

Accelerated Life Testing and Service Lifetime Prediction for PV Technologies in the Twenty-First Century

A.W. Czanderna and G.J. Jorgensen

*Presented at Photovoltaics for the 21st Century
Seattle, Washington
May 4, 1999*



NREL

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-98-GO10337

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling 423-576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
703-605-6000 or 800-553-6847
or
DOE Information Bridge
<http://www.doe.gov/bridge/home.html>



ACCELERATED LIFE TESTING AND SERVICE LIFETIME PREDICTION FOR PV TECHNOLOGIES IN THE TWENTY-FIRST CENTURY

A.W. Czanderna and G. J. Jorgensen

Engineering and Reliability Division
National Center for Photovoltaics
National Renewable Energy Laboratory (NREL), Golden, CO 80401-3393

Abstract. The purposes of this paper are to (1) discuss the necessity for conducting accelerated life testing (ALT) in the early stages of developing new photovoltaic (PV) technologies, (2) elucidate the crucial importance for combining ALT with real-time testing (RTT) in terrestrial environments for promising PV technologies for the 21st century, and (3) outline the essential steps for making a service lifetime prediction (SLP) for any PV technology. The specific objectives are to (a) illustrate the essential need for ALT of complete, encapsulated multilayer PV devices, (b) indicate the typical causes of degradation in PV stacks, (c) elucidate the complexity associated with quantifying the durability of the devices, (d) explain the major elements that constitute a generic SLP methodology, (e) show how the introduction of the SLP methodology in the early stages of new device development can reduce the cost of technology development, and (f) outline the procedure for combining the results of ALT and RTT, establishing degradation mechanisms, using sufficient numbers of samples, and applying the SLP methodology to produce a SLP for existing or new PV technologies.

INTRODUCTION

The conventional product requirement triad of cost, performance, and durability is illustrated in Fig. 1. For photovoltaic (PV) systems, these need to be thought of as an initial system cost, PV conversion efficiency [$P(0)$], and the service lifetime prediction of future PV performance, i.e., the durability, $P(t)$. As documented elsewhere in this volume, excellent pro-

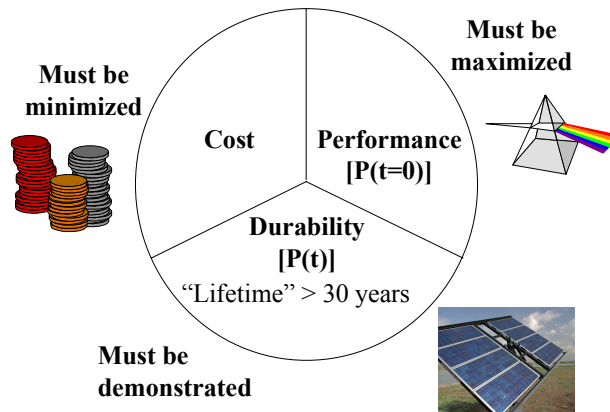


FIGURE 1. The product requirement triad of cost, performance, and durability (lifetime).

gress has been made in improving PV efficiency since the 1970s, and the initial system cost has been reduced to several dollars per watt, most recently through the PV Manufacturing Technology partnerships between the PV industry and the U.S. Department of Energy (DOE). Of the several billions of dollars spent worldwide for developing PV technologies, nearly all has been spent to improve PV conversion efficiencies or reduce the initial system cost. For durability, unfortunately, most of the remaining funds have been spent for deploying complete systems for monitoring $P(t)$ through real-time testing (RTT) at various terrestrial locations. It is only in the last decade that accelerated life testing (ALT) techniques have been used properly for encapsulated PV cells and minimodules, and the focus of the work has only been related to improving the service life of the ethylene vinyl acetate (EVA) pottant (1). For current PV technologies and those for the 21st century, we conclude that ALT, RTT, and service lifetime prediction (SLP) must be used to replace the present dependence of the PV community on deploying large systems for performance monitoring. We developed the rationale for this conclusion from our past work with solar mirrors, encapsulated PV cells and minimodules, and electrochromic windows, and from developing a SLP methodology for application to multilayer stacks of materials. We think SLPs must be made and validated before critical multibillion dollar decisions will be made to purchase PV systems by the electric utility industry.

