Methodology and systems to ensure reliable amorphous-silicon thin-film photovoltaic modules

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ABSTRACT

The reliability of United Solar Ovonic (Uni-Solar) triple-junction amorphous-silicon thin-film photovoltaic modules is critical to their success in an increasingly competitive PV market. Modules must show useful operating lifetimes of 20 to 30 years, and although module efficiency is very important, the total energy that a module will produce largely depends on its operating lifetime. Thus, module reliability must be evaluated to estimate lifetime and establish customer warranty periods. While real-world outdoor exposure testing is necessary and important, accelerated environmental test methods must also be utilized to provide more rapid feedback regarding failure modes, design flaws and degradation mechanisms. The following paper gives an overview of the methodology used to ensure long-term reliability of Uni-Solar flexible thin-film modules.

Introduction

From initial design and development through manufacturing, methods and systems must be employed to ensure the quality and reliability of Uni-Solar's amorphous-silicon thin-film photovoltaic modules. These methods and systems must also continue to improve and evolve to raise the level of module reliability to assure service lifetimes of 20 to 30 years. (Service lifetime is defined by ASTM as the time at which performance degrades below a predefined level [1].) The process starts at the design and development stage where alternative materials are specified or alternative cell and/or module designs are developed. Once material selection or design is completed, screening tests are conducted to down-select the best material candidate or design. Close collaboration with material suppliers takes place at this stage to ensure a material meets specification requirements. Once screening is done, component level testing is performed, followed by module validation testing. After material and design are approved, quality assurance protocols are initiated to ensure supplier and product quality.

Qualification testing relies heavily on accelerated environmental testing (AET). Since real-time outdoor exposure tests are an impractical method to evaluate 20- to 30-year lifetimes, accelerated lifetime testing must be used under simulated environmental conditions to evaluate and improve PV module reliability. Still, passing all of the required qualification tests defined by IEC-61646 and UL-1703 does not guarantee module reliability and 20- to 30-year service lifetimes. There are several reasons for this. First, IEC-61646 is based largely on the qualification tests and associated degradation mechanisms for crystalline-silicon modules, so a single approach may not apply. For this reason, Uni-Solar has had to develop unique tests for flexible thin-film modules. Second, it is difficult to undertake rigorous studies encompassing all of the interactive effects that may occur in the various environments to which a module may be exposed. Third, supplier quality issues can have an effect on module reliability. Finally, without correlation to long-term outdoor exposure tests, the true reliability or service lifetime of the module design based on simulated environmental tests is very hard to predict.

Relatively few references exist to correlations between AET duration and real outdoor exposure [2,3]. Those correlations are necessary to translate specific AET exposure durations into accelerated lifetime tests (ALT). The dilemma is that one must design for a 20- to 30-year lifetime based on ALT with limited correlations to real-time outdoor exposure. It is more accurate to say that passing qualification tests demonstrates that the module design does not suffer from any serious design flaws that would severely limit the service lifetime.

The central component of the company's flexible PV laminate product consists of a series of multijunction thin-film amorphous silicon-based cells, manufactured via a proprietary chemical vapor deposition approach using a paper-thin metallic substrate [4,5,6] (see Figure 1). Each side of the PV cell has a robust encapsulant material. Covering the encapsulant over the optically active region of the laminate construction, the superstrate provides electrical insulation, cut and impact resistance and unique self-cleaning characteristics because of its hydrophobic properties attributed to having a low surface energy. Directly under the encapsulant on the backside of the multilayer construction, a polymeric film provides additional electrical insulation, creating a product that is safely building integrated, using a high-tack adhesive

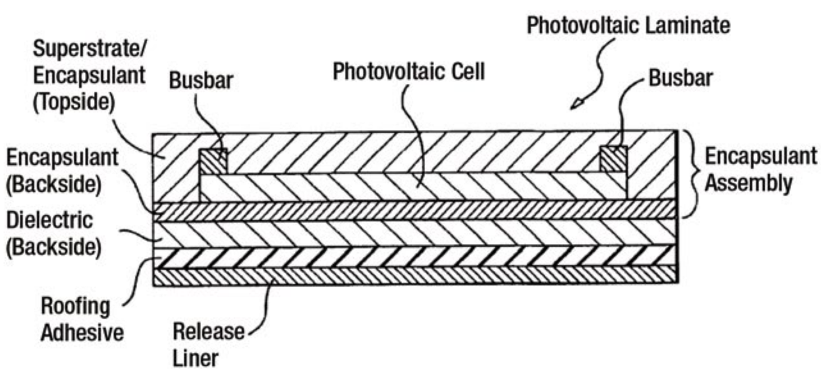

Figure 1. Cross-sectional diagram of Uni-Solar's multilayer flexible photovoltaic laminate construction [7].

