**NISTIR 7971**

# Roadmap for Developing Measurement Science for Predicting the Service Life of Polymers Used in Photovoltaic (PV) Systems

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National Institute of Standards and Technology
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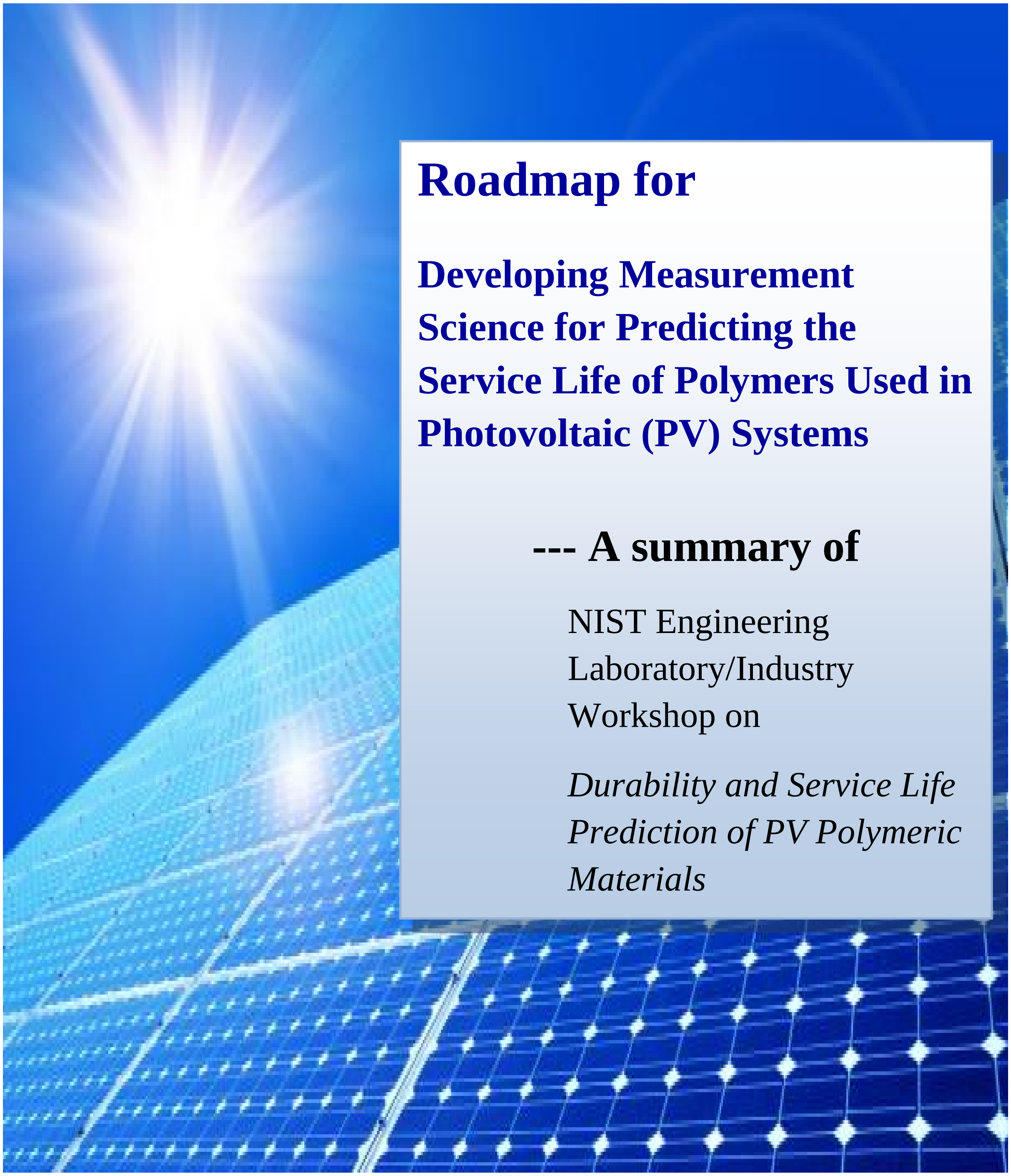

# Roadmap for

## Developing Measurement Science for Predicting the Service Life of Polymers Used in Photovoltaic (PV) Systems

**--- A summary of**

NIST Engineering Laboratory/Industry Workshop on

*Durability and Service Life Prediction of PV Polymeric Materials*

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# EXECUTIVE SUMMARY

The technology roadmap for developing measurement science for predicting the service life of polymers used in PV systems has been drafted in this report. This roadmap was developed from the NIST Engineering Laboratory/Industry Workshop on *Durability and Service Life Prediction of PV Polymeric Materials*, and the research proposal and Statement of Work (SOW) on *Service Life Prediction of Polymers in Photovoltaic Systems* for a NIST/industry consortium.. The workshop on *Durability and Service Life Prediction of PV Polymeric Materials* was held at NIST, Gaithersburg, Maryland during September 23-24, 2010, with two follow-up meetings held at NIST in March 2011 and October 2011. The objectives of this workshop were to solicit industry feedbacks in identifying critical measurements needed to assess performance and predict service lives of polymeric materials used in PV systems, and to determine the best mechanism for engaging with PV industry and aligning with previous and existing efforts in reliability and performance of PV systems. The critical measurement science needs in four areas were discussed in the workshop including 1) PV materials, 2) cells/modules, 3) reliability and testing, and 4) safety standards and codes, with emphasis on what critical measurement science needed to link accelerated tests with outdoor performance and to enable prediction of PV system service lives. The workshop inputs have been used to develop a Statement of Work for a proposed NIST/industry PV consortium. With a strong collaborative effort between NIST and PV industries, such a consortium has been recently formed. The industry partners include suppliers of polymeric components for PV systems, cell and module manufacturers, and PV users. This roadmap supports NIST Strategic Goal of *Sustainable and Energy-Efficient Manufacturing, Materials, and Infrastructure* through the program of *Net-Zero Energy, High-Performance Green Buildings.* It also can be used by both the public and private sectors to guide policy, Research and Development, and other decision making relevant to important areas in PV materials and module reliability.

# 1. INTRODUCTION

## A. Background and Broad Challenges for PV Technology

Solar energy is the most abundant renewable energy resource on the planet. The limitless supply of solar energy makes PV an ideal alternative for power generation. In the past few years, the global PV industry has shown exponential growth, and it is forecast that worldwide annual capacity will reach 200 GW in 2020, 300 GW in 2025[1]. Meanwhile, the costs and prices have been rapidly reduced.

However, a number of major challenges remain despite significant progresses have been made in the PV technology. The reports from *NIST Grand Challenges for Advanced Photovoltaic Technologies and Measurements Workshop*[2] identified six broad challenges in PV technology and measurement.

(1) Materials to device analysis.

(2) Inline manufacturing tests.

(3) Module characterization.

(4) Solar resource.

(5) Reliability studies and accelerated lifetime tests.

(6) Regulation and permitting.

Among these challenges, reliability concerns of the PV products ultimately influences customer confidence in this technology; hence, we will specifically address this issue and develop the strategic plans towards how to establish the reliability-based accelerated lifetime tests.

[1] US Department of Energy, 2008 Solar Technologies Market Report, January, 2010.

[2] Reports of NIST Workshop: Grand Challenges for Advanced Photovoltaic Technologies and Measurements, May 11–12, 2010, Denver, Colorado. (http://events.energetics.com/NISTGrandChallenges2010/downloads.html)

## B. The Need for Reliability Studies and Accelerated Lifetime Tests

The success of PV technologies depends in large part on a clear demonstration of the long-term reliability of PV modules and systems. Reliability studies and development of effective accelerated lifetime tests are crucial to this goal, ensuring consumer confidence and product lifetime guarantees. Today's performance warranty is typically 80 % of rated power after 25 to 30 years. However, most current PV products only have a few years or less of field history. The development of new materials and the efforts to lower the costs such as changes in processing, materials, or structures of PV modules, will result in more products with unknown field histories. Since outdoor tests take too long (i.e., > 25 years), accelerated laboratory tests must be developed and utilized to qualify the new products. Nevertheless, developing a reliability-based accelerated laboratory tests that are capable of evaluating PV module lifetime performance is not a simple task.

Currently, some qualification and safety tests are used by manufacturers as a means for assessing the product quality, safety and reliability. These commonly used qualification and safety tests are listed below.

- IEC 61215, "Crystalline silicon terrestrial photovoltaic (PV) modules-Design qualification and type approval"
- IEC 61646, "Thin-film terrestrial photovoltaic (PV) modules-Design qualification and type approval"
- IEC 62108, "CPV terrestrial photovoltaic (PV) modules-Design qualification and type approval"
- IEC 61730, "Photovoltaic (PV) module safety qualification" (for all modules)
- UL 61730, "Standard for Flat-Plate Photovoltaic Modules and Panels"

Among those tests, the IEC61215, IEC61646 and IEC62108 are designed for performance evaluation of PV modules. Figure 1 shows the flow charts of IEC 61215 tests for crystalline silicon PV modules. As seen, the environmental stresses of UV preconditioning, thermal cycling, humidity freeze or damp heat (85 °C, 85 % Relative Humidity (RH)) are sequential applied to PV modules during these tests. The visual, mechanical, and electrical properties of the products are assessed to determine if they pass or fail the criteria.  The test procedures for thin-film PV and concentrated PV in IEC 61646 and IEC 62108, respectively, are similar to those shown for IEC61215. The safety tests of IEC 61730 describe the fundamental construction requirements for PV modules to provide safe electrical and mechanical operation during their expected lifetime.