The objectives of this paper, stated in (a) through (f) in the abstract, are all driven by and relate to achieving a goal of more than 30-year service lifetimes (SL) for PV systems (1). The reliability and SL goals for developing PV technologies for the 21st century are to (i) identify, understand, and then mitigate the causes of changes in cell and module materials that alter crucial materials properties and reduce the performance or limit the service lifetime, or both, of cells/modules, and (ii) develop new or improved materials that offer greater promise for a module service life expectancy of more than 30 years. These goals are generic for most multilayer, energy efficiency (e.g., conservation) or renewable energy (EERE) conversion devices. They can be modified by simply changing "material" in (i) or (ii) to cell, array, or system for other PV-specific goals or by changing "module" in (i) or (ii) to some other EERE device such as a solar mirror, electrochromic window, or flat-plate collector glazing or absorber (2). For the service lifetime of other elements, the word "materials" may be changed to be broader, e.g., component or subassembly. In keeping with the generality of the stated goals, we first discuss the general principles behind the requirements for establishing the service lifetime of EERE multilayer devices used for solar energy conversion or conservation and then show how these principles are being applied to PV cells and minimodules.

Because emerging advanced multilayer solar energy conversion devices (SECD) are expected to exhibit service lifetimes of more than 20 to 30 years, technology development cannot be based solely on using real-time weathering for establishing long lifetimes. Typical multilayer SECD include silvered reflectors, present-generation PV modules, flat-plate collectors, electrochromic windows, and photoelectrochemical cells. Many U.S. companies are at a critical juncture in marketing improved products, such as protective coatings, interior lighting reflectors, and polymer-based coatings for many uses, whose service lifetime must be predicted. Without confident knowledge from an accurate and reliable SLP methodology, warranties may be at high risk. Life-cycle costs require knowing accurately a service lifetime, as well as the obvious initial cost of the delivered product, cost of initial capital, future costs discounted to present value, and future costs for the operating, maintenance, repair, replacement, demolition, and removal activities.

DURABILITY RELATED DEFINITIONS AND DESIRED SERVICE LIFETIMES

The service lifetime of materials, devices, or systems is the time at which their (time-averaged) performance degrades below a prescribed or required value, i.e., a total failure or a failure to perform at a preassigned value. This definition is deduced from the American Society for Testing and Materials (ASTM) definitions for durability, serviceability, and service life (3). Durability (3) is the capacity to maintain the serviceability of a product, component, assembly, or construction over a specified period of time. Serviceability (3) is the capability of a product, component, assembly, or construction to perform the function(s) for which it was designed and constructed. For PV devices, the effective definition of durability is the capability of the device to perform its designed function, i.e., device performance versus time. ("Reliability" is interchangeable with this operative definition of "durability.") Thus, service life requires the selection of some minimum performance criteria, e.g., a PV module rated at 50 W at the normal operating temperature condition (NOTC) may be a "failure" when its power output falls below 40 W. *The minimum acceptable performance (i.e., "failure") needs to be defined for a SLP of cells/modules of any PV technology.* The prediction of the service life is based on criteria and calculated using the protocol outlined later in this paper.

Because the desired PV module lifetimes are greater than 30 years, accelerated lifetime testing (ALT) in (simulated) weather environments and an SLP methodology must be used. As is the case with PV and other EERE devices, U.S. industry (working in areas such as coatings, lighting devices, and polymeric-based devices) cannot wait for the results from RTT so ALT and SLP must be used. We illustrate the vision of being able to predict the service lifetime of an encapsulated PV module in Fig. 2. We have arbitrarily chosen a generic PV module with 100% of its rated output at NOTC. If no loss in performance occurs, the module will produce 100% forever. However, losses in PV *systems* range from a low of 1% per year to 2.5% per year (1), as shown by the solid lines in Fig. 2.

