Service Lifetime Prediction for Encapsulated Photovoltaic Cells/Minimodules

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Abstract. The overall purposes of this paper are to elucidate the crucial importance of predicting the service lifetime (SLP) for photovoltaics (PV) modules and to present an outline for developing a SLP methodology for encapsulated PV cells and minimodules. The specific objectives are (a) to illustrate the generic nature of SLP for several types of solar energy conversion or conservation devices, (b) to summarize the major durability issues concerned with these devices, (c) to justify using SLP in the triad of cost, performance, and durability instead of only durability, (d) to define and explain the seven major elements that comprise a generic SLP methodology, (e) to provide background about implementing the SLP methodology for PV cells and minimodules including the complexity of the encapsulation problems, (f) to summarize briefly the past focus of our task for improving and/or replacing ethylene vinyl acetate (EVA) as a PV pottant, and (g) to provide an outline of our present and future studies using encapsulated PV cells and minimodules for improving the encapsulation of PV cells and predicting a service lifetime for them using the SLP methodology outlined in objective (d). By using this methodology, our major conclusion is that predicting the service lifetime of PV cells and minimodules is possible.

INTRODUCTION

The objectives of this paper are given in (a) through (g) in the Abstract, which are all driven by and related to achieving a goal of a 30-year service lifetime for PV systems (1). Our task goals are (i) to identify, understand, and then mitigate the causes of changes in module materials that alter crucial materials properties and reduce the performance and/or limit the service lifetime of cells/modules and (ii) to develop new or improved materials that offer greater promise for a module service life expectancy of over 30 years. These goals are generic for most multilayer, energy efficiency (e.g., conservation) or renewable energy (EERE) conversion devices and 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. For the service lifetime of other elements, the word materials may also be changed to be broader, e.g., component or subassembly. In keeping with the generality of the stated goals, we will discuss first the general principles of what is required to establish 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.

The Solar Environment and Collecting Solar Energy

The major problem in solar energy technologies is not discovering how to collect the radiant flux, but how to collect it at a competitive cost (2). The latter is one of the reasons ethylene vinyl acetate (EVA) was chosen for use in PV modules rather than other more expensive known polymers with better properties (3). Solar energy reaching the Earth has a typical power density of 500 to 1000 W/m^2, which means large collection areas are required for any solar technology (2). The cost of the materials utilized, 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 thin (or thick) films or coatings for various collection schemes, e.g., mirrors, PV systems, electrochromic windows, and flat-plate collectors (as illustrated in Figure 1), and that these be made from inexpensive, durable, and easily processed materials.
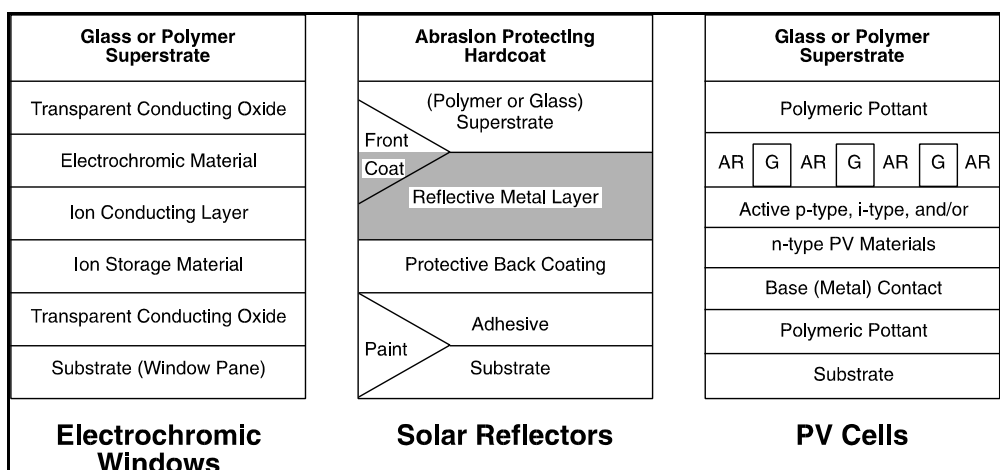
Glass or Polymer Superstrate	Abrasion Protecting Hardcoat	Glass or Polymer Superstrate
Transparent Conducting Oxide	Front Coat > (Polymer or Glass) Superstrate	Polymeric Pottant
Electrochromic Material		AR | G | AR | G | AR | G | AR
Ion Conducting Layer	Reflective Metal Layer	Active p-type, i-type, and/or n-type PV Materials
Ion Storage Material	Protective Back Coating	Base (Metal) Contact
Transparent Conducting Oxide	Paint > Adhesive	Polymeric Pottant
Substrate (Window Pane)	Substrate	Substrate
Electrochromic Windows	**Solar Reflectors**	**PV Cells**