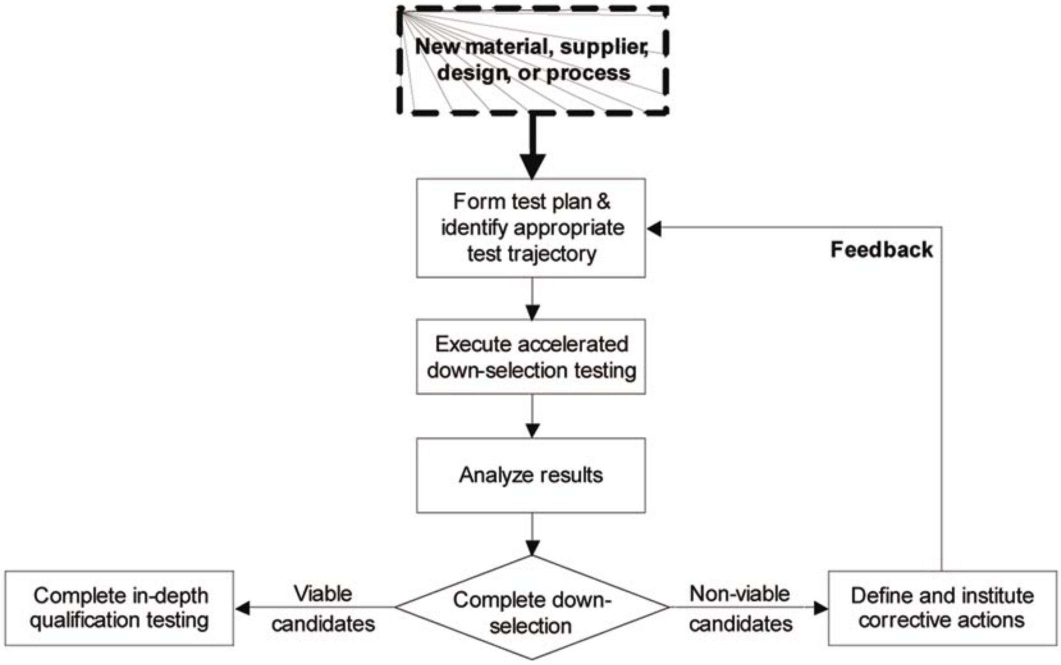

Figure 2. Generic down-selection process flow diagram.

with a removable release liner to provide ease of installation. Enabling a module to maintain a high level of performance, regardless of environmental conditions that may be deleterious to some competitive technologies, the multilayer polymeric system is sealed via a vacuum lamination process and is integral for long-term reliability.

Design and qualification

Design and development process to ensure thin-film module reliability

One primary objective is the design of reliability into material and product specifications. Uni-Solar has developed a four-stage product development process, in which reliability is addressed at each stage. The basic product reliability requirements are defined in the first stage and refined in the second stage. Reliability testing and validation testing occur in the third stage. The fourth stage is authorization to mass produce and can have a subsequent delivery review where reliability is again examined. This process can be iterative at each stage and projects can be sent back for corrective actions for re-entry to earlier stages. After the fourth stage is complete, field monitoring and customer feedback then provide input for continuous improvement.

Material selection and screening process

With a robust material set already in place for the company's commercially produced PV laminate products, the emphasis is on refining existing industry-leading technology so that it is directly competitive with grid-based electricity on a widespread basis without sacrificing performance or durability. While incremental advancements in PV conversion efficiency and improved economies of scale, as operations expand, provide a significant driving force, a considerable effort is also spent on evaluating alternative materials with reduced costs and developing multifunctional materials that have the potential to render a cost reduction by effectively decreasing the part count. An active approach to product development is taken, with material-level reliability at the focal point of the new/alternative material qualification process. Improvements can be made in a controlled manner by becoming technically involved with suppliers to develop and test high-performance, low-cost materials, and by working from a set of detailed specification sheets aimed to accurately define key material properties and create a framework for establishing effective quality control measures.

The development of new/alternative materials often involves the creation of multiple configurations, in an attempt to isolate variables via design of experiment methodologies. With time being a premium commodity, there is substantial motivation to efficiently and effectively down-select among different candidate materials so that resources can be directed toward those with the most promise.

The first layer of analysis used to filter candidate materials involves quantifying fundamental material properties with proven analytical techniques. For instance, measuring the transmission and refractive index of a given superstrate sample is a routine part of the process to ensure proper optical performance. For candidate encapsulant materials, determining rheological properties can yield information relating to the processability under standard production laminating conditions and an indication of structural changes that may occur as a function of time and temperature.