The actual losses are shown for the Carissa Plains, CA, 5.2-MW system (4-6) that is the most extreme case of degradation reported (1). The losses in real systems are from *all* causes, and not just in the modules. Because data are not yet available to allow sufficiently accurate projection of future output from a cell, module, or a system, several hypothetical projections are illustrated by the dashed lines. The area under the projected curves would permit calculating the predicted output per year until failure is reached, and life-cycle costs could then be calculated from the total power that would be produced and from the other life-cycle costs,

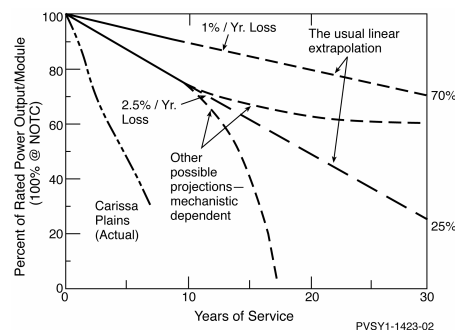


FIGURE 2. Actual and potential percentage losses in efficiency (performance) of current-generation PV *systems*.

e.g., initial, operating, and maintenance costs. The major issue for any new PV technology for the 21st century is to resolve what (time-averaged) loss in performance, i.e., power output, is permitted until the time (in years) of failure is reached.

It is clearly possible to reach the vision of being able to predict the power output of systems for their operational lifetime, but two significant problems must be resolved. First, the technical reasons for the power losses must be determined. The losses plotted in Fig. 2 are *system* losses; causes of performance losses need to be identified and then mitigated for cells, modules, or any other balance-of-systems components. No studies have been completed that establish the relationships between the accelerated degradation of individual modules and RTT. From prior work, some of the losses have clearly resulted from EVA browning (1,7). Secondly, resources need to be increased substantially for a proactive technical approach that will result in improving *existing* and *new* PV products. Research and development using ALT at an *early state can reduce the cost of developing advanced PV technologies*. For example, the deployment of the 5.2-MW system of full-size modules at Carissa Plains (CP) cost 82 million dollars. The EVA browning problem that was discovered after real-time exposure for only three years at CP has been replicated, understood in detail, and significantly mitigated for less than 4 million dollars using laboratory-scale encapsulated cells and minimodules (1).

In addition to ALT, the experimental approach needs to include (a) monitoring the RTT performance of appropriate statistically significant sets of individual PV cells and minimodules in the early stages of research (and ultimately with full-size modules), (b) deducing causes of failure in *these* products, and (c) studying new or improved materials and designs at the cell and minimodule level. A SLP then becomes possible by adopting such an approach for identifying and isolating failure modes or degradation mechanisms at the cell/minimodule, module, and other component levels, as is detailed elsewhere (8). At present, RTT of *individual* module performance is being monitored at different sites for three cases (9-11), but without complete *initial* characterization before deployment. Eventually, ALT needs to be performed on sets of "identical" modules for accelerating the degradation of design/materials weaknesses and/or for comparing the rates with the RTT results; the RTT data need to be taken at several environmentally diverse sites. From the work we are now doing, we fully recognize that establishing PV device/module service lifetimes of 30 years or more involves solving many synergistically driven problems.

CONVERTING SOLAR ENERGY INTO ELECTRICITY WITH PV TECHNOLOGIES IN A TERRESTRIAL ENVIRONMENT

The major problem in solar energy technologies is not discovering how to collect the radiant flux, but rather is establishing how to collect it in a way that is cost competitive with conventional power generation (12). The latter is one of the reasons that EVA was chosen for use in PV modules, rather than other more expensive polymers known to have better properties (1,13). The solar energy reaching the Earth has a typical power density of 500 to 1000 W/m², which means collection areas of about 1000 m²/quad (400 mi²/quad) are required for a typical PV system (15% efficiency, tracking, and 1000 W/m²) (14). The cost of the materials used, device production processes, and the operation and maintenance of systems must be held to a minimum. This requires, for example, using multilayered stacks of superstrates, substrates, and the active PV thin (or thick) films or coatings. These must be made from inexpensive, durable,

and easily processed materials. For example, if we assume PV devices can be made in 5.5-m widths using a continuous process (in vacuum) moving at 0.46 m/s (1.5 ft/s) for 24 h/day and 365 days/year, then this manufacturing unit will produce only 26.35 km² (10.18 mi²) of PV collectors. At 15% efficiency and optimum tracking, the energy output will be 0.025 quads per year, and 40 of these manufacturing units will be needed to produce about 1% of the current annual U.S. energy consumption of 94 quads. A process rate of 0.46 m/s (1.5 ft/s) is about 100 times faster than many current production processes, as described elsewhere in this volume.