FIGURE 1. Cross sections of typical multilayer stacks used for solar reflectors, electrochromic (EC) windows, and PV cells. The front coat and paint layers are optional additions for solar reflectors. Different detailed mechanisms of failure are expected for the passive reflectors when compared with the active (ion or electron transport) PV or EC devices.

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 "real-world" stresses that may alter their *stability* and, hence, their performance and life cycle costs in addition to the initial costs of the systems. These stresses include ultraviolet (UV) radiation, temperature, atmospheric gases and pollutants, 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, thermal expansion mismatches, etc., may impose additional losses in the performance of a

solar device. These stresses and 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. After the requisite stability of the "bulk" materials is achieved, interface reactions are known to be thermodynamically driven because of the higher free energy state of atoms at interfaces (4). A further need may then be to choose the different materials carefully to permit achieving a 30-year "stability" (5a) or to modify the interfaces for attaining the same goal (5b). A service lifetime goal of over 20 or 30 years is targeted for all the devices in Figure 1. For projecting a service lifetime to yield the desired time-dependent level of performance, much more SLP-directed work is needed. Furthermore, the detailed application of the SLP methodology will be more challenging for the active (PV and EC) devices than for the passive solar mirror constructions.

   The goals cited in (i) and (ii) above are for the type of research needed to develop an understanding of the behavior of low-cost, high-performance, active and encapsulation materials that can be used to extend the service lifetime or to identify materials that offer new options for use in the device. For the conventional triad of requirements that includes low (initial) cost, high performance, and long-term durability (reliability), we substitute service lifetime to replace durability (reliability) as this is what is really desired. A service lifetime *prediction* (SLP) is the ability to project the future time dependence of the performance that defines the durability. 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 EERE 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 decrease the 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, theorists on lifetime prediction, etc., 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.

SERVICE LIFETIME AND MAJOR ELEMENTS FOR PREDICTION

The service lifetime of materials, devices, or systems is the time at which its (time-averaged) performance degrades below a prescribed/required value, i.e., a failure or a failure to perform at the preassigned value. We deduce this definition from the American Society for Testing and Materials (6) definitions for durability, serviceability, and service life. Durability (6) is the capacity of maintaining the serviceability of a product, component, assembly, or construction over a specified period of time. Serviceability (6) is the capability of a product, component, assembly or construction to perform the function(s) for which it was designed and constructed. For EERE devices, the effective definition of durability is the capability of the device to perform its designed function, i.e., device performance vs time. (Reliability can be interchanged with this operative definition for durability.) Service life (6) is the period of time after installation during which all properties exceed the minimum acceptable values when routinely maintained. 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 PV modules***. SLP is the estimated service life based on criteria and using the protocol outlined later in this section.

Desired lifetimes of typical EERE devices are as follows: polymeric or glass reflector constructions for mirror applications, > 20 years; PV modules, > 30 years; electrochromic windows, > 20 years; flat plate collectors, > 10 years; and Lo E coated windows, > 20 years. Because the desired lifetimes range from > 10 years to > 30 years, accelerated lifetime testing (ALT) in (simulated) weather environments and a predictive methodology must be used. The lifetimes of EERE devices are not unique in U.S. technology and several first-rate SLP groups have been developed at a few major U.S. corporations; as with EERE devices, U.S. industry (e.g., coatings, lighting, polymeric-based devices) cannot wait for the results from real-time testing (RTT) so must use ALT and SLP. Many U.S. companies are at a critical juncture for marketing products with a stated lifetime but need a SLP. Without a SLP, warranties will either be stated conservatively or have high risk.