After screening base material properties, a limited number of subscale samples are typically produced for down-selected configurations, with a statistically relevant number of experimental and control samples. If the experimental and control samples perform comparably during initial testing, the subscale samples are then submitted to a brief period of extreme conditions in an attempt to induce a measurable, yet meaningful, separation between the control and experimental samples during postexposure testing. For this purpose, hot-water immersion testing is useful in the rapid evaluation of polymeric materials [8]. Figure 2 shows the generic down-selection process flow diagram being employed.

Component-level qualification testing

The objective of material and cell/module-level qualification testing is to validate the performance and durability of a new or alternative component against that of a known control or benchmark design. Overall, qualification testing is an in-depth extension from the initial down-selection process, while additional testing determines whether a given new/alternative component meets predefined requirements. The inclusion of a combination of recognized AET methods such as humidity-freeze cycling (HF = -40°C to +85°C, 85% RH), thermal cycling (TC = -40°C to +90°C), and damp heat exposure (DH = +85°C, 85% RH) [9] is critical for a complete qualification test plan. Candidate materials entering into the test trajectory should be of production quality to yield results that could be considered representative of full-scale operations and to establish a sound baseline for later quality control mechanisms and reliability studies. In designing the sample

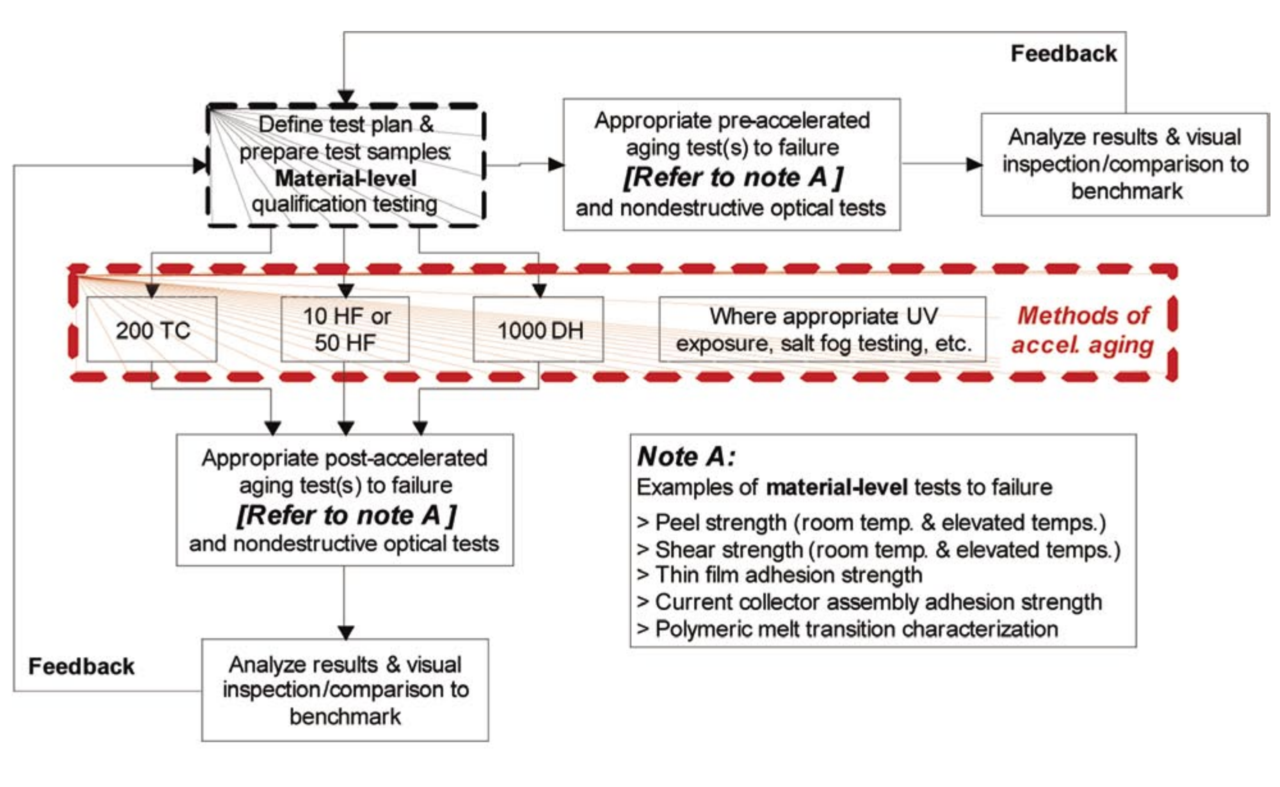

Figure 3. Example of generic material-level qualification testing process flow diagram.