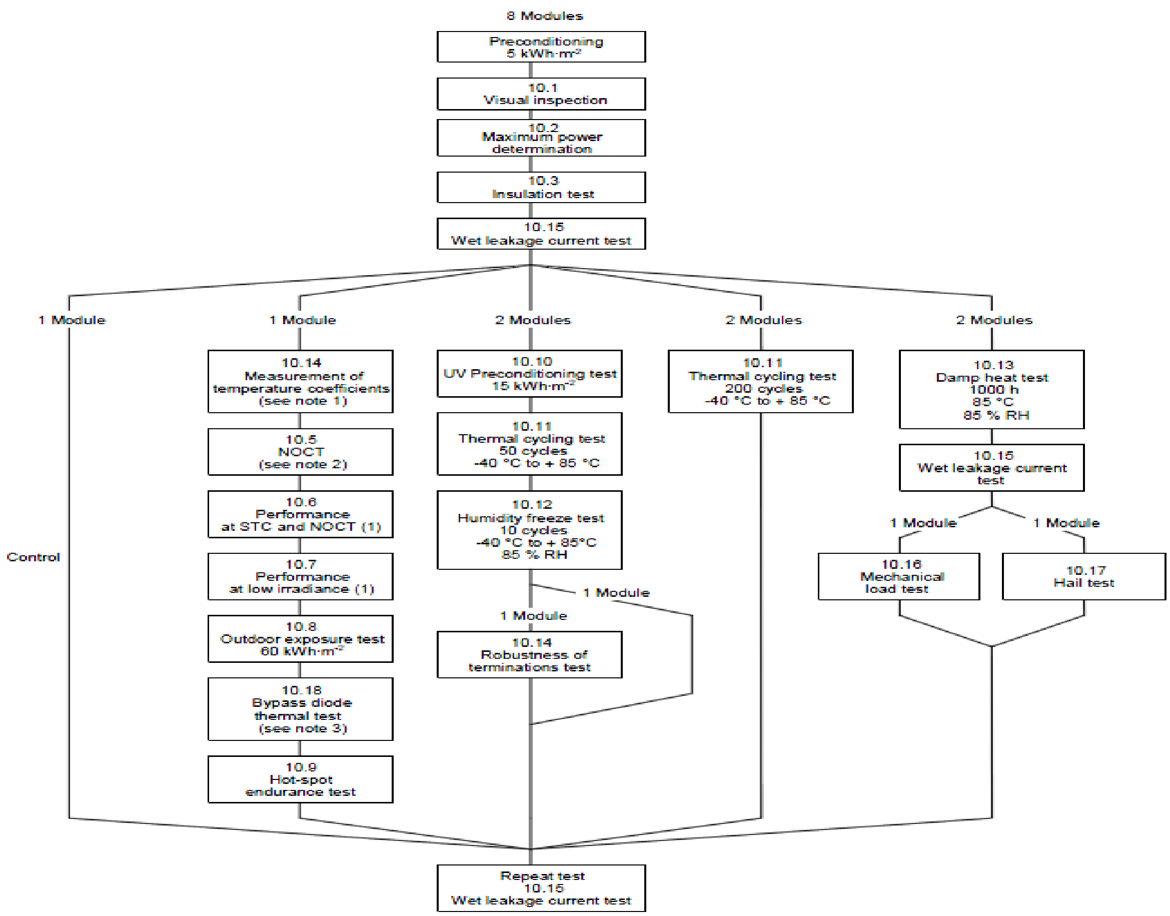


Figure 1. The flow charts of IEC 61215 environmental tests.

Note that these qualification and safety tests are for short-term "infant mortality"; *they do not and cannot predict lifetime data. Therefore, they are not the reliability tests.* Their deficiencies can be reflected in the following aspects: (1) the qualification tests are based on known field failure mechanisms; they may not identify the failure mechanisms that occur with new technologies for which field data does not exist[3], (2) the qualification tests are sequential single-

[3] J.H. Wohlgemuth, "Reliability of PV System", Proc. of SPIE Vol.7048 704802 (2008)

stress tests, such as UV preconditioning, or thermal-cycling without UV irradiation; they cannot identify the failure mechanisms that are caused by simultaneous multiple stresses, especially when synergistic effects between different stresses exist, (3) the duration time or/and the dose used in these tests lacks a scientific foundation, they may not identify the failure mechanism that appears after long term outdoor exposure. Therefore, even after passing the above tests, the failures ~~still~~ can still be observed from these products during their expected service lifetime.

Table 1. Common Failure Modes for Crystalline Silicon Modules

| |
|---|
| Broken Interconnects, Broken Cells, Broken Glass |
| Corrosion |
| Interlayer Delamination and/or Loss of Elastic Properties (Creep) |
| Encapsulant Discoloration |
| Solder Bond Failure |
| Hot Spot |
| Arcing |
| Ground Faults |
| Junction Box and Module Connection Failures |
| Structure Failures |
| Bypass Diode Failures |

Wohlgemuth and Kurtz[4] from NREL have summarized the major field failure modes for crystalline silicon PV modules, thin film PV modules and concentration PV modules. As an example, the common failure modes for crystalline silicon modules are listed in Tables 1. Among these modes, some failures are probably related to installations, such as broken interconnects or broken glass. However, many failures could be related to material properties, especially for polymeric components including encapsulants, frontsheets, backsheets, edge seals and junction boxes which are susceptible to environmental and mechanical attacks. Figure 2 provides some representative pictures of the failures resulted from degradation of polymeric materials. These failures include discoloration of the encapsulant or the backsheet, delamination between backsheet and encapsulant, junction box detachment, connector brittleness, etc.

[4] J.H. Wohlgemuth and S. Kurt, "Reliability Testing Beyond Qualification as a Key Component in Photovoltaic's Progress Toward Grid Parity", Proc. IEEE International Reliability Physics Symposium (2011)

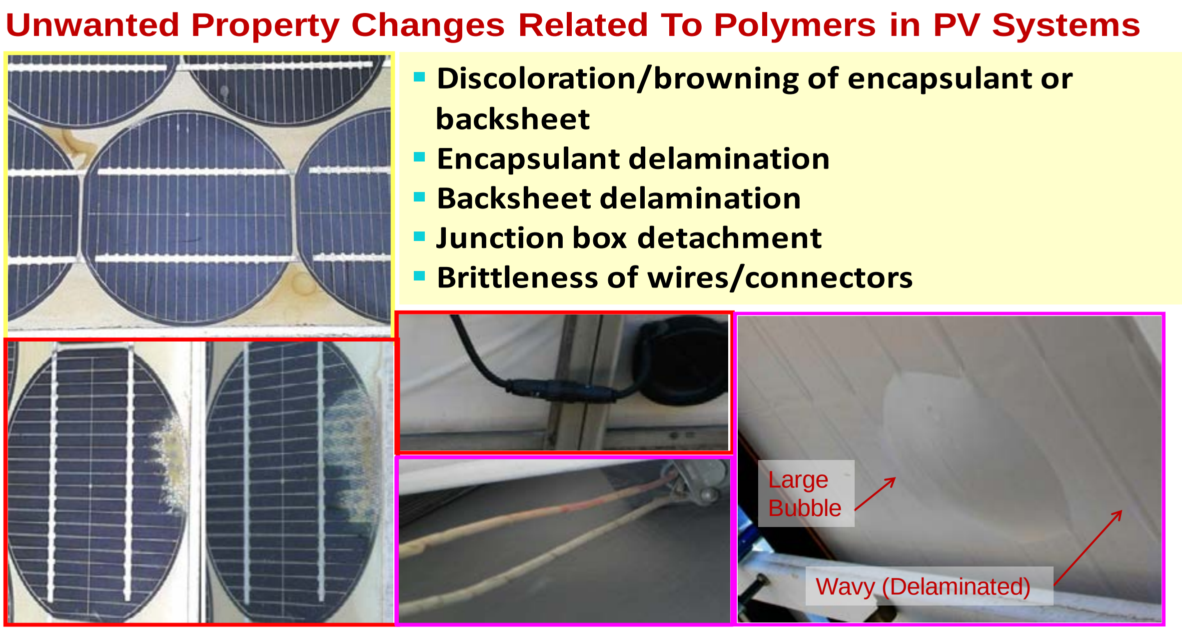


Figure 2. Examples of common failure modes for PV modules related to polymeric materials.

Unfortunately, current standardized test methods used for qualifying PV polymers are only useful for detecting premature failures or comparing the performance of one against another, and not for predicting service life or ensuring long-term reliability of products. *No validated accelerated aging test currently exists to enable prediction of PV performance and reliability for 30+ years.*

## C. Workshop Scope and the Process

In response to the need to ensure that measurement science keeps pace with the needed technology innovations, the Polymeric Materials Group at Engineering Laboratory, NIST collaborated with Underwriter Laboratory to sponsor and host the *NIST/Industry Workshop on Polymers in PV Applications* on September 23-24 at NIST, Gaithersburg, Maryland. Experts from industry, government, national laboratories, and academia (Appendix A) attended this workshop. The scope and the objectives of the workshop were to

- Solicit industry feedback in identifying critical measurements needed to assess performance and predict service lives of polymeric materials used in PV systems, and how to best develop measurement science to ensure long-term reliability and safety of these components.

- Determine the best mechanism for engaging with PV industry and for aligning with previous and existing efforts on the reliability and performance of PV systems.