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. (7) and outlined in publications from various forums (6-8), as well as with the PV (9-12) and electrochromic windows (13) communities. 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. 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).

We now summarize the seven major elements of a service lifetime prediction methodology in which the first sentence states the element and subsequent comments clarify the element. The major advantage of the sequence given is that the first four elements can be used for improving multilayer devices until the optimum design and materials are obtained. Examples of how some of these elements have been used are available for mirrors (8, 12a, 12b, 14, 15), PV encapsulants (1, 16), and coatings (11).

SLP Element 1. The "final" design/materials selections are needed for the multilayer stack. For improving the durability of the device, each *prototype* design and the materials used can be considered as "final" for elements 1 through 4. When several prototype designs are studied, statistical methods are used to identify a test matrix of the best candidate combinations. Ultimately, a set of materials and a particular design will be identified that permits proceeding to element 5.

SLP Element 2. The "stresses" imposed on the device in real time use and the same types of stresses for ALT need to be identified and quantified. As discussed in the Introduction, the "stresses" have been identified for EERE devices used in a solar terrestrial environment. 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, which means having 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 (8, 17), and have rejected other sources such as fluorescent lamps because they do not simulate reality. Zussman indicates that the solar spectrum cut-off at sea level is 285 nm, and radiation between 290 nm and 300 nm is routinely incident at the Earth's surface (18). UV radiation can severely damage polymers if their activation spectra are at wavelengths from 290 to ca. 380 nm (19). With appropriate filters (20,21), 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 W/m^2 at the wavelengths of interest. The materials degradation from a Xe-arc light exposure may not match the in-service experience (18). This may result, in part, from the promotion of chemical effects of secondary processes in materials by the synergism of temperature, humidity, O_2, and other weathering factors (19). 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.

SLP Element 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. Typically, the

device performance is evaluated periodically with time from measurements made by moving the samples to the instrument(s). Ideally, the measurement(s) should be made in situ either by using probes so the sample is never removed from its test location, i.e., an outdoor exposure rack or accelerated test chamber, or by using portable measuring equipment at the sample test location. The success in correlating ALT and RTT results depends crucially on the sensitivity, accuracy, and reproducibility of the measurement of the performance parameter, e.g., if a device performance is degrading at 1% per year, a measurement of the changes in the performance of 0.1% or even less is needed if the ALT data are to be correlated with the RTT data for "reasonable" RTT exposure times. For solar mirrors, specular reflectance is correlated to loss in performance and changes can be measured accurately and reproducibility (12a). *A measurement of PV performance with a sensitivity comparable to the specular reflectance of solar mirrors needs to be identified for PV cells or modules.*

SLP Element 4. The mechanisms of degradation of bulk materials and/or reactions at interfaces must be identified and understood. The degradation mechanism must result in a loss in performance of the device and/or compromise the materials function to be of concern. If the rate of performance loss from the degradation is fast relative to the expected service lifetime, the cause of degradation must be mitigated, and the sequence of elements 1 through 4 must be repeated for the new or modified materials or design used initially. If the rate of degradation is slow and the activation energy can be determined for the rate-controlling reaction, it is reasonable to proceed to element 5. At present, the design for silvered polymeric mirrors (Figure 1) is the only EERE multilayer stack that is ready for proceeding to element 5. Substantial additional efforts are required with *PV cells* so we will be able to proceed to element 5 in 2002.