The materials chosen not only provide device-specific functions but also environmental protection, which is crucial for the long service lifetimes that will reduce life-cycle costs and increase the market value of the devices. When in use, man-made solar energy conversion systems are subjected to a unique set of in-service degradation factors that may alter their *stability* and, hence, their performance and life-cycle costs, in addition to the initial cost of the system. Degradation factors include biological (microorganisms, fungi, bacteria), incompatibility (physical or chemical materials interactions), sustained or periodic stresses, use (system design, normal wear, installation and maintenance, abuse), and weathering. For solar energy collecting devices, the weathering factors include irradiance (especially ultraviolet (UV) radiation), temperature, atmospheric gases (O₂, O₃, CO₂) and pollutants (gases, mists, particulates), diurnal and annual thermal cycles, and, in concentrating systems, a high-intensity solar irradiance. In addition, rain, hail, condensation and evaporation of water, dust, wind, freeze-thaw cycles, and thermal-expansion mismatches may impose additional losses in the performance of a PV device. All degradation factors must be considered not only individually, but also collectively for degradative effects that may result from their synergistic action on any part of the system. The first prerequisite is that the bulk properties of the superstrate, substrate, thin film, coating, and other materials be stable. For example, photothermally induced degradation can be the predominant factor for polymeric or organic-based materials. The activation spectrum depends on the bond strengths in the polymer and is sensitive to the incident UV wavelengths. Any laboratory-scale UV testing must correctly simulate the solar irradiance during in-service use. Scientists at the National Renewable Energy Laboratory have used xenon arc lamps with appropriate filters for nearly 20 years for simulating the UV and visible solar irradiance, but only recently for PV-related durability studies (1).

After the requisite stability of the "bulk" materials is achieved, interface reactions that are known to be thermodynamically driven because of the higher free energy state of atoms at interfaces must be addressed (14). A further need may then be to choose the different materials carefully to permit achieving a 30-year "stability" (15a) or to modify the interfaces for attaining the same goal (15b). For projecting a service lifetime to yield the desired time-dependent level of performance, substantially more SLP-directed work is needed. The detailed application of the SLP methodology will be more challenging for PV devices.

IMPORTANCE, COMPLEXITY, AND NEEDS FOR THE SERVICE LIFETIME PREDICTION OF PV TECHNOLOGIES

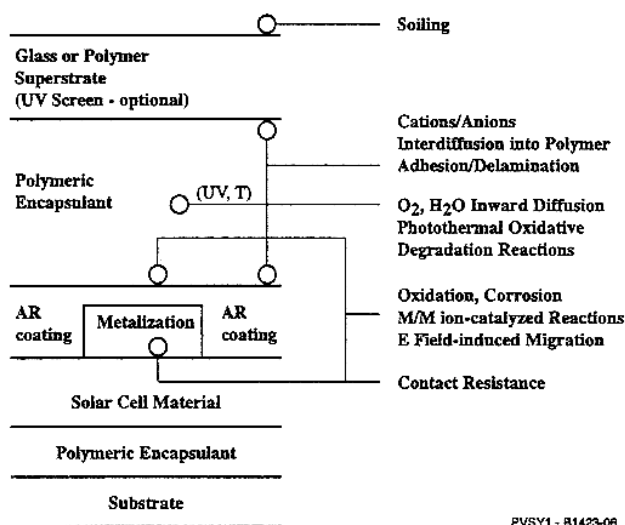
As stated earlier, service lifetime must be known to determine the life-cycle cost for using a device of known initial cost and initial performance, i.e., efficiency in PV cells. The cost-effective deployment of any PV device is partly limited by the durability and life-cycle cost of the materials used. Research on the active and encapsulating materials and studies that

