crystalline silicon