SLP Element 5. Models need to be developed for correlating ALT data and RTT data taken at several geographic sites with diverse stresses. The rate of degradation is site dependent because the stresses that cause degradation vary from site to site. For example, the total UV insolation in the sunny southwest deserts in the U.S. is a more aggressive stress than in the cloudy northeastern states. The models for correlating the ALT data and RTT data must be able to accommodate different magnitudes of the stresses including time-dependent variations and any synergism of the stresses. For a successful SLP, it is critical that correct mathematical interpretations be made of the experimental results that relate or correlate the key environmental stresses (e.g., UV, T, RH).

SLP Element 6. Stress and materials response data bases must be established that include data from different outdoor sites. This element follows directly from element 5. While some latitude may result from considering similarities in sites, enough data must be accumulated at sites with the climatic extremes and those in between to permit reasonable interpolation to any site for planned deployment of EERE devices.

SLP Element 7. Predictive service lifetime models are then developed from the data in 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 (22). 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. The Gaussian distribution, which is a special case of several types of distributions (7), can be used to illustrate this point. Initially, the Gaussian distribution is characterized by a full width at half maximum (FWHM) that is only limited by the uncertainty in measuring the initial performance parameter. As the sample set ages, the FWHM broadens because the performance of each individual device will degrade differently from others in the set (23). Thus, the distribution for aged samples will be the superposition of the distribution itself and that imposed by the uncertainty in measurement of the performance parameter(s). With the definition of "failure," the distribution of aged samples yields the time dependence of failures. Various types of models can be applied to describe the aged distribution (7, 22). For the best prediction results, large sample sets and ultrasensitive measurements of the performance parameter are required. Both these requirements increase the cost of making a SLP. The increased cost with increasing sample numbers is obvious. The performance parameter may require several measurements or developing 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.

SERVICE LIFETIME PREDICTION OF ENCAPSULATED PV CELLS AND MODULES

We illustrate the vision of being able to predict the service lifetime of an encapsulated PV module in Figure 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 Figure 2. The actual losses are shown for the Carissa Plains, CA, 5.2 MW system (24-26), which is the most extreme case of degradation reported. Because some of the modules were removed from the plant after 1991, the projection to seven years was made based on the efficiencies of the remaining modules. The losses in real systems are from *all* causes, and not just in the modules. Because it is not known how to project future output from a cell, module, or a system, several possible hypothetical

projections are illustrated by the dashed lines for over nine years. These include projections with a simplistic linear extrapolation, with a decreasing rate of loss (perhaps from self-passivating reactions), and with an increasing rate of loss (perhaps from autocatalytic reactions). If the performance could be accurately predicted, 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, e.g., initial, maintenance, and operating costs. The major issue the PV community needs to resolve is what (time-averaged) loss in performance, i.e., power output, is permitted until the time of failure (in years) is reached.
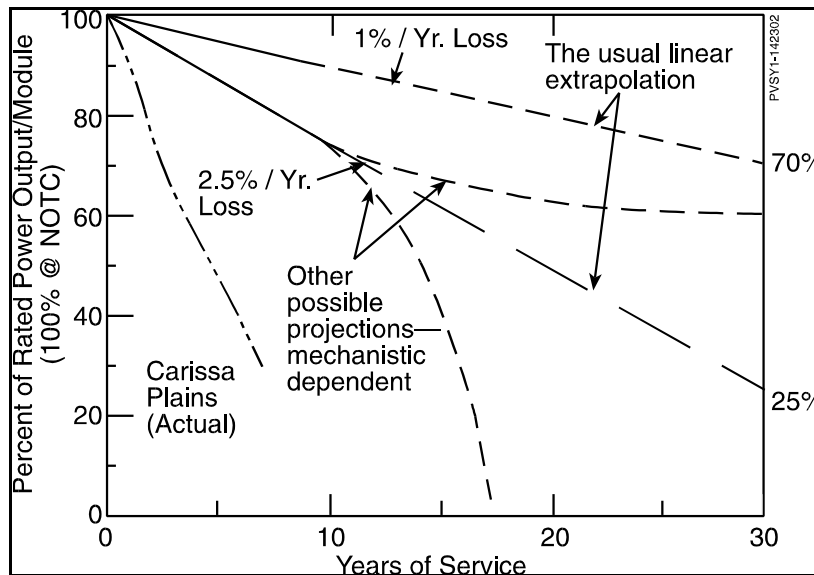

FIGURE 2. Actual and potential percentage losses in efficiency (performance) of PV *systems*.