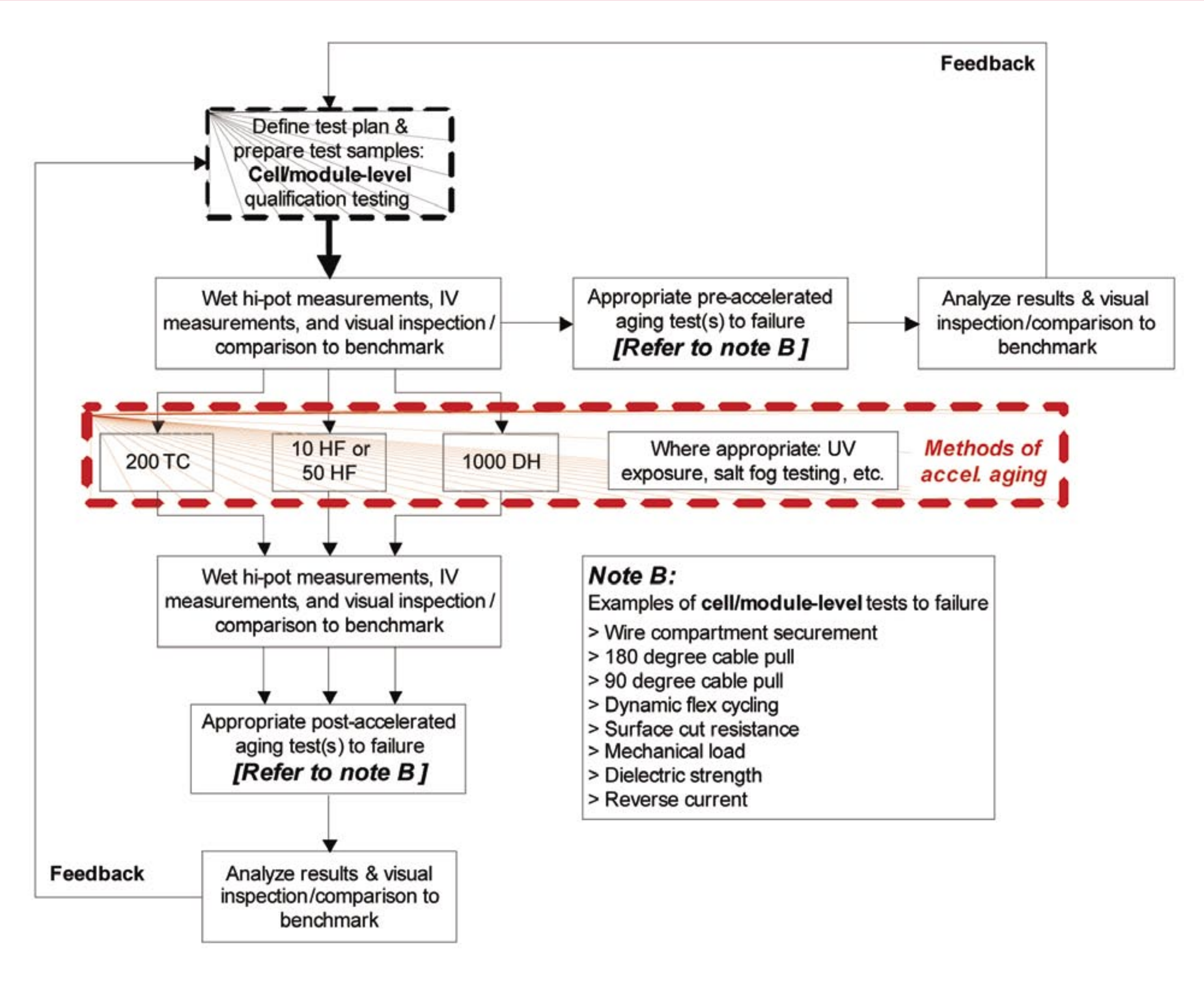

Figure 4. Example of generic cell/module-level qualification testing process flow diagram.