address the influence of the materials degradation on device performance are of critical importance, especially to understand soiling of surfaces, degradation of polymeric materials, the effects of oxygen and water vapor permeation, corrosion, the degradation of the active materials, and degradation at interfaces. The ultimate need is to identify materials that will not result in a decreased PV device performance during exposure to actual use conditions for the desired/required service lifetime of the device. Establishing a service lifetime prediction requires a multidisciplinary team of experts, plus supporting diagnostic expertise. These include people knowledgeable in the disciplines of materials science, materials engineering, surface science, corrosion science, polymer science, solid-state physics, physics, physical and analytical chemistry, electrochemistry, statistical methods, and theorists on lifetime prediction, who have (or can access) sophisticated diagnostic and measuring equipment. Appropriate capabilities for accelerated and real time weathering of devices are also essential. If done properly, predicting a service lifetime of any device requires significant resources, but is essential before major investment decisions will be made.

DEFINING THE PROBLEM AND UNDERSTANDING THE CAUSES OF DEGRADATION IN PV COLLECTION EFFICIENCIES

Before implementing a SLP methodology, it is essential to define the problem as exactly as possible. The in-service performance requirements and criteria for the device must be established. The materials in the device must be characterized thoroughly for structure, composition, critical performance characteristics, properties that indicate degradation, range and type of degradation factors, and all possible degradation mechanisms. Postulated degradation mechanisms for a contemporary crystalline-silicon PV cell are shown schematically in Fig. 3; additional detail is given in ref. (1).

The glass cover-plate may or may not contain a UV screen such as cerium dioxide, or a modified polymer may or may not be laminated between it and the pottant. A primer may or



PVSY1 - 81423-06

FIGURE 3. Schematic cross-section of an encapsulated PV cell and relevant reactions and processes that may reduce the cell performance or service lifetime, or both (1,16).

may not be used in the EVA formulation or be coated onto the glass substrate. The pottant in nearly all deployed monocrystalline (c-Si) or polycrystalline silicon (pc-Si) systems is EVA, and about 95% of the installed PV capacity (~650 MW) is pc-Si or c-Si. An antireflection (AR) coating (typically 50 nm of SiO₂) may or may not be deposited onto the metalization or oxide surface of the Si solar cell(s). The active solar cell material(s) may be several multilayers and have a back or base contact. Another layer of EVA that is shielded from exposure to UV and the supporting substrate complete the module encapsulation. In a PV module, solar cells (e.g., 36 to 72 or more in a typical module) are joined by interconnects that are also embedded between the two EVA layers. Power output terminals are provided on each module.

As is also illustrated in Fig. 3, degradation can occur by weathering and/or soiling of the cover glass; photothermal, oxidative, or other degradation of the pottant (1,16,17); interdiffusion of ions into the pottant; metalization corrosion; electric field-induced ion migration or degradation; and polymer/metal oxide interface reactions or delamination. Many of these processes may depend on initial impurity concentrations and trapped gases (vapors) and on concentration changes during use. We emphasize this complexity of the entire module here because we have to establish which degradative reactions must be mitigated (besides pottant discoloration) and which ones are too slow to impact the performance adversely for lifetimes of greater than 30 years.

Further problem definition involves postulating procedures for accelerating the potential degradation mechanisms (Fig. 3) to be used in the preliminary testing. The elevated stress levels, e.g., in UV, T, relative humidity (RH), and cycle frequency, must be carefully chosen. A number of criteria are necessary for *accelerated testing* to be successful with a *goal* of making service lifetime predictions; these are discussed in some detail by Fischer et al. (18) and outlined in publications from various PV-related forums (15b-17, 19-21). These include, for example, that the accelerated test must not alter the degradation mechanism(s); the mechanisms and activation energies of the dominant reaction(s) at normal operating conditions and accelerated test conditions must be the same; both the specimens (including materials and components only) and accelerating parameters (UV, T, RH, product entrapment, etc.) must simulate reality; cells and/or modules that simulate reality must be used in the initial accelerated tests; and the time-dependent performance loss (e.g., power loss for PV modules) must be correlated with the degradative reactions.