   Realizing the vision of being able to predict the power output for a system is clearly possible, but two significant problems must be resolved. First, the technical reasons for the power losses must be determined. The losses plotted in Figure 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 are known to be in progress that will establish relationships between the accelerated degradation of individual modules and RTT. In the last two years, we have gradually been able to direct the focus of our task, "Improving the Stability/Durability of Encapsulated PV Cells and Minimodules," to combine ALT and RTT of *individual* PV cells. In our prior work, we have clearly demonstrated some of the losses result from EVA browning (1, 27). Secondly, resources need to be increased substantially for a proactive technical approach that will result in improving *current* and *next-generation* PV products, e.g., by (1) monitoring the RTT performance of appropriate statistically-significant sets of individual PV cells, minimodules, and modules, (b)

deducing causes of failure in *these* products and (c) by studying new/improved materials and designs at the cell and module 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 outlined (22). At present, RTT of *individual* module performance is being monitored at different sites for three cases (28-30), 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 (SLP Element 3); the RTT data needs to be taken at several environmentally diverse sites (SLP Element 5).

Past Focus: Improving/Replacing EVA

   In the last year, two key summary papers were published about EVA (1, 31). The first provides a critical review about using EVA as a pottant in encapsulated PV modules (1) and the second summarizes what can be done to retard the rate of discoloration (31). A summary of the qualitative reports of discoloration, quantitative reports of power losses in PV systems, EVA degradation mechanisms, the status of what we do and do not know about EVA discoloration, the inherent and process sources that result in accelerated discoloration, etc. are included (1). Critiques of why "lifetime projections" for EVA made in the 1980s are not valid and the reasons for the errors are also available (1,16). The most serious unrealistic projections made in the past can be avoided by determining and using actual activation energies from the Arrhenius equation or variants of it (7, 16) instead of the "rule of thumb" that reaction rates double for every 10 K increase, by considering the synergistic influences of UV, T, RH, etc. in laboratory test matrices (14-16), by simulating the reality of pottant confinement in ALT conditions (16), by operating the PV devices during ALT (16), and by using laboratory test samples that permit degradation products to accumulate when simulating hermetically sealed module designs (1,16). Our most recent progress for improving EVA or replacing it is given elsewhere in this volume by Pern (32) and Pern and Glick (33). As we have stated consistently since 1990, the stability of encapsulated PV modules is much more than a pottant degradation problem; our past and present work has addressed the EVA discoloration problem because it was identified as a major concern to the PV industry and is known to result in performance losses (27).

Future Studies Using Encapsulated PV Cells and Minimodules

   In earlier work, we established that the same type of EVA discoloration observed in field-degraded modules could be simulated in the laboratory by using *individually encapsulated PV cells* (27). The PV cell and module stability problem is not only

more than a pottant degradation problem, but is also complex as shown in Figure 3 (1, 9), which is a cross section of a contemporary multilayer PV cell. 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 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 ca. 500 MW of installed PV capacity is pc-Si or c-Si. An antireflection (AR) coating (typically, 50 nm of SiO_2) 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 Figure 3, degradation can occur by weathering and/or soiling of the cover glass; photothermal, oxidative, or other degradation of the pottant (1, 16, 31); interdiffusion of ions into the pottant; metalization corrosion; electric field-induced ion migration or degradation; and polymer/metal oxide interface reactions or delaminations. Many of these processes may depend on initial impurity concentrations and trapped gases (vapors), and concentration changes during use. We emphasize this complexity of the entire module here because we have to establish which other degradative reactions must be mitigated (besides pottant discoloration) and which ones are too slow to impact the performance adversely over 30 years.