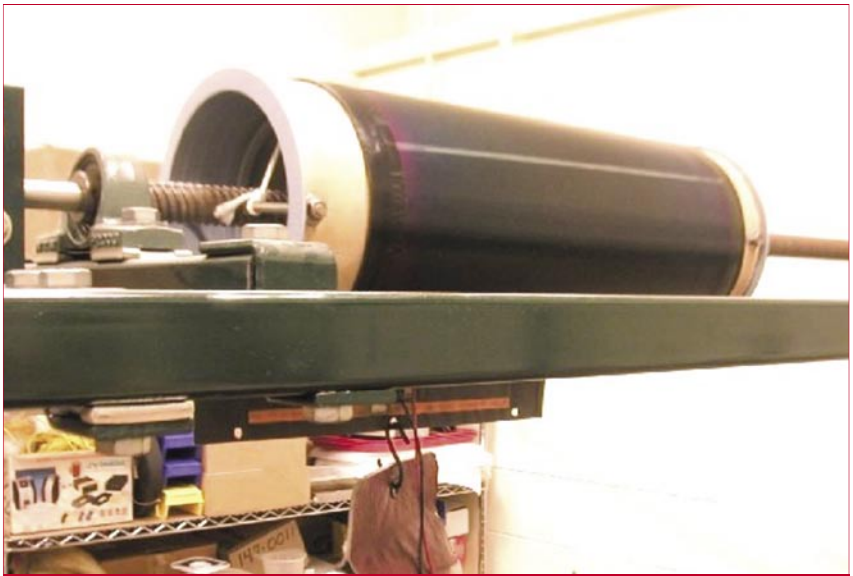

Figure 5. Uni-Solar cyclic flex tester, shown with coiled laminate.

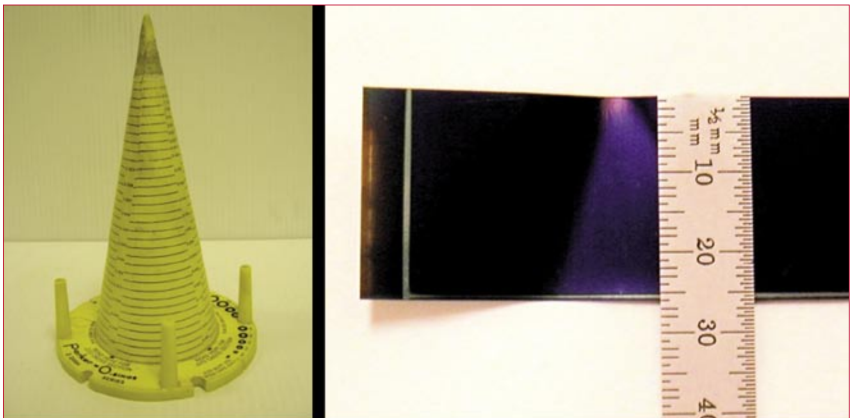

Figure 6. A thin-film adhesion test cone (left) and a formed sample showing thin-film compressive failure (right).

set, accommodations should be made to test all key interactions in an isolated manner, both before and after accelerated aging. For example, evaluating an alternative busbar material would require the creation of a series of peel test samples featuring every relevant interface and a set of electrically active subscale test modules. The scope of a qualification test plan depends on the component in focus and should feature all relevant tests to failure in an attempt to isolate key differences from the performance of the benchmark. Figures 3 and 4 illustrate the test plans for generic material and cell/module-level qualification.

Module and cell components are typically subjected to the AET in a worst-case scenario configuration. For example, when evaluating backsheet designs, the laminate remains completely exposed rather than bonded to a roofing substrate as would occur in a real field application. This not only allows for maximum moisture permeation through the backsheet film, but it enables complete visual inspection after exposure. Individual cells are also routinely tested in an unencapsulated, unprotected state. Current-biasing at rated maximum operating current (I_{mp}) or short-circuit current (I_{sc}) levels is often applied to cells and modules during accelerated tests.

Encapsulant peel and shear tests

Because of the multilayer nature of the encapsulation, a significant amount of effort is dedicated to evaluating interlayer adhesive bond strengths, before and after accelerated aging. Polymeric bond strength is measured via ASTM D903 [10]. By maintaining a standard peel test procedure, quantitative comparisons can be made before and after accelerated aging with statistics applied where appropriate. As each peel test is completed, the failure mode is analyzed and data are recorded. For samples that stretch or break, the maximum force obtained during the peel stroke is recorded. In the event that a sample fails cohesively or adhesively between two specific layers of the multilayered construction, the moving average of the force obtained midpeel is also recorded. Elevated temperature peel tests are also used to down-select and qualify materials where temperature resistance is a required property, such as between the backside encapsulant and the metallic substrate. Lap joint shear tests based on ASTM D1002 [11] are also performed on samples before and after accelerated aging tests and at various temperatures. One material where the test is most applicable is the adhesive component that bonds the PV laminate to the roofing substrate.