Figure 3. NIST/Industry PV Workshop Announcement

The workshop was comprised of technical presentations and breakout brainstorming sessions. Presentations included "Market Overview", "Technical Challenges and Measurement Needs of PV technology", and "Methodology for Service Life Prediction of PV materials" (Appendix B). In the breakout session, the participants were divided into four groups, discussing about what were the critical measurement science needs in the areas of 1) PV Materials, 2) Cells/modules, 3) Reliability and testing, and 4) Safety standards and codes, and what was critical measurement science needed to link accelerated tests with outdoor performance and enable prediction of PV system service lives. Each group was rotated through each breakout session. To establish measurement science priorities, participants were given five votes and asked to assign these votes to the measurement barriers they considered to be most critical in terms of ensuring long-term reliability and safety of the PV modules.  The results of the votes are summarized in the next chapter.

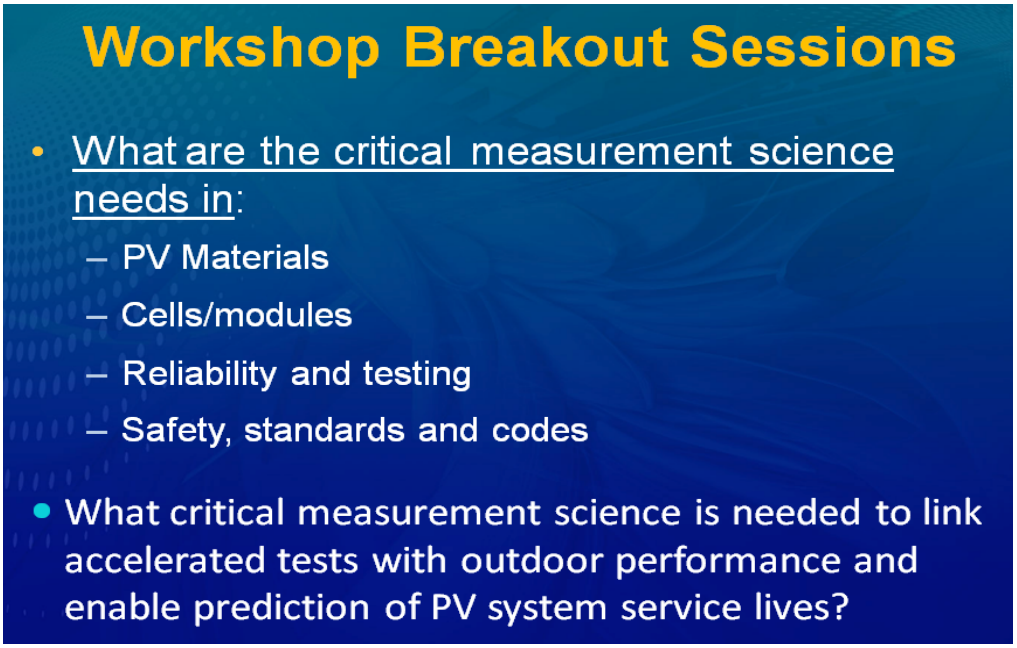


Figure 4. NIST/Industry PV Workshop Breakout Sessions

There were two follow-up meetings held at NIST in March 2011 and October 2011 after this workshop. The purposes of these meetings were (1) to identify  the most critical measurement needs generated from breakout sessions, (2) to determine whether  a NIST/industry consortium on service life prediction of polymers for photovoltaic systems is need, (3) to convene interested parties to develop draft statements of work for inclusion in a Cooperative Research and Development Agreement (CRADA) statement.

The remainder of this report summarizes the outcome of the above workshop and meetings, and presents a roadmap for measurement science needed to predict service lives of PV polymeric materials, components, and modules.  A Statement of Work (SOW) for a NIST/industry consortium on *Service Life Prediction of Polymers in Photovoltaic Systems* that was developed from the results of the workshop and follow-up meetings is also given in the report. The industry partners in this consortium include suppliers of polymeric components for PV systems, cell and module manufacturers, and users. This report will guide NIST projects on developing measurement science for predicting the service life of polymers used in PV systems, and also will be used by both the public and private sectors to guide policy, R&D, and other decision making relevant to the important area of reliability of PV modules.

## 2. WORKSHOP BREAK-OUT SESSION SUMMARY

The raw data from the break-out session votes are listed in Table 2 by the topic areas of 1) PV Materials, 2) Cells/modules, 3) Reliability and testing, and 4) Safety standards and codes. An additional summary is made by integrating the same type of measurement science needs from the top choices in different topic areas. By this way, the most critical measurement needs to assess performance and to ensure long-term reliability and safety of the materials, modules and systems are identified and shown in Tables 3 and 4.

Table 2. Raw data from the break-out session votes by the topic areas (● = one vote)

**PV Workshop Breakout Sessions – Raw Data**

## 1. PV Materials

1.1. Include electric field as added stress factor and determine appropriate voltage

1.2. Establish common form factor for test method and end-use application

1.3. Develop rapid test for cured encapsulant (i.e. OEM test method for cross-linked density, residual volatility, etc).

1.4. Develop test method for adhesion of interfaces with need to develop appropriate stress in addition or replacement of damp heat.

1.5. Correlation of SPHERE test method and conditions to standard weathering equipment used by industry.

1.6. Comparison of cyclic vs. constant aging test protocols.

1.7. Establish test regimes for polymer classes based on physical (material) properties such as fundamental understanding of polymer hydrolysis.

1.8. Measure ingress of $O_2$, $H_2O$, etc. in a fielded module from multiple representative climates; measure permeation/diffusion rate of $O_2$, $H_2O$, etc.

1.9. Study failure modes connected to fundamental material properties.

1.10. Develop standard test measurements for optical properties such as color, transmission, gloss, etc. (normalized to thickness).

1.11. Maintain and provide representative formulation of standard EVA used for theoretical basis to develop test methods.

1.12. QC control for EVA to determine level of "precure."

1.13. Provide example study involving corrosion measurement of mirror coatings to understand degradation mechanism.

1.14. Develop standard reference measurement for basic component materials to establish benchmark interlab test results.

1.15. Provide test method for interfacial adhesion of polymer/polymer, polymer/metal, polymer/glass that relates to lifetime of component, not just a release spec.

1.16. Collect information (via database) for environmental pollution (acid rain) test method or other regional (climate) specific tests.

Table 2. Raw data from the break-out session votes by the topic areas (continued)

1.17 Provide a mechanistic study of fundamental understanding of polymer degradation for common/benchmark materials (standard reference materials).

1.18. Provide forum to develop test methods and standard development or fundamental scientific understanding.

1.19. Provide guidance for material test results translated to module or system performance/safety.

1.20. Develop "early warning" analytical test for materials

1.21. Establish standard form factor for testing.

1.22. Establish common database to determine validity of accelerated aging for different materials.

1.23. Determine/identify material requirements for different or specific end-use applications.

1.24. In-line method to measure quality of lamination or curing process.

1.25. Develop standard test method for specific failure mode – qualification test indicative of actual lifetime.

1.26. Develop (predictive) adhesion test method or specific (common) delamination interfaces corresponding to observed failures based on appropriate loads.

1.27. Fundamental adhesion measurement science for multilayer films and coatings – i.e. interconnection failure points between polymer and wire.

1.28. Determine compatibility of materials under specific loads and accelerated aging.

1.29. Investigate heterogeneous failure modes

1.30. Develop standard tests (such as UV) method for high performance materials – maxium performance (with appropriate safety factor) not minimum requirements.

## 2. Cells and Modules

2.1. Supply chain accountability (cell and module)

2.2. Chemical degradation measure at low concentrations – interfacial surface concentration

2.3. UV resistance of polymers used to protect cells

Table 2. Raw data from the break-out session votes by the topic areas (continued)

2.4. Early detection of early failures – arcing, chemical measurement relating to early degradation. ●●●●●●●●●●●●

2.5. End of life tests for polymers

2.6. Bonding and Adhesion ●

2.7. Balance of system effects on modules? (i.e. high voltage ac component transmitted to modules through inverter?)

2.8. Solder bonds, bypass diodes, cell breakage (measurement by electro-luminiscence), j-box adhesion.

2.9. Lifetime variability – what happens to materials after 20 years in the field? ●●●

2.10. Non-destructive field tests to determine polymer degradation – electroluminescence field kit. ●●

2.11. Effect of module fire rating – in specific applications●

2.12. In-line dielectric tests during manufacture

2.13. FTIR analysis for item 2.2, above.

2.14. Non-destructive interfacial tests during manufacturing, plus field ●●

2.15. Corrosion testing – at cell level

2.16. Module level failure analysis to uncover weak links – FMEA and relationship to polymeric materials. ●

2.17. Look at back contact material failures and relation to polymers and conductive adhesives.

2.18. Soiling – testing thereof; accelerated laboratory tests. ●●

## 3. Testing and Reliability

**Qualification Testing**

3.1. Add UV exposure as a environmental stressor ●●●●

3.2. Standardize between multiple versions of different qualification tests ●

3.3. Make changes to partial discharge test – results show a high degree of scatter

3.4. Inexpensive, accelerated tests that correlate to field performance; scientific basis for selection of conditions would inspire more confidence. ●●●●●●●●

3.5. Some qualification test conditions should be revisited, e.g. 85/85 damp heat test. ●●●●●●●

Table 2. Raw data from the break-out session votes by the topic areas (continued)