For individual cells, we reported on post-mortem results from a retrofited cell from Carrisa Plains (34). We have carried out one detailed study on single cell minimodules (27) as a precursor to future studies in which we plan to correlate performance changes with encapsulant and other degradation in the cells. Although degradation processes in cells are complex (Figure 3), a number of complications from individual modules are eliminated, e.g., interconnect degradation, cell/module mismatch, and differences in degradation in each cell
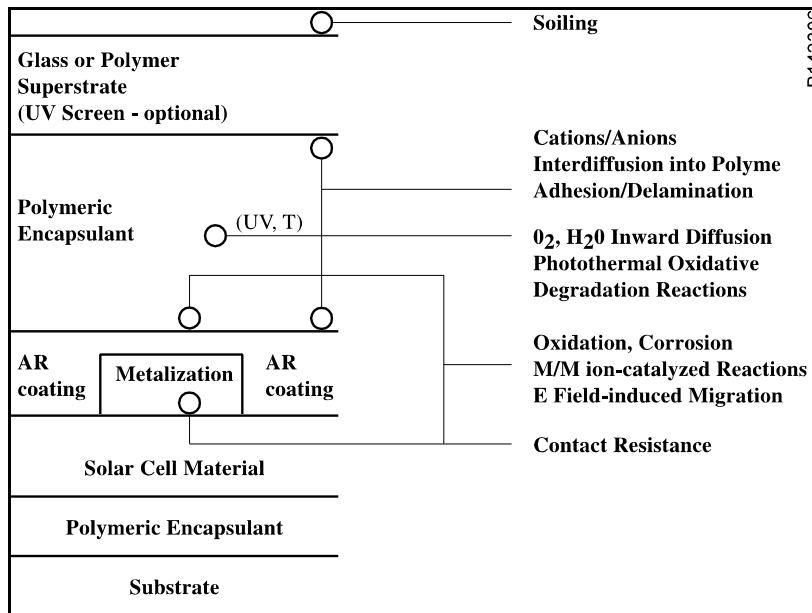
FIGURE 3. Schematic cross-section of an encapsulated PV cell and relevant reactions/processes that may reduce the cell performance and/or service lifetime (adapted from Refs. 1 and 9).

that are averaged for the entire module. Because of the presence of Cyasorb UV 531 in commercial EVA formulations, which absorbs UV light below 350 nm, and the 91% optical transmission of EVA that optically couples with the solar cells and soda-lime glass superstrate, a low percentage of the efficiency loss (ca.~1%-2%) that is measured for encapsulated modules results from the optical loss. Efficiency losses in c-Si and pc-Si solar cells resulting from direct contact with the EVA laminate have not been reported.

In a study comparing the effects of *accelerated,* simulated, thermal, and photothermal degradation on the EVA-encapsulated solar cells, Pern (27) measured losses of 13% in the short-circuit current (I_{sc}) and 19% in the efficiency that resulted directly from the reduction in light transmission through browned EVA, which was obtained by exposure to 85°C and UV from filtered RS-4 lamps for 198 days. Examples have been published showing the continuously decreasing spectral response (absolute quantum efficiency) as the EVA film discolored increasingly to a light yellow color in the solar cell heated in an 85°C oven for 198 days or to a brown color when exposed to an RS4 UV light source at 85°C for 198 days (1, 27). All solar cells showed little change in open-circuit voltage (V_{oc}) or fill factor (an important quantitative relationship for describing the performance of PV cells and modules), except for the noticeable decreases in I_{sc} caused by EVA discoloration. Electrically, except for one solar cell, no significant change in the series resistance was measured (by dark I-V) for the solar cells studied over the 198-d period (27).