Module validation and reliability

Module validation tests

Once material screening and component level tests have been successfully completed, representative module laminates are fabricated for standard validation or qualification tests, with applied test trajectories based on IEC and UL standards. Because of the extensive nature of the complete IEC and UL test trajectories, it is common to perform only the test sequences applicable to the alternative material or design being tested. In other words, the test trajectories for a particular design or material are chosen based on the performance requirements and potential failure modes for the design or material being evaluated. For example, validation of an alternative dielectric backsheet material concentrates on dielectric tests after humidity-freeze and damp-heat exposure, while an alternative front-side encapsulant would require additional optical, electrical performance, UV exposure, and surface cut resistance tests.

Since Uni-Solar module laminates can reach 18 feet in length and the current environmental test chambers are limited in size, smaller representative modules are manufactured for testing. The subscale modules incorporate all elements of a full-size module with only the number of series cells and interconnects reduced. In addition to accelerated testing, full-size modules are subjected to outdoor exposure at company and other sites [12,13]. A recent study shows a 0.6 % per-year degradation rate over a two-year period of outdoor exposure in Florida [14].

Reliability tests

Accelerated tests are occasionally extended to observe longer-term reliability [15]. One example of note consisted of the qualification of a recent design change. The humidity-freeze (HF) cycle test was extended to 150 cycles, or 15 times the IEC-61646 qualification test specification. This duration includes the equivalent of 3000 hours of damp-heat (DH) exposure. A set of nine modules were exposed and removed every 10 cycles for electrical performance measurement. Degradation of the average module maximum power was <5% after 150 cycles. Another positive result from this test revealed the integrity of the encapsulation, since no visual defects were observed.

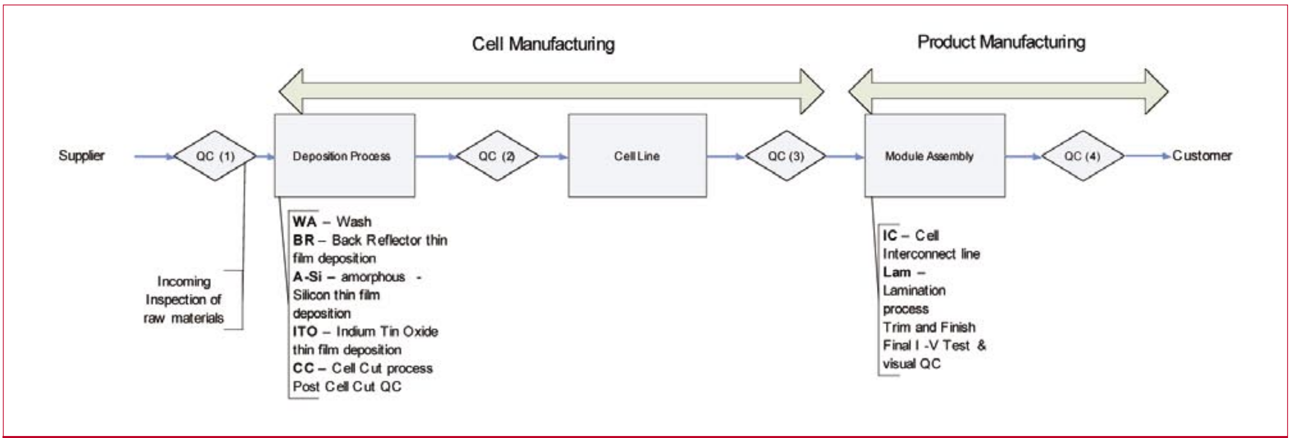

Figure 7. Quality control process flowchart.

A second example consisted of a test sequence which included 50 HF cycles followed by 1000 hours of DH exposure, or the total equivalent of 2000 hours of DH exposure, used to verify module integrity. The laminates were not bonded to a substrate and were fully exposed at both sides during the accelerated tests, allowing maximum moisture permeation. Postexposure visual inspection showed no visible delamination of the front- or backside encapsulants. The laminates also passed postaging wet insulation tests, and electrical performance indicated <1% degradation in maximum power.

Thin-film module tests

Because of the flexible nature of Uni-Solar modules and laminates, a test method was developed to ensure module durability when subjected to coiling and flexing forces during manufacturing, packaging, installation, or the customer application. The cyclic flex test, or fatigue test, is a unique method applicable to flexible modules, one not specifically defined by IEC or UL standards.

A test apparatus was constructed to stress the module by cyclic coiling and uncoiling around a six-inch diameter mandrel. Figure 5 shows a photo of the test apparatus with a module in a coiled state. Each cycle consists of one coiling and one uncoiling every two seconds. The module is coiled in both orientations: front side then back side. Tension is applied to the module to ensure contact with the motor-driven coiling mandrel. The coiling diameter is six inches, which is approximately three times smaller than the maximum recommended coiling diameter of the module. The test is performed on nonaged and aged modules under ambient conditions. The test is instrumental in evaluating interconnect and bus designs. The test also yields information regarding the mechanical integrity of thin-film and encapsulant adhesion.