3.6. In-situ, non-destructive, analytical (chemical and physical) tests of in-service modules. ●●

3.7. Tests for interfaces/adhesion (particularly interfacial corrosion), involving temperature/moisture cycling.

3.8. Qualification tests for materials and components, rather than just modules. ●

3.9. Simple/rapid/inexpensive test involving multiple stressors and multiple evaluation tests, in one package. ●●●●●●●●●●●●●●●

3.10 Improved power output testing

**<u>Service Life Prediction</u>**

3.11. Tests that correlate to fundamental mechanisms of degradation. ●●

3.12. Tests that identify/isolate failure modes

3.13. NIST standard reference cell or component

## 4. Safety, Standards and Codes

**<u>PV Materials/Polymers (Properties)</u>**

4.1. Maximum temperature (RTI) ●●●●●●●●

4.2. Flammability

4.3. Optical transmission ●

4.4. Dielectric properties ●●

4.5. CTI (question validity)

4.6. Degradation conditions (radiation, temp, RH)

4.7. Define degradation reaction pathways ●●●●●●●●

4.8. Classification of materials

4.9. Dynamic mechanical analysis

Table 2. Raw data from the break-out session votes by the topic areas (continued)

**PV Components (properties)**

4.10. Maximum temperature

4.11. Flammability

4.12. Interfacial adhesion (between components) ● ●

4.13. Electrical performance

4.14. Degradation (radiation, temp, RH, DC voltage)● ●

4.15. Consider composite mock-up (powered, non-powered) for qualification tests ● ● ● ● ● ● ●

4.16. Consider risk assessment of mock-up approach ●

4.17 Define combinations of materials and need for additional testing (define guidance)

**PV Modules (performance)**

4.18. Fault tree analysis (FTA/FMEA) of system ● ● ●

4.19. Electrical insulation

4.20. Electrical performance

4.21. Flammability (UL SolarABC study) ● ● ● ●

4.22. Evaluate relationship of dimensions on fire performance

4.23. Assessment of First Responder requirements

4.24. Define exposure conditions (radiation, temp, RH)

4.25 Classification end-use applications (thermal ratings) ●

4.26. Correlation of material properties to performance is not well understood ● ● ●

Based on these raw data, we ranked the topics with the most votes among all break-out sessions; the top ten most voted needs are listed below with the identification of measurement category.

1. Provide simple/rapid/inexpensive test involving multiple stressors and multiple evaluation tests, in one package. (3-9, **15 votes**) ---*Accelerated test*
2. Provide a mechanistic study of fundamental understanding of polymer degradation for common/benchmark materials (standard reference materials). (1-27, **12 votes** ) ---*Mechanism/fundamental study*
3. Early detection of early failures – arcing, chemical measurement relating to early degradation.( 2-4, **12 votes** ) ---*Early detection*
4. Provide inexpensive, accelerated tests that correlate to field performance; scientific basis for selection of conditions would inspire more confidence. (3-4, **8 votes** ) ---*Accelerated test*
5. Define degradation reaction pathways (4-7, **8 votes**)
6. Maximum temperature (RTI) (4-1, **8 votes**)
7. Develop test method for adhesion of interfaces with need to develop appropriate stress in addition or replacement of damp heat. (1-5, **7 votes**)---*Adhesion/interface*
8. Develop (predictive) adhesion test method or specific (common) delamination interfaces corresponding to observed failures based on appropriate loads.(1-26, **7 votes**) ---*Adhesion/interface*
9. Some qualification test conditions should be revisited, e.g., 85/85 damp heat test. (3-5, **7 votes**) ---*Accelerated test*
10. Consider composite mock-up (powered, non-powered) for qualification tests (4-15, **7 votes**) ---*Accelerated test*

As shown above, some topics have the same measurement needs, for example, *"Provide simple/rapid/inexpensive test involving multiple stressors and multiple evaluation tests, in one package*" and *"Provide inexpensive, accelerated tests that correlate to field performance; scientific basis for selection of conditions would inspire more confidence";* both address the same measurement science needs as development of accelerated test. By combining the needs under the same category, the overall summary of the topics with greatest interest for service life prediction, long-term reliability and safety of the materials and modules are identified and displayed in Tables 3. Based on this result, a Statement of Work (SOW) for a consortium on *Service Life Prediction of Polymers in Photovoltaic Systems* has developed. The R&D roadmap for developing measurement science for predicting the service life of polymer materials used in PV systems is also proposed. These will be presented in the following chapters.

**Greatest Interest from Break-out Session**

- Fundamental study of PV polymer degradation and mechanistic pathways in regards to UV, temperature, and moisture; development of knowledge base for use in detection of early failures.
- Scientifically-based material/module qualification test involving multiple stressors (temperature, moisture, UV) and multiple property tests.
- Test method to assess long-term adhesion of PV module components.
- Module Safety – maximum temperature, flammability

Table 3. Areas of greatest interest from break-out sessions for fervice life prediction and long-term reliability of PV materials and modules

# 3. STATEMENT OF WORK (SOW) FOR A NIST/INDUSTRY CONSORTIUM ON SERVICE LIFE PREDICTION OF POLYMERS IN PHOTOVOLTAIC SYSTEMS

The results of the above NIST Engineering Laboratory/industry workshops on durability of PV polymeric materials have been used to identify key technical issues in the performance of polymeric materials in PV modules, and guided the development of a Statement of Work for a NIST/industry consortium on Service Life Prediction of Polymers in Photovoltaic Systems. CRADA packages incorporating this SOW have been signed by six industrial partners. These industry partners include suppliers of polymeric components for PV systems, cell and module manufacturers, and users. With a strong collaboration between NIST and industrial partners, a NIST/industry consortium on Service Life Prediction of PV Materials has been formally formed. As shown in this chapter, the SOW addresses the most important issues resulted from the workshop, presents a scientific-based technical plan including characterization, exposure and modeling, and creates a model to produce, implement and transfer measurement science to industrial stakeholders for developing reliability-based accelerated laboratory tests for predicting service life of polymers in PV systems.

# STATEMENT OF WORK

## Title: Development and Validation of Reliability-based Accelerated Laboratory Tests for Predicting the Service Life of Polymers in Photovoltaic Systems

**Objectives:** (1) Develop accelerated laboratory tests for predicting the service life of photovoltaic (PV) polymeric materials, components, and mini-modules using the NIST **S**imulated **P**hotodegradation via **H**igh **E**nergy **R**adiant **E**xposure (SPHERE); (2) Develop measurement science tools capable of discerning degradation mechanism(s) and failure mode(s) of PV polymeric materials, components, and mini-modules exposed to multiple simultaneous environmental stresses including UV radiation, temperature, and moisture; (3) Develop mathematical models for linking field and laboratory exposure results for PV polymeric materials and components using a reliability-based methodology.

## Opportunities:

The success of PV technology will ultimately depend on a clear demonstration of the long-term reliability of PV products[5]. Common photovoltaic performance warranties guarantee 80% of initial rated power for 25 to 30 years, but many PV products, including existing and newly developed module designs have limited field exposure histories. Reliability studies and accelerated lifetime testing are critically needed, and are also considered as one of the grand challenges facing the acceptance and implementation of advanced PV technologies[6]. Existing test standards such as IEC 61215 and IEC 61646 are qualification tests which may be useful in screening for early failures, but are neither designed to predict service life nor ensure long-term reliability. This lack of effective accelerated laboratory tests for lifetime prediction of PV

[5] S. Kurtz, "*Reliability Challenges for Solar Energy*", ATCAE Solar, 2009

[6] Reports of *NIST Workshop: Grand Challenges for Advanced Photovoltaic Technologies and Measurements*, May 11–12, 2010, Denver, Colorado. http://events.energetics.com/NISTGrandChallenges2010/downloads.html

materials, components, and modules significantly hinders innovation, development, assurance, and acceptance of PV technology.

## Technical Approach:

Reliability-based accelerated laboratory tests will be developed on the basis of common failure modes observed in field-exposed PV modules. Degradation mechanisms and failure modes observed in the accelerated laboratory tests will be compared to those observed in field exposure. The NIST SPHERE will be used for accelerated aging tests. The exposure environments of the SPHERE offer high repeatability and reproducibility and, hence, provide effective and efficient screening tests for durability of PV materials, components, and mini-modules. The SPHERE additionally provides a fundamental understanding of degradation mechanisms and failure modes of these systems under multiple, simultaneously-applied stressors, including different levels of UV irradiance, temperature, and moisture. Its optional capabilities include mechanical loading, electrical bias, and thermal cycling. In this work, metrologies for accelerated testing and degradation characterization will first be developed for PV polymeric materials recommended by the Consortium members. This data will form the basis for gaining a better understanding of the degradation mechanisms and failure modes at the PV system level, specifically, the degradation of individual PV components and mini-modules. All data generated during this exposure will be catalogued in a database and made available to individual consortium members. Both existing and emerging module designs will be considered, including thin film modules, flexible modules, and crystalline silicon-based modules with different encapsulant designs.

Non-destructive techniques, such as Raman spectroscopic imaging and fluorescence spectroscopy, will be developed for characterizing the degradation of polymeric materials and components while being utilized in PV mini-modules. The interfacial interactions and adhesion between different PV materials will be investigated for the multi-component laminates during accelerated laboratory exposure. Novel adhesion testing methods, such as the shaft-loaded blister test, will be developed for multi-component laminated coupons. Degradation mechanisms and failure modes observed in accelerated laboratory conditions will be compared to field data from modules containing similar PV materials and components. If the degradation mechanisms and failure modes are the same, linkages between laboratory and field exposure results will be made for these materials via reliability-based predictive models.