For future work our protocol will be based on preparing encapsulated PV cells and minimodules as active devices consisting of the multilayer stack as required for the

seven elements of a SLP methodology. As a typical example of Element 1, the approach is illustrated in Figure 4 for c-Si or pc-Si cells or minimodules. The multilayer stacks will consist of a glass or polymer superstrate with or without a UV screen/pottant polymer/active PV device, e.g., c-Si with a base contact and AR coating/polymer/substrate. The active devices will be of the same construction as those in contemporary modules and be a minimum of 3 cm x 3 cm and a maximum of 10 cm x 10 cm with output leads suitable for obtaining I-V and efficiency measurements. During this element, we are developing an ALT protocol and being challenged to prepare replicate test specimens. The stresses (SLP Element 2) have been identified and will be quantified for our ALT chambers (WeatherOmeters[TM] and Oriel solar simulators). After characterization with sensitive and other measures of performance behavior, sets of "identical" test specimens (Element 3) will be subjected to accelerated testing in controlled T and RH chambers, and with (a) a Xe-arc light source of 1 or 2 suns or (b) a condensed Xe-arc light source (solar simulator) of 5 to 17 suns from 290 nm to 400 nm in which all the test variables simulate reality. We would also like to be able to subject specimens to UV accelerated testing in an outdoor environment in which the minimodule T will be maintained at normal operating temperatures, but natural sunlight will be concentrated at 10 times e.g., by using *modified* DSET EMMA[TM] or EMMAQUA[TM] test capabilities that presently concentrate natural sunlight by about 5 times. When sufficient stability is demonstrated for the multilayer stacks made in SLP Element 2 and the degradation mechanisms have been mitigated or are sufficiently slow, we would then (SLP Element 5) deploy minimodules at six or more sites in the United States with representative and carefully recorded natural environmental exposure conditions. For SLP Element 6, we can benefit from NREL's present activities in establishing and using sites for testing candidate solar mirror materials and constructions (12a, 12b, 22, 35) and methodologies developed by them (15). Specimens at these "real-time testing" sites would be periodically monitored for their efficiency and other measurements that correlate with the cell/minimodule performance. Degradation mechanisms will be deduced from specimen "failures" from accelerated lifetime testing (ALT) and real-time testing (RTT). When they are the same, models will be developed to relate the complexity or simplicity of the multiplying factor from ALT to those for RTT, and the service lifetime will be estimated based on the interpretation of all the data acquired (SLP Element 7).