Another unique test for the modules is the thin-film adhesion test, which is conducted at the cell level on small cut samples. The total cell stack consists of 13 individual layers. The test quantifies the level of compressive or tensile strain at which the thin-film adhesion fails. A conical mandrel is used to form a one-inch-wide cell sample, inducing varying levels of tensile or compressive strain. The percentage of strain is measured at film adhesion failure. The failure mode is a visible separation at one of the film-layer interfaces. This test method is quicker and less subjective than a tape test such as ASTM D3359 for thin, malleable substrates. Figure 6 shows the test device and a tested sample. A criterion has been established to ensure adequate film adhesion.

One direct correlation has been observed between an initial thin-film adhesion test and a field-related failure – in this case, low power resulting from increased series resistance. Subsequent investigation into the failure revealed that the cell material used for the modules suffered from relatively poor adhesion at deposition layer interfaces. Thin-film adhesion test results confirmed a lower level of strain failure after HF test exposure. The cause of the poor interlayer adhesion was traced to organic contamination.

Product quality and process control

The company's quality assurance program exists to maintain high quality and reliability of manufactured modules. The program ensures product conformity and has been developed on systems that can deliver proof of conformance to the customer. It consists of incoming inspections, in-process inspections and final inspections, which are also known as quality control checkpoints, each of which has clearly defined acceptance and rejection criteria. In addition to the QC checkpoints, quality is assured through validation testing, process audits, process failure mode and effects analysis (PFMEA) methodology, analysis of customer feedback, and field performance data (see Figure 7).

Incoming inspection

The incoming inspection process verifies that material from suppliers conforms to specified requirements prior to releasing the material to production. Incoming inspection of raw materials is controlled by utilizing incoming inspection test plans (IITPs). IITPs have been developed for all critical materials used in the manufacturing of Uni-Solar products. Once inspection tests are performed on the incoming material, the records are saved in the manufacturing execution system (MES), a centralized database that stores process parameters of machines used in the manufacturing of the solar laminates as well as the raw material characteristics and in product characteristics. This database provides a link between raw materials properties to process parameters and finished product performance. For material that does not pass inspection, it is classified as nonconforming material and segregated for secondary review between the supplier and management. Corrective actions are also issued to the suppliers if needed.

The incoming inspection process also ensures that records of supplier conformance are retained, such as certificates of compliance. All material requirements are defined for suppliers prior to their shipments. These requirements are documented in the supplier control plans for each critical material. The methods needed for inspection are then determined, such as testing equipment and sampling plans. The incoming inspection process may also call for random audits on supplier compliance per Uni-Solar's request.

In-process inspection

Once material is released to production, in-process quality inspections control the manufacturing of the products. The in-process portion of quality control is the largest of the three QC pieces, since it contains multiple checkpoints throughout the entire solar laminate manufacturing process. These checkpoints include a check before cells are cut to size, after cells are cut, after cells are finished, and after connecting to form solar laminates. In-process quality inspections and tests use clearly defined standards for acceptance and rejection of product.

After the solar cells are cut to their designated size, they are printed with a unique serial number for traceability and put through a series of tests for conformance. One out of every 100 cells is tested for electrical characteristics (I-V curve) film adhesion strength, low light performance, and visual defects. All in-process inspection data are collected and stored in the MES. Again, material that does not pass acceptance criteria at any point is classified as nonconforming material and segregated for secondary review. Corrective actions are also issued to the appropriate department as required.

Final inspection

The last QC checkpoint consists of final production line tests performed on all finished product. Laminates go through a final electrical test, an insulation test (wet hi-pot), and visual inspection for cosmetic defects. Each laminate or module is given a unique serial number and the inspection data are entered automatically in the MES. As in the other major quality checkpoints, if at any point in the final inspection process the laminate does not pass the listed criteria, it is rejected and segregated as nonconforming for secondary review.

Ongoing product/process validation

In addition to verification of product quality characteristics, the company validates that raw materials and finished products meet expected long-term performance through AET. During normal production runs, materials are pulled from inventory and subjected to critical tests performed during the design qualification phase of the product. Samples are made using standard production equipment and production materials, and standard operating procedures. Once samples are manufactured, they are subjected to the cyclic humidity-freeze test, the thermal-cycle test, and the damp-heat test as defined by IEC-61646. Following the accelerated environmental exposure, visual inspections, electrical testing, bond strength, and robustness of terminations are measured to verify product performs within specified limits.