To develop reliability-based accelerated laboratory tests for PV polymeric materials, components, and mini-modules, three major tasks will be undertaken:

- ***Task 1: Characterize degradation mechanism and failure mode of PV polymeric materials and components exposed in well-controlled accelerated laboratory tests under multiple stressors, including UV, temperature, and moisture, singly and in combination.***

  PV material(s) or component(s) with extensive field history (recommended by Consortium members) will be selected as model polymeric system(s) for accelerated testing on the SPHERE. The model material(s) will be chosen from a variety of encapsulants, frontsheets, backsheets, or sealant materials, in either crystalline silicon based modules or thin film modules, or from lens materials in concentrator modules.

Figure 5. The NIST SPHERE.

The NIST SPHERE will be used for accelerated laboratory testing of the model PV material(s) or component(s). The SPHERE is an integrating sphere-based weathering device, providing uniform and intense source of collimated UV radiation on all sample locations. It is equipped with 32 exposure chambers, in which panel temperature, exposure relative humidity (RH), spectral UV intensities, and spectral UV wavelength can be independently and accurately controlled. It also offers the capability of mechanical loading and electrical bias. A factorial experiment will be designed to assess the effects of key environmental factors on the main degradation mechanisms of the model material(s) or component(s) during exposure to multiple stresses, including different levels of temperature, relative humidity, spectral UV intensity and wavelength, with optional mechanical loading and electrical bias if desired.

Figure 6. Photos of FTIR spectrometer, Confocal microscope and atomic force microscope (from left to right) at NIST Engineering Laboratory to be used for PV polymeric materials studies.

The degradation mechanism of the model system at different accelerated conditions will be investigated. Chemical, optical, mechanical, morphological and electrical properties of the model PV material(s) or component(s) will be characterized at multiple length scales during accelerated laboratory exposures on the SPHERE. Chemical degradation of the model material will be characterized using FTIR, in transmission, reflectance or photo-acoustic modes. Raman spectroscopy, which is sensitive to conjugated molecular structures, will be used to complement FTIR for characterization chemical changes. The optical properties of the material will be followed by UV-visible spectroscopy as function of exposure. Bulk mechanical properties will be measured by dynamic thermal mechanical analysis or quasi-static testing.  Surface morphology, including roughness, pitting and cracking, will be examined at multiple scales using high resolution microscopic techniques such as laser scanning confocal microscopy, atomic force microscopy, and/or scanning electron microscopy.  Changes in surface mechanical properties during exposure can be measured by nanoindentation. Electrical and fire hazard measurements will be performed (provided by UL). Degradation will be followed as a function of exposure time and UV dose, and degradation rates can be estimated in an accurate, precise and timely manner.

The laboratory degradation results obtained under different exposure conditions will be compared to those observed in the field. In the event that the same degradation mechanism is observed, the acceleration factor of the laboratory exposure with respect to the outdoor environment will be estimated. If the degradation mechanism observed in the laboratory exposure has never been observed during the field exposure, the parameters for the accelerated tests will then be reconsidered.

- ***Task 2: Derive and validate mathematical models for linking laboratory and field exposure results and predicting service life of PV materials and components.***

  The prediction of service life of PV materials and components will be based on the mathematical modeling of the accelerated test results and field data. In order to correlate accelerated SPHERE results to field performance, we will first determine if the degradation mechanisms of the studied material exposed in the laboratory accelerated test and field are the same. Correlations between the laboratory and field exposure will be assessed only for systems that exhibit the same degradation mechanism in the laboratory and field. Next, we will apply the NIST service life prediction methodology[7,8] based on reliability theory and cumulative damage concepts, to link the relevant PV material property data from the SPHERE exposure to the same data collected in the field. In our previous coatings consortium, similar models have been successfully used to link the laboratory and outdoor exposures for a neat polymer coating, and correlations between time-to-failure in accelerated testing and time-to-failure in field were established.

- ***Task 3: Define, design, and expose model mini-module(s) for use in developing accelerated laboratory testing metrology for PV modules.***

  To extend the methodology developed in Task 2 for linking laboratory exposure results to field performance of a model PV material, model mini-module(s) that are similar in construction to modules with known field history will be defined and designed (with the

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[7] Gu, et al., *"Linking Accelerated Laboratory Test with Outdoor Performance for a Model Epoxy Coating System"* in Service Life Prediction for Polymeric Materials: Global Perspectives, Eds: J. Martin, R. Ryntz, J. Chin, R. Dickie, Springer Press, 2009.

[8] Meeker, et al., *"A Statistical Model for Linking Field and Laboratory Exposure Results for a Model Coating,"* Proceedings of 4th International Symposium on Service Life Prediction: Global Perspectives, Key Largo, Florida (2008).

help of Consortium partners) for use in accelerated SPHERE testing. A number of commercialized module designs will be considered, such as incumbent crystalline silicon-based modules, emerging thin-film modules, and PV modules with newly introduced encapsulants, frontsheets, or backsheets. To understand the interactions of different materials in the mini-modules during weathering, multi-component laminates based on proposed mini-module designs will be fabricated as well. Expansion of the NIST SPHERE capability will be carried out to enable the accelerated laboratory testing of mini-modules under different levels of UV irradiance, temperature, RH, and possibly with thermal cycling or electrical bias. The SPHERE exposure, measurement of relevant properties, and characterization of degradation mechanism(s) and failure mode(s) will be performed for multi-component laminates and mini-module(s). Non-destructive techniques, such as Raman spectroscopic imaging or fluorescence spectroscopy, for characterization of polymer degradation in mini-module(s) will be developed. Novel adhesion testing methods, such as the shaft-loaded blister test, will be developed to identify the location of the weakest interfacial adhesion in multilayer systems. The failure mode(s) of the mini-module(s) observed under different accelerated conditions will be examined, and compared to those observed in the field-exposed modules. If similar degradation mechanisms are observed between mini-module laboratory exposures and field exposures, recommendations for mini-module test protocols and standards will be developed in a future phase of the consortium.

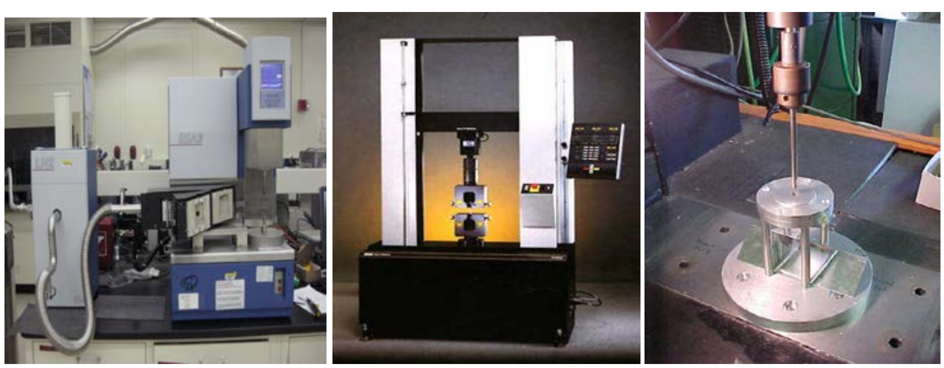


Figure 6. Photos of dynamic thermal analyzer, Instron testing machine, and shaft-loaded blister test apparatus (from left to right) at NIST Engineering Laboratory to be used for PV polymeric materials studies.

## Milestones:

Year 1

- Identify, acquire, and prepare model PV polymeric material or component for accelerated laboratory testing using a reliability-based methodology. Selection of materials with extensive field history will be recommended by Consortium partners.
- Modify SPHERE technology for accelerated laboratory testing of PV polymeric materials and components under different levels of temperature, relative humidity, spectral UV intensities and wavelengths, and additional capabilities of mechanical loadings and electrical bias.
- Develop measurement tools to characterize changes of relevant material properties (chemical, physical, optical, mechanical, etc.) and investigate the degradation mechanism(s) in the model systems.
- Start exposure of the model PV polymeric system(s) on the SPHERE using a factorial experimental design including different levels of temperature, relative humidity, spectral UV intensities and wavelengths, with optional mechanical loading and electrical bias.
- Define and design model mini-module(s) similar in construction to real-world modules having extensive field history, with the recommendation and help of Consortium members.

  Similar multi-component laminates will be designed, prepared or acquired based on the same design of mini-module(s).

**Deliverables:** Improved SPHERE technology for accelerated laboratory testing of PV polymeric materials with multiple, simultaneously-applied stresses; advanced measurement tools for degradation mechanism study of PV polymeric materials during accelerated laboratory tests.

## Year 2

- Continue to expose the model PV polymeric system on the SPHERE using a factorial experimental design including different levels of temperature, relative humidity, spectral UV intensities and wavelengths, with optional mechanical loading and electrical bias.
- Systematically characterize the chemical, mechanical, optical and morphological properties for the exposed model material system, and assess the degradation mechanism(s) and failure mode(s) under different accelerated testing conditions.
- Expand SPHERE capability for accelerated laboratory testing of mini-modules under conditions of UV intensities temperature, and RH, with optional thermal cycling.
- Acquire model mini-module(s) defined in Year 1 with assistance of Consortium partners, and begin SPHERE exposure them under different accelerated conditions. Similar exposures will be conducted for multi-component laminates based on the same design of mini-module(s).
- Develop non-destructive techniques (such as Raman spectroscopic imaging or fluorescence spectroscopy) to characterize degradation of polymers contained in mini-module(s).