In the last three years, we have added to our task the necessary capabilities at NREL for Elements 1 through 3 with a miniextruder for extruding sheets of our own candidate pottants, a laminator for simulating industrial practice, additional characterization capabilities (I-V, yellowness index, quantum efficiency, etc.) to complement our UV-vis, color indices, and fluorescence analysis equipment for sensitive measures of PV cell performance losses, two WeatherOmeters to complement our Oriel condensed Xe-arc light sources, and DSET Suntest CPS table top units for conducting accelerated testing.
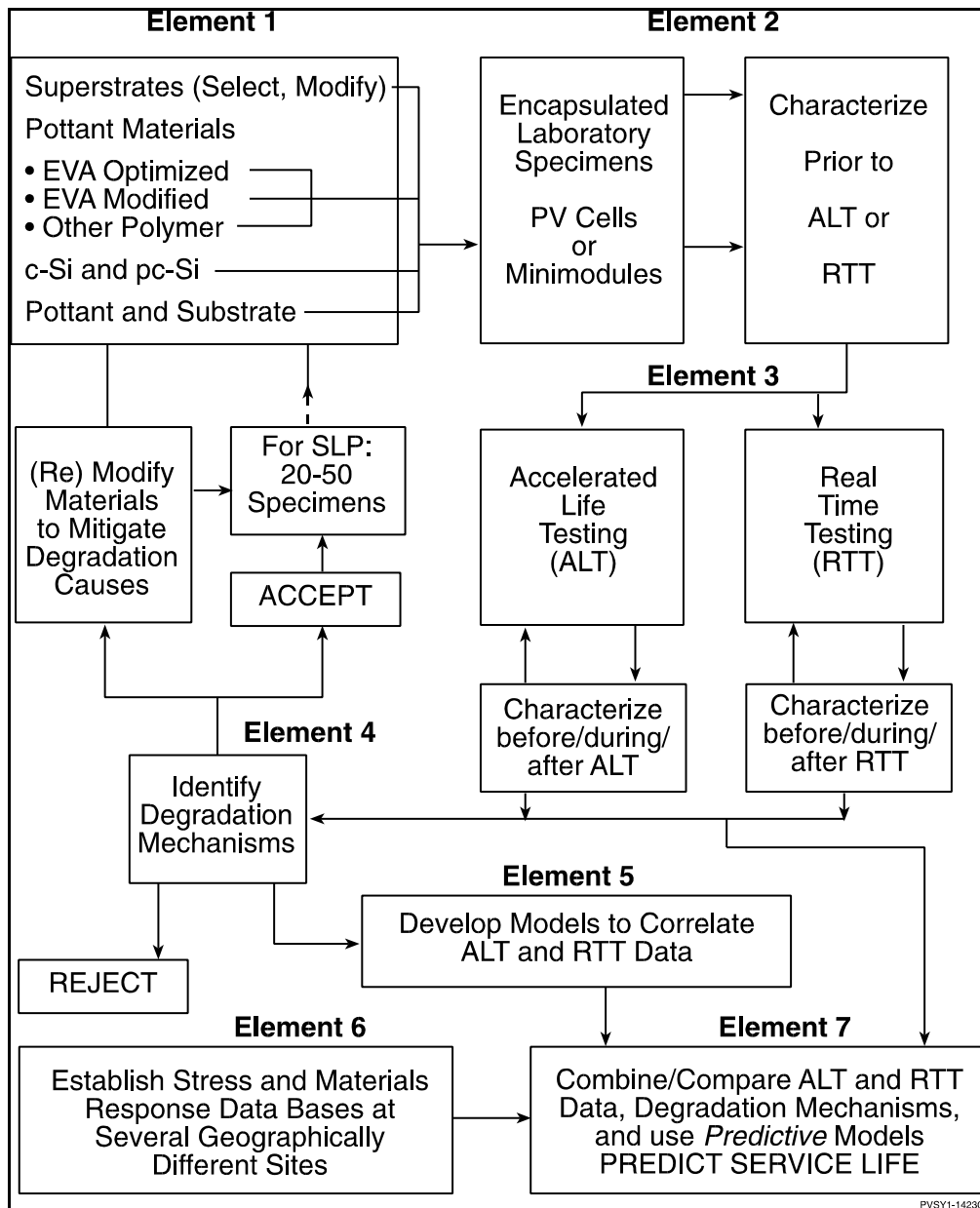
FIGURE 4. Technical approach for specifically applying SLP Elements 1 through 7 for PV cells and minimodules, but the scheme can be used for other PV components (e.g., modules) and EERE multilayered devices.

CONCLUSIONS

A methodology for predicting the service lifetime of multilayered EERE devices has been outlined and related specifically to PV cells and minimodules. The SLP methodology is not limited to PV and EERE devices but also can be applied to U.S. industrial needs. Developing the technology base for predicting 30-year PV module lifetimes requires a 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 utilizing the most appropriate experimental methods. Module service life prediction and material system concepts depend on correctly identified degradation mechanisms that reduce the performance or limit the service life of the module, and their appropriate applicability to reality. Long-term degradation mechanisms usually result from complex synergistic reactions between the environment and PV cell or module materials. The predominant degradative reactions may change during the module life, making analytical modeling extremely difficult. Degradation of polymeric materials can be catalyzed by their own reaction products, by solar cell metalization materials, or from ion transport into them that can eventually result in enhanced discoloration, cracking, moisture ingress, and failures in other module component materials. An increase of moisture in the encapsulant may facilitate electrochemical corrosion and progress to the point where dielectrical breakdown may occur between the cell circuit and the module ground. All of these and other degradative phenomena are critical to module durability. NREL now has the capabilities and equipment to proceed with SLP elements 1 through 4. NREL will make progress towards predicting service lifetime of PV cells and modules at a rate that depends on the resources available.

ACKNOWLEDGMENTS

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