Quality management systems

Although not certified, a quality management system has been implemented that is designed to be compliant with the requirements of the ISO 9001:2000 standard and the needs of customers, with production processes conducted under controlled quality conditions. All critical steps in the process are documented in standard operating procedures within the document control system.

QC audits are also conducted on the entire quality assurance program to ensure conformity. Quality engineers and management perform audits on the incoming inspection process, solar cell cut process, cell lines, final QC process, and calibration systems. The audits verify that sufficient controls are in place to provide a high quality product compliant with specifications.

A PFMEA methodology is used to prevent and predict failures in manufacturing. The process identifies ways in which a process can fail to meet critical customer requirements, and evaluates the current control plan for preventing these failures from occurring and prioritizes actions that should be taken to improve the process. The use of PFMEA is a proactive, rather than reactive, method to improve product quality.

In addition to the internal quality checkpoints and audits, final product quality and reliability are tracked through the external users. All customer feedback and claims are recorded in an electronic customer database. By tracking such customer information, corrective actions can be issued to appropriate departments and improvements can be made to the product designs and processes in place.

Continuous improvement

Hard-lined QC systems have proven highly effective in eliminating time-zero defects and early-stage manufacturing mistakes. Since reliability can be conceptualized as a change in quality over time, reliability testing is integral for ensuring long-term quality. Dynamic screening, qualification and validation processes have been developed, with feedback loops strategically placed, in order to improve product reliability. As a result, ongoing reliability studies have a direct impact on the continual improvement of manufacturing and quality control systems.

As manufacturing and quality control systems evolve, the scope of future work relating to reliability testing must be adjusted to meet the elevated target. The company's future work includes developing additional tests to failure, investigating alternative highly accelerated life test (HALT) and highly accelerated stress screening (HASS) approaches, finding better correlations between time in the field and ALT, and working on improved acceleration models.

References

[1] American Society for Testing and Materials, *ASTM Book of Definitions*, 1996.

[2] Ott, D. & Ross, R.G. 1984, 'Assessing photovoltaic module degradation and lifetime from long term environmental testing,' *Proceedings of 30th Institute of Environmental Science Annual meeting*, p. 121.

[3] Ricaud, A.M. & Petersen, R.C. 1988, 'Environmental stress tests: Acceleration of corrosion,' *8th PVSEC*, p. 549.

[4] Guha, S., Yang, J., Banerjee, A., Glatfelter, T., Hoffman, K., Ovshinsky, S.R., Izu, M., Ovshinsky, H.C. & Deng, X. 1994, 'Amorphous silicon alloy photovoltaic technology – from R&D to production,' *Materials Research Society Symposium Proceedings*, Vol. 336, p. 645.

[5] Yang, J., Banerjee, A. & Guha, S. 1997, 'Triple-junction amorphous silicon alloy solar cell with 14.6% initial and 13.0% stable conversion efficiencies,' *Applied Physics Letters*, 70, pp. 2975-2977, (1997).

[6] Guha, S. & Yang, J. 2006, 'Recent progress in amorphous, nano/microcrystalline, and film silicon materials and devices,' *Proceedings of 4th World Conference on Photovoltaic Energy Conversion*, May 7-12, 2006, Waikoloa, Hawaii.

[7] Nath, P. et al. 2004, 'Self adhesive photovoltaic module,' United Solar Systems Corp. U.S. Patent 6,729,081.

[8] Hanoka, J.I. 1999, 'Advanced polymer PV system,' NREL/SR-520-24911.

[9] International Electrotechnical Commission, IEC-61646 Ed. 2.0 2008-05, 'Thin-film terrestrial photovoltaic modules – Design qualification and type approval.'

[10] ASTM D903: Standard test method for peel or stripping strength of adhesive bonds, 2004.

[11] ASTM D1002: Standard test method for apparent shear strength of single-lap-joint adhesively bonded metal specimens by tension loading metal-to-metal, 2005.

[12] Adelstein, J. & Sekulic, B. 2005, 'Performance and reliability of a 1-kW amorphous silicon photovoltaic roofing system,' NREL, IEEE PVSC, January 2005.

[13] Adelstein, J., 'USSC system.' NREL, October 11, 2003.

[14] NREL, UCF/FSEC, 'Outdoor monitoring and high voltage bias testing of Uni-Solar photovoltaic modules', Uni-Solar Supplemental Analysis, June 17, 2008.

[15] Osterwald, CR. 2008, 'Terrestrial photovoltaic module accelerated test-to-failure protocol,' NREL/TP-520-42893, March 2008.

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