**Deliverables:** Advanced SPHERE technology for accelerated laboratory testing of PV mini-modules with multiple, simultaneously-applied stresses; key parameters for accelerated laboratory testing and new knowledge on degradation mechanism(s) of PV materials at different exposure conditions; non-destructive techniques for characterization of polymer degradation in mini-modules.

## Year 3

- Analyze laboratory exposure data and field history of the model PV polymeric material(s). Compare degradation mechanism(s) and failure mode(s) between field exposure and laboratory tests.
- Develop and validate preliminary mathematical model (s) to quantitatively link field and laboratory exposure results for model polymeric material(s).
- Continue to expose the model mini-module(s) and characterize degradation during SPHERE exposure. Novel adhesion testing methods will be developed to identify the weakest interfacial regions in multilayer system. Long-term adhesion tests will be conducted on the multi-component laminates during similar accelerated exposure.
- Collect data on degradation of model mini-module(s) properties during SPHERE exposure. Analyze laboratory failure mode(s) of the mini-module(s) based on the SPHERE exposure data, and compare the results with those observed in field modules. In the event that the same degradation mechanism is observed, acceleration factor of the laboratory exposure with respect to the outdoor weathering will be estimated.

**Deliverables:** Preliminary experimentally-validated mathematical models for linking field and laboratory exposure results and service life prediction of polymeric material(s); novel adhesion testing methods for multi-component laminates; new knowledge on degradation mechanism(s) and failure mode(s) of mini-modules under different laboratory testing conditions; scientific basis and recommendations for developing standards and accelerated laboratory testing methods for PV polymeric materials.

# 4. PROPOSED ROADMAP FOR DEVELOPING MEASUREMENT SCIENCE FOR PREDICTING THE SERVICE LIFE OF POLYMERS USED IN PV SYSTEMS

As an outcome of the above workshops, a NIST/industry consortium on Service Life Prediction of Polymers in PV System has successfully been formed. The work planned in this consortium is the primary contributor to the development of a roadmap for measurement science needed to predict service lives of PV polymeric materials, components, and modules.  By engaging industrial stakeholders, NIST is continuously receiving inputs and feedbacks from consortium members and other PV industry stakeholders in developing program and experimental plans in PV reliability.

In this Chapter, the roadmap for developing measurement science for predicting the service life of polymers in PV Systems is presented. This roadmap is aligned with the Statement of Work of the NIST/Industry PV consortium, and provides a timeline for short-term goal (0-3 years), mid-term goal (3-5 years) and long-term goal (5-8 years) to achieve the ultimate goal of predicting service life for polymers used in PV systems. The three detailed plans (a-c) are focused on the short-term goal, which are tailored to match the first phase research of the NIST/Industry PV consortium. This roadmap supports NIST Strategic Goal of *Sustainable and Energy-Efficient Manufacturing, Materials, and Infrastructure* through the program of *Net-Zero Energy, High-Performance Green Buildings.* It can also be used by both the public and private sectors to guide policy, R&D, and other decision making relevant to important areas in PV materials and module reliability.

## Proposed Roadmap- Measurement Science for Predicting the Service Life of Polymers Used in PV Systems

### Scope

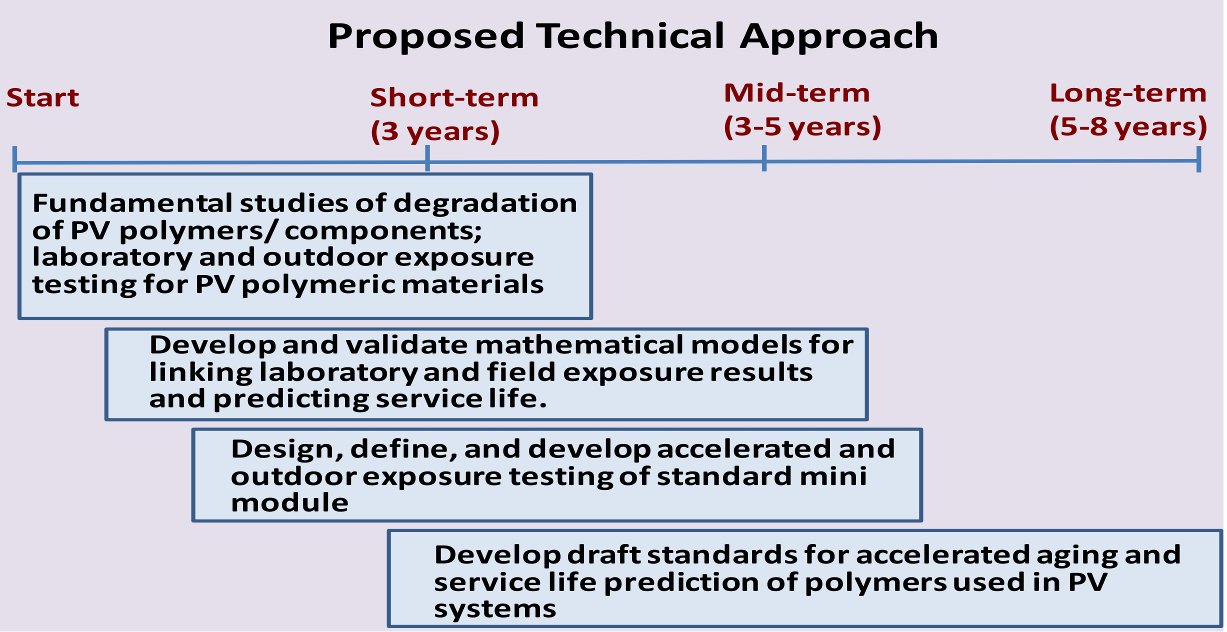
**To develop and implement measurement science for predicting the lifetime of polymeric materials used in PV applications.**

### Technical Components

**For PV polymers, components, and mini-modules, to develop:**

- Accelerated laboratory test for predicting service lives using the NIST SPHERE
- Measurement tools capable of discerning degradation mechanism(s) and failure mode(s)
- Mathematical models for linking field and laboratory exposure results
- Test standards for accelerated aging and service life prediction of polymers

### Technical Approach



## 4A. Development of Reliability-based Accelerated Laboratory Tests for PV Polymeric Materials and Components

**Objectives:**

(1) Develop accelerated laboratory tests for PV polymeric materials and components based on NIST SPHERE technology

(2) Develop measurement tools to investigate degradation mechanism(s) and failure mode(s) of PV polymeric materials and components exposed to multiple environmental stresses including UV, temperature and moisture

(3) Develop mathematical models for linking field and laboratory exposure results for PV polymeric materials and components using reliability-based methodology

**Challenges:**

Today's performance warranty typically guarantees 80 % of initial rated power for 25 to 30 years, but most current PV products have field histories of only a few years or less.

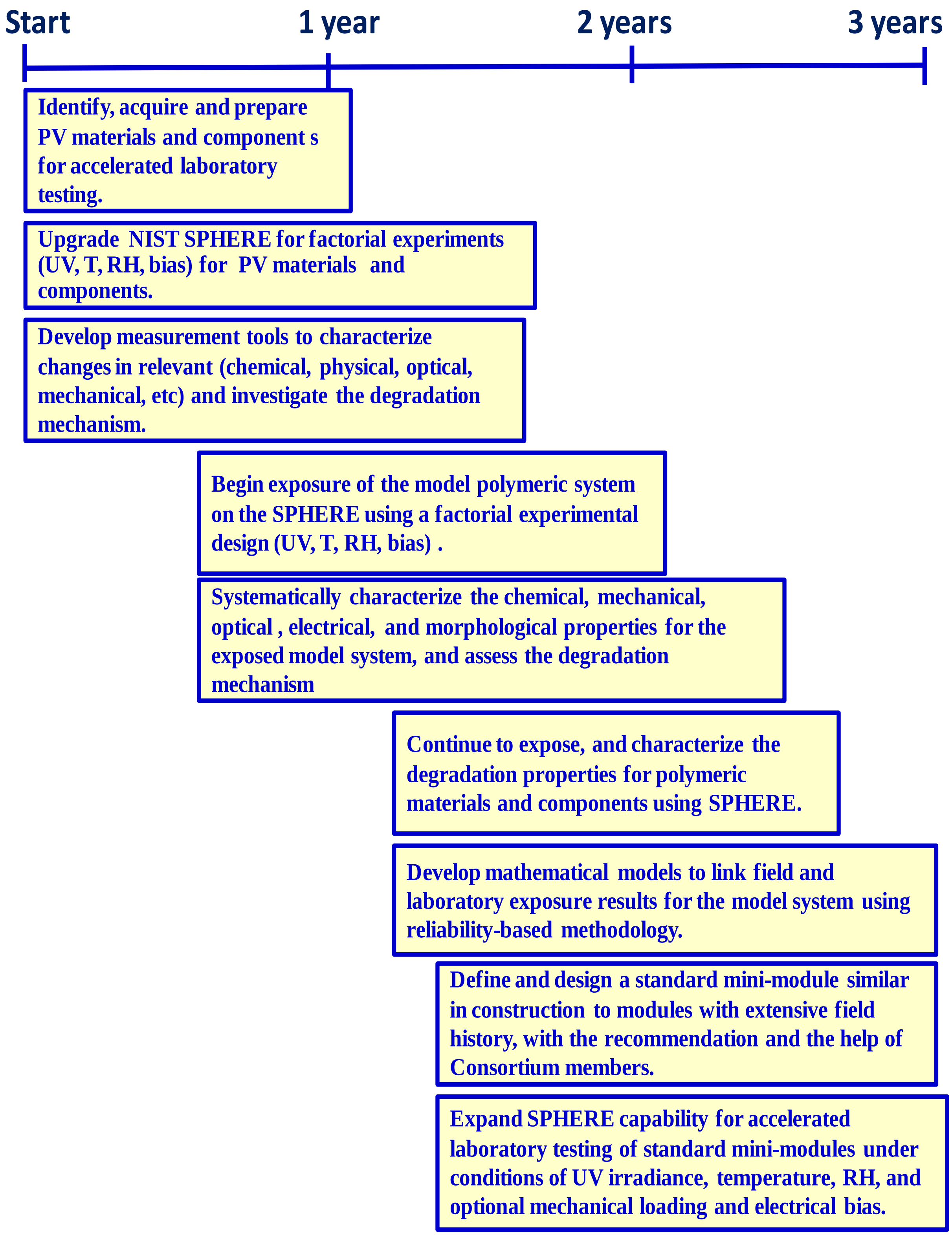
Existing test standards such as IEC 61215 or IEC 61646 are mainly qualification tests which are useful in screening for infant mortality failures, but are not designed to predict service life nor ensure long-term reliability.