For testing sequences and design of experiments, preliminary testing is conducted to identify property changes likely to be degradation indicators, the rank order of degradation factors, mechanisms that result in changes in properties, and the intensities of degradation factors that are needed to induce property changes. Advanced testing is then used to determine the relationship between degradation rates and exposure conditions, to design and perform tests for ALT and RTT conditions, and to measure rates of change in key properties. The testing design needs to include deploying specimens for long-term in-service tests and conducting predictive service life tests. The test matrix must account for the synergistic influences of the stresses, e.g., UV, T, and RH, used during ALT. The encapsulated PV device should be operated during the ALT. Finally, the actual activation energies must be used in the Arrhenius equation for calculating rates of degradation, rather than using the “rule of thumb” of “rates double for every 10 K increase in the temperature” (1). Ultimately and ideally, the accelerated tests must be made on commercial-scale modules that are the same size as those sold to the consumer, but this ideal *may* not be necessary if predictions from laboratory-scale specimens are reliable predictors of the commercial products. Obviously, a SLP requires a definition of

"failure," i.e., what loss in efficiency is acceptable after how many years; failure needs to be defined for a PV module in keeping with the power losses of 1% to 2.5%/yr being observed in systems deployed in the terrestrial environment (1).

MAJOR ELEMENTS FOR SERVICE LIFETIME PREDICTION

We now summarize the seven major elements of a SLP methodology. Because we have elaborated on these elements in prior work and published a detailed figure showing the technical approach (2), we include only one sentence to identify each of the SLP elements. The major advantage of the sequence of these SLP elements is that the first four elements can be used to improve the performance and durability of multilayer devices, e.g., PV technologies for the 21st century, until the optimum design and materials are identified. Repeated use to improve the performance of these four elements is often termed *"screening" of design or materials options, or both*. The seven-element, simplified SLP methodology is illustrated in Fig. 4 of ref. (2) for c-Si or pc-Si cells or minimodules. For existing and 21st century PV technologies, the device construction in SLP element [1] is simply used for the relevant technology. Examples are available of how some of these SLP elements have been used for PV encapsulants (1,21) and how the SLP methodology has been developed (22). Substantial additional effort is required with ALT and RTT, and in establishing degradation mechanisms for *PV cells* so that we will be able to proceed to SLP element [5] in 2003!

The seven SLP elements are as follows: [1] the "final" design and materials selections are needed for the multilayer stack; [2] the degradation factors imposed on the device in real-time use and the same types of factors for ALT need to be identified and quantified; [3] the complete devices are subjected to ALT and RTT to determine their durability, and *the most sensitive measurement(s) of the performance loss* (or of a parameter that can be correlated to the performance) is measured; [4] the mechanisms of degradation of bulk materials and reactions at interfaces must be identified and understood, and the degradation mechanism must result in a loss in performance of the device, or compromise the materials function, or both, to be of concern; [5] models need to be developed for correlating ALT data and RTT data taken at several geographic sites with diverse stresses; [6] databases of stresses and materials response must be established that include data from different outdoor sites; and [7] predictive service lifetime models are then developed from the data obtained in SLP elements [2] through [6] by using statistical approaches and life distribution models. A sufficient number of replicate samples must be part of the test matrix to deduce the life distribution model from the degradation (8). For example, an initial set of samples, which may range from a minimum of about 12 to 15 up to 50 and that all have "identical" performance, will degrade into a distribution of performances during use or aging. Large sample sets and ultrasensitive measurements of the performance parameter are required, if we are to achieve the best prediction results. Both of these requirements increase the cost of making a SLP. Obviously, costs increase with increasing sample numbers. The performance parameter may require several measurements or the need to develop a beyond-the-state-of-the-art measurement to achieve the desired result; in either case, the cost for making a SLP is increased. Therefore, it is critical to use efficient, statistical, experimental designs.

Obtaining a SLP for performance may be difficult for several reasons. These include the challenges of dealing with a large variability in failure times, determining the appropriate

stresses causing performance degradation, extrapolating the results from ALT at elevated stress levels to the normal stress level, defining what is a "failure" of material(s) or system(s), having to use small lifetime data sets for economic reasons, and demonstrating that the degradation mechanism in ALT is the same as in RTT.