The lack of effective accelerated laboratory tests for lifetime prediction of PV materials, components and modules significantly hinders innovation, development, assurance and acceptance of PV technology.

**Potential Solutions:**

- Characterize degradation mechanisms and failure modes of PV polymers and components exposed to SPHERE-based accelerated laboratory tests under multiple stressors (UV, temperature, moisture, etc), singly and in combination.
- Derive and validate mathematical models for linking laboratory and field exposure results and predicting service life for polymeric materials and components.
- Design, define, and expose model mini-modules for use in developing accelerated laboratory testing metrology for PV modules. Relate accelerated laboratory results to field exposure for mini-modules.

**Milestones:**


Start
1 year
2 years
3 years
Identify, acquire and prepare PV materials and component s for accelerated laboratory testing.
Upgrade NIST SPHERE for factorial experiments (UV, T, RH, bias) for PV materials and components.
Develop measurement tools to characterize changes in relevant (chemical, physical, optical, mechanical, etc) and investigate the degradation mechanism.
Begin exposure of the model polymeric system on the SPHERE using a factorial experimental design (UV, T, RH, bias) .
Systematically characterize the chemical, mechanical, optical , electrical, and morphological properties for the exposed model system, and assess the degradation mechanism
Continue to expose, and characterize the degradation properties for polymeric materials and components using SPHERE.
Develop mathematical models to link field and laboratory exposure results for the model system using reliability-based methodology.
Define and design a standard mini-module similar in construction to modules with extensive field history, with the recommendation and the help of Consortium members.
Expand SPHERE capability for accelerated laboratory testing of standard mini-modules under conditions of UV irradiance, temperature, RH, and optional mechanical loading and electrical bias.

## 4B. Development of Long-term Adhesion Tests for PV Module Components

**Objectives:**

(1) Develop test methods to characterize interfacial adhesion between module components

(2) Assess long-term adhesion as a function of laboratory accelerated exposure (UV, temperature, relative humidity)

(3) Correlate material properties with adhesion degradation and interfacial failure of the module components

**Challenges:**

Delamination, resulting from the loss of adhesion between the laminated module components, is a common failure mode observed in field-tested PV modules.

Delamination provides a pathway for moisture ingress which could further degrade module performance and create safety concerns for modules.

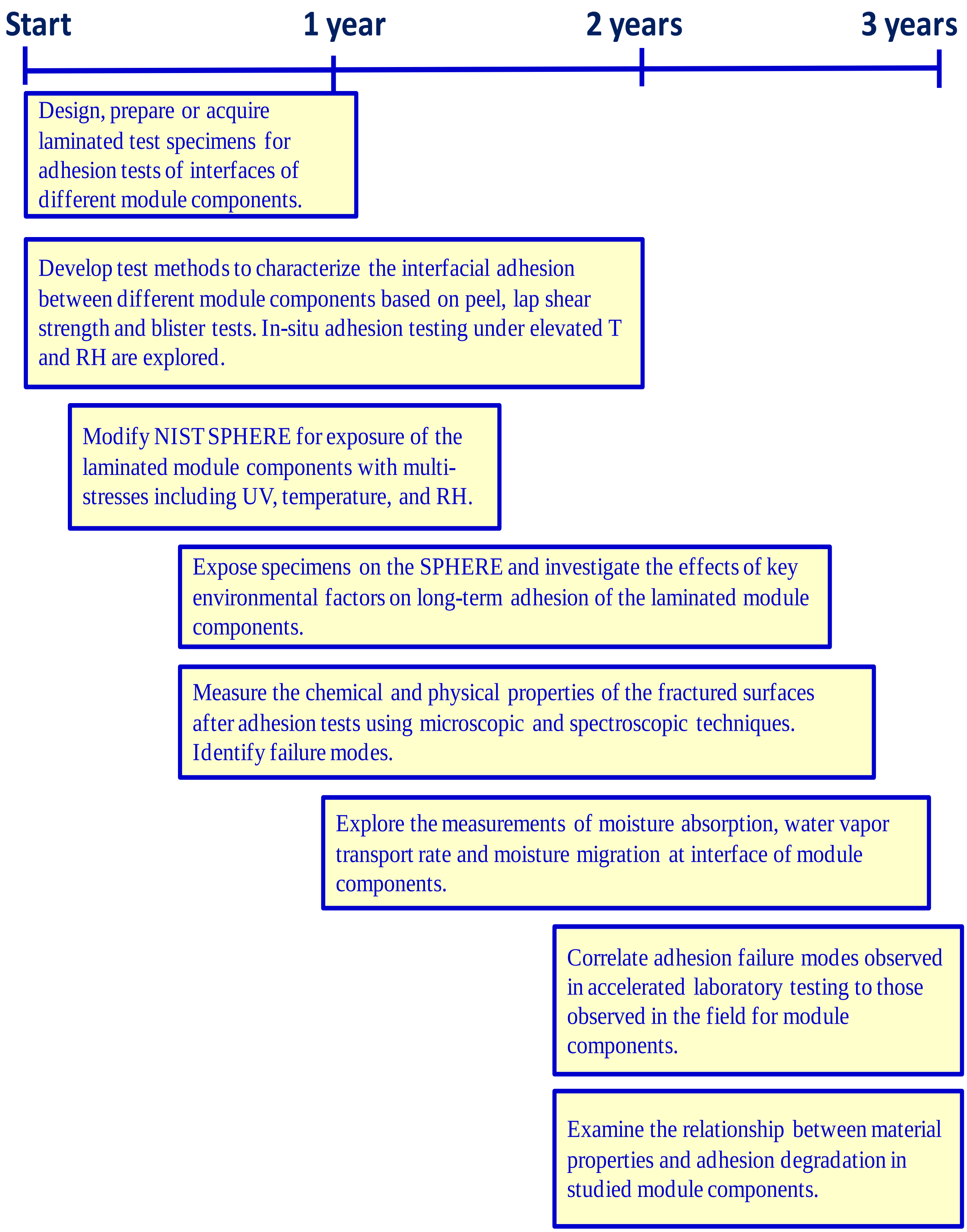
This problem is particularly challenging for developing long-term reliable flexible thin-film technology because of the high moisture ingress of flexible polymer films.

The relationship between the material degradation and adhesion loss is not clear; studies are lacking.

**Potential Solutions:**

- Develop test methods to characterize the interfacial adhesion between different module components
- Measure long-term adhesion as a function of laboratory accelerated exposure (UV, temperature, RH) and outdoor exposure
- Identify the cause of adhesion degradation and correlate to material degradation

**Milestones:**



Start
1 year
2 years
3 years
Design, prepare or acquire laminated test specimens for adhesion tests of interfaces of different module components.
Develop test methods to characterize the interfacial adhesion between different module components based on peel, lap shear strength and blister tests. In-situ adhesion testing under elevated T and RH are explored.
Modify NIST SPHERE for exposure of the laminated module components with multi-stresses including UV, temperature, and RH.
Expose specimens on the SPHERE and investigate the effects of key environmental factors on long-term adhesion of the laminated module components.
Measure the chemical and physical properties of the fractured surfaces after adhesion tests using microscopic and spectroscopic techniques. Identify failure modes.
Explore the measurements of moisture absorption, water vapor transport rate and moisture migration at interface of module components.
Correlate adhesion failure modes observed in accelerated laboratory testing to those observed in the field for module components.
Examine the relationship between material properties and adhesion degradation in studied module components.

## 4C. Failure Mode Analysis and Non-destructive Polymeric Material

(1) Develop techniques for characterizing chemical and optical properties of polymer components in degraded/failed PV modules from laboratory and field exposures

(2) Assess contribution of polymer degradation to primary failure modes of PV modules

## Characterizations for PV Modules

**Objectives:**

**Challenges:**

Common failure modes of PV modules, such as corrosion, delamination, encapsulant discoloration, etc, could be due to the aging of polymeric components.

Current criteria used to detect failures mainly depend on electric property loss in maximum power and insulation resistance, or the presence of visible visual defects.