As an important addendum for accelerated environments and for simulating the reality of the solar UV and visible radiation, it is essential that any UV source match the wavelengths reaching the Earth's surface. This means we must have precise knowledge of the spectral irradiance incident on the EERE device and that the UV source intensity be a reasonable multiple of the solar intensity. For these reasons, NREL scientists have used filtered Xe-arc lamp sources since 1978 (17,23) and have rejected other sources, such as fluorescent lamps because they do not simulate reality. Zussman indicates that the solar spectrum cutoff at sea level is 285 nm, and radiation between 290 nm and 300 nm is routinely incident at the Earth's surface (24). UV radiation can severely damage polymers if their activation spectra are at wavelengths from 290 to ca. 380 nm (25). With appropriate filters (26,27), the Xe-arc light source simulates the solar spectrum very well from 285 to 500 nm. The source intensities usually refer to the number of suns, which are simply multiples of the solar intensity in watts per square meter at the wavelengths of interest. The materials degradation from a Xe-arc light exposure may not match the in-service experience (27). This may result, in part, from the promotion of chemical effects of secondary processes in materials by the synergism of T, RH, O₂, and other weathering factors (25). Similar detailed considerations are required for all imposed stresses unless it is shown that the degradation in performance is not related to a particular stress.

CONCLUSIONS

A methodology for predicting the service lifetime of multilayered PV devices has been outlined and related to present and future PV technologies. The SLP methodology is not limited to PV and EERE devices, but can also be applied to U.S. industrial needs. Developing the technology base for predicting PV module lifetimes of greater than 30 years requires a generously funded, multiyear research effort. A "failure" in the performance level (efficiency) needs to be defined for PV modules and is necessary for making a SLP. Furthermore, an extremely sensitive measurement of a PV cell or module performance or one that is directly correlated to the performance, also needs to be identified. The multiyear effort must also result in understanding degradative reaction mechanisms and their relative importance, establishing the expected levels of degradation, and using the most appropriate experimental methods. SLP must be an essential element for developing any present or future PV technology. A durability (reliability) and SLP expert must be an integral part of any PV technology team to assist in defining a scientifically sound technical approach. ALT, establishing degradation causes, and improving the new PV technology should be a part of the *initial* research and development program, to narrow the materials/design options through preliminary testing. The complete SLP methodology, which includes ALT, RTT, modeling, and analysis for obtaining a SLP, can be done most cost-effectively as a research and development effort on *laboratory-scale but complete PV minidevices*. SLP is an essential element for calculating life-cycle costs of any next-generation technology. Accurate SLP is possible if the methodology is properly applied. Finally, SLP is a complex problem that requires significant resources and a commitment for attaining and retaining a critical mass of people for performing the work.

ACKNOWLEDGMENTS

The authors are grateful to F.J. Pern for his technical insight and comments about the manuscript. The authors thank R. Hulstrom for his encouragement, C. Gay and B. Marshall for their support from the Directors Development Fund for developing the SLP methodology, and the U.S. Department of Energy for its support of this work under Contract No. DE-AC36-98-GO10337.

REFERENCES

1. A. W. Czanderna and F. J. Pern, "Encapsulation of PV Modules Using Ethylene Vinyl Acetate Copolymer as a Pottant: A Critical Review," *Solar Energy Materials and Solar Cells*, **43**, pp. 101-183 (1996).
2. A. W. Czanderna, in *Future Generation Photovoltaic Technologies*, R. D. McConnell, Editor, p. 55, Conf. Proc. 404, American Institute of Physics, Woodbury, NY, (1997).
3. "ASTM Book of Definitions," *American Society for Testing and Materials*, W. Conshohocken, PA, (1996).
4. C. F. Gay and E. Berman, *Chemtech*, pp. 182-186 (March 1990).
5. A. L. Rosenthal and C. G. Lane, *Solar Cells: Their Science, Technology, Applications and Economics*, Elsevier Sequoia, **30**, 563 (1991).
6. H. J. Wenger, J. Schaefer, A. Rosenthal, R. Hammond, and L. Schlueter, *Proc. 22nd IEEE Photovoltaic Specialists Conference (PVSC)*, New York, IEEE, p. 586 (1991).
7. F. J. Pern, in *Proc. PV Performance and Reliability Workshop*, L. Mrig, Editor, NREL/CP-411-5148, Golden, CO: National Renewable Energy Laboratory, (Sept. 1992), pp. 327-344.
8. G. J. Jorgensen, *Proc. Photovoltaic Performance and Reliability Workshop*, B. Kroposki, Editor, NREL/TP-411-21760, Golden, CO: National Renewable Energy Laboratory, (October 1996), pp. 193-216.
9. A. Rosenthal and S. Durand, in *NREL Photovoltaic Program FY 1995 Annual Report*, S. Smoller, coordinator, NREL/TP-410-21101, (June 1996), pp. 377-380.
10. D. Berman, S. Biryakov, and D. Faiman, *Solar Energy Materials and Solar Cells*, **36**, 421 (1995).
11. L. Mrig, T. Strand, B. Kroposki, R. Hansen, and E. van Dyck, in *NREL Photovoltaic Program FY 1995 Annual Report*, S. Smoller, coordinator, NREL/TP-410-21101, (June 1996), pp. 350-355.
12. R. S. Claasen and B. L. Butler, in *Solar Materials Science*, L.E. Murr, Editor, p. 3, Academic, New York, (1980).