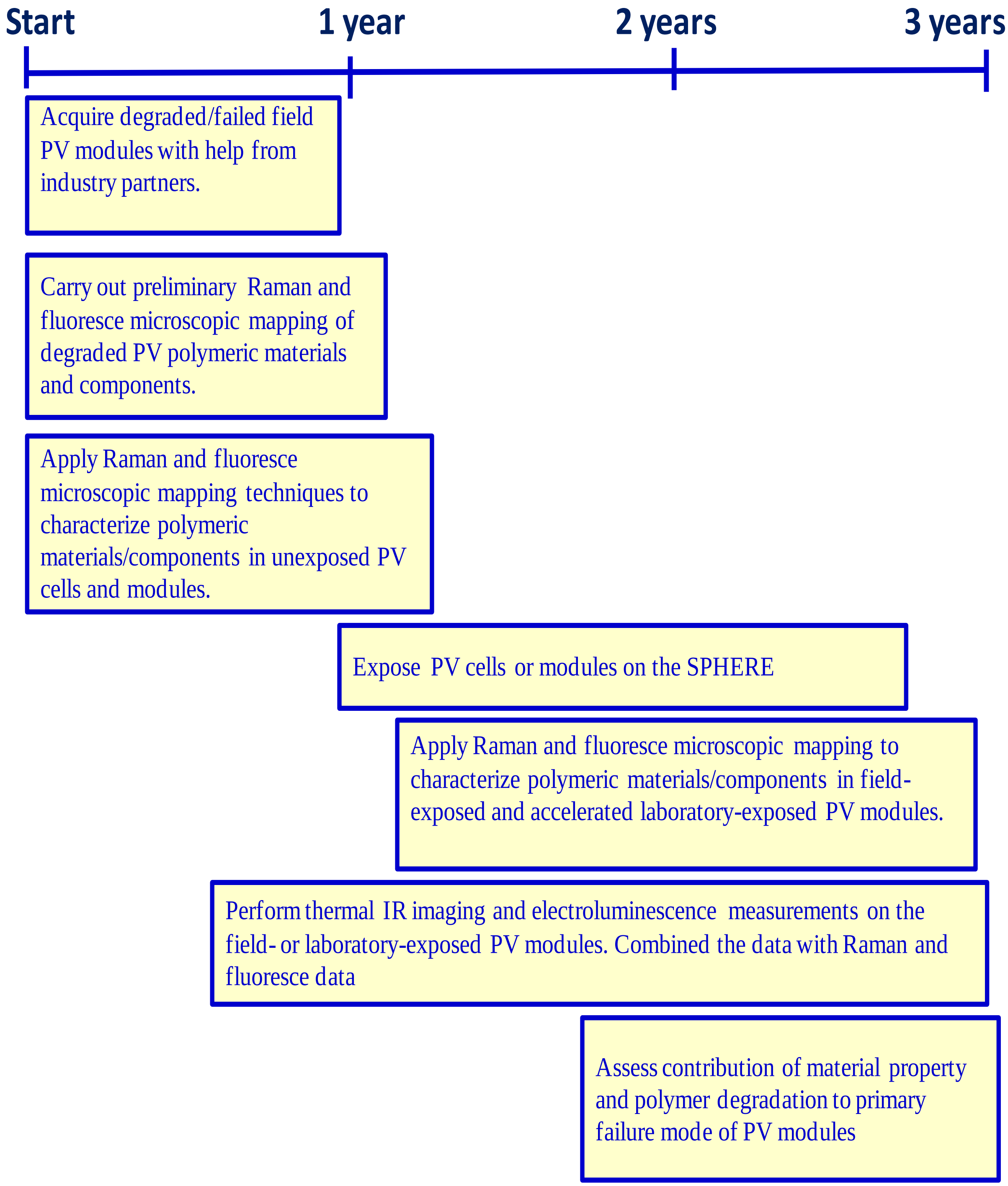
It is difficult to isolate, investigate and identify specific causes for module failures even when the failures have been detected.

Techniques, especially non-destructive ones, for characterizing the polymer materials and components in PV modules are lacking.

**Potential Solutions:**

- Develop *non-destructive* characterization techniques for polymeric materials/components in degraded/failed PV modules from laboratory and field exposures
- Assess contribution of polymer degradation to primary failure modes observed in PV modules

**Milestones:**


Start
1 year
2 years
3 years
Acquire degraded/failed field PV modules with help from industry partners.
Carry out preliminary Raman and fluoresce microscopic mapping of degraded PV polymeric materials and components.
Apply Raman and fluoresce microscopic mapping techniques to characterize polymeric materials/components in unexposed PV cells and modules.
Expose PV cells or modules on the SPHERE
Apply Raman and fluoresce microscopic mapping to characterize polymeric materials/components in field-exposed and accelerated laboratory-exposed PV modules.
Perform thermal IR imaging and electroluminescence measurements on the field- or laboratory-exposed PV modules. Combined the data with Raman and fluoresce data
Assess contribution of material property and polymer degradation to primary failure mode of PV modules

## APPENDIX A: LIST OF WORKSHOP ATTENDEES

| NAME | AFFILIATION |
|---|---|
| Alex Bradley | DuPont |
| Nancy Phillips | 3M |
| Aaron Foster | NIST |
| Allen Zielnik | Atlas-MTS |
| Andy Goodwin | Dow Corning |
| Chris White | NIST |
| David Avison | Madico |
| Debbie Stanley | NIST |
| Elizabeth Orlowski | Dow Corning |
| Eric Byrd | NIST |
| Greg O'Brien | Arkema |
| Hsinjin Edwin Yang | UL |
| Jason Eckstein, | Lux Research |
| Jason Reese | Dow Chemical |
| Jeffrey Prate | Madico |
| Jerry Eng | Cytec |
| Joannie Chin | NIST |
| Jon Martin | NIST |
| Ken Milam | Daikin America |
| Kurt Scott | Atlas-MTS |
| Leobardo Lopez | DOW |
| Lipiin Sung | NIST |
| Marina Temchenko | Madico |
| Nick Shephard | Dow Corning |
| Rafal Mickiewicz | Fraunhofer |
| Robert Pleydon | Saint-Gobin |
| Roger French | Case Western Reserve University |
| Ron Hendershot | Daikin America |
| Sari-Beth Samuels | Cytec |
| Shyam Sunder | NIST |
| Stephanie Watson | NIST |
| Tinh Nguyen | NIST |
| Tom Chapin | UL |
| Xiaohong Gu | NIST |
| Zhengjue (Jack) Zhang | First Solar |

## APPENDIX B: WORKSHOP AGENDA

| Thursday, September 23, 2010 | **Workshop on Polymers for Photovoltaic Systems**<br>**NIST Administration Building, Employee Lounge** |
|---|---|
| 8:00 AM to 8:30 AM | **Continental Breakfast** |
| 8:30 AM to 8:45 AM | **Welcome**<br>Dr. Shyam Sunder<br>Director, Building and Fire Research Laboratory |
| 8:45 to 9:00 AM | **Opening Remarks and Workshop Scope**<br>Joannie Chin, Polymeric Materials Group/NIST<br>Hsinjin (Edwin) Yang, UL |
| 9:00 AM to 9:30 AM | **North American Photovoltaic Market Overview**<br>Jason Eckstein, Lux Research |
| 9:30 AM to 10:00 AM<br><br>10:00 AM to 10:30 AM | **Technical Challenges and Measurement Needs, Part I**<br>New Materials Innovations for Photovoltaics - Jeff Sternberg, DuPont Photovoltaic Solutions<br>Building Integrated Photovoltaic Challenges: A Summary of Design, Process, Safety, and Performance Challenges for a Growing Market – Jason Reese, Dow Chemical |
| 10:30 AM to 10:45 AM | **BREAK** |
| 10:45 AM to 11:15 AM<br><br>11: 15 AM to 11:45 AM | **Technical Challenges and Measurement Needs, Part II**<br>Polymeric Testing Considerations for Photovoltaic Applications – Mike Kempe, NREL<br><br>Photovoltaic Systems: The Safety and Reliability Continuum - Tom Chapin, UL |
| 11:45 AM to 1:00 PM | **LUNCH**<br>NIST Cafeteria (courtesy of UL) |
| 1:15 PM to 2:15 PM | **Reliability Approach for Service Life Prediction of Polymeric Materials**<br>Dr. Xiaohong Gu, Polymeric Materials Group/NIST |
| 2:15 PM to 2:30 PM | **BREAK** |
| 2:30 PM to 5:00 PM | **Breakout Sessions**<br>Industry moderators |
| 5:00 PM | **Adjourn Day 1** |
| 5:30 PM to 6:15 PM | **Optional Laboratory Tours – NIST SPHERE, Photovoltaics Laboratory** |
| 7:00 PM | **GROUP DINNER**<br>Buca Di Peppo, 122 Kentlands Blvd., Gaithersburg, (301) 947-7346 |

| Friday, September 24, 2010 | **Workshop on Polymers for Photovoltaic Systems**<br>**NIST Administration Building, Employee Lounge** |
|---|---|
| 8:00 AM to 8:30 AM | **Continental Breakfast** |
| 8:30 AM to 10:15 AM | **Summary of Breakout Sessions**<br>Industry Moderators |
| 10:15 AM to 10:30 AM | **BREAK** |
| 10:30 AM to 11:00 AM | **The Next Steps**<br>Terry Lynch, NIST Office of Technology Partnerships (OTP) |
| 11:00 AM to 12:00 PM | **Presentation of path forward and key action items for consortium-building**<br>Joannie Chin, Polymeric Materials Group/NIST |
| 12:00 PM | **Adjourn meeting** |