13. E. Cuddihy, C. Coulbert, A. Gupta, and R. Liang, *Flat-Plate Solar Array Project, Final Report, Volume VII: Module Encapsulation*, JPL Publication 86-31, Jet Propulsion Laboratory, Pasadena, CA, (October 1986).
14. A. W. Czanderna, in *Solar Materials Science*, L.E. Murr, Editor, p. 93, Academic, New York, (1980).
15. (a). A. W. Czanderna and R. Gottschall, Guest Editors, *Materials Science and Engineering*, **53**, 1(1982); (b). A. W. Czanderna and A. R. Landgrebe, Guest Editors, *Critical Reviews in Surface Chemistry*, **2**, Nos. 1-4, **3**, No. 1 (1993).
16. A. W. Czanderna, in *Proc. PV Module Reliability Workshop*, L. Mrig, Editor, p. 159, SERI/CP-4079, Solar Energy Research Institute, Golden, CO, (October 1990).
17. A. W. Czanderna, in *Proc. PV Module Reliability Workshop*, L. Mrig, Editor, NREL/CP-410-6033, p. 311, National Renewable Energy Laboratory, Golden, CO, (September 1993).
18. R. M. Fischer, W. M. Ketola, J. Martin, G. Jorgensen, E. Mertz, U. Pernisz, and G. Zerlaut, *Critical Reviews Surface Chemistry*, **2**, 317 (1993).
19. J. P. Wineburg, in *Proc. Photovoltaic Performance and Reliability Workshop*, L. Mrig, Editor, NREL/CP-411-5184, p.365, National Renewable Energy Laboratory, Golden, CO, (September 1992).
20. (a). G. J. Jorgensen, *Proc. Photovoltaic Performance and Reliability Workshop*, L. Mrig, Editor, NREL/CP-411-20379, p. 151, National Renewable Energy Laboratory, Golden, CO, (November 1995). (b). W. Putman, *ibid.*, p. 279.
21. A. W. Czanderna and F. J. Pern, in *Durability Testing of Nonmetallic Materials*, R.J. Herling, Editor, ASTM STP 1294, p. 204, American Society for Testing and Materials, Philadelphia, PA, (1996).
22. H-M. Kim, G. J. Jorgensen, D. E. King, and A. W. Czanderna, in *Durability Testing of Nonmetallic Metals*, R. J. Herling, Editor, p. 171, ASTM STP 1294, American Society of Testing and Materials, Philadelphia, PA, (1996).
23. J. D. Webb and A. W. Czanderna, *Solar Energy Materials*, **15**, 1 (1987).
24. H. W. Zussman, p. 372, 1A, *Plastics Encyclopedia*, (September 1959).
25. N. D. Searle, in *Advances in the Stabilization and Controlled Degradation of Polymers*, A. V. Patsis, Editor, p. 62, Vol. **1**, Technomic Pub. Co, Lancaster, PA, (1986).
26. J. D. Webb and A. W. Czanderna, *Macromolecules*, **19**, 2810 (1986).
27. J. D. Webb, A. W. Czanderna, and P. Schissel, in *Polymer Stabilization and Degradation*, Vol. 2, H.H.G. Jellinek, Editor, p. 373, Amsterdam, Elsevier, (1989).