DuraMat Capability 4:
Module Prototyping and Accelerated Durability Testing

Poster Number	Capability Name	Short Paragraph Description of Capability (300 words same as the abstract. Summarize what it does and value to DuraMat and Module Materials)	Capability Expert (principal contact)	Organization Name and Type - (National Laboratory - NL, Academic Institution - AI, Company- C)	Which Capability Area Best Fits This Work (Select One)	Define from an industry perspective what. (100 words)	Link to Your Website (if available)
42	Module Prototyping and Accelerated Durability Testing	This capability provides a platform for assembling and testing new module materials, components, prototypes (mini-module and full-size) to evaluate durability and performance using novel simultaneous and combinatorial accelerated stress testing (C-AST). While existing mechanism-specific tests are helpful to understand the occurrence, rates, and theory of specific, known failure mechanisms, they require numerous modules and multiple parallel tests. Further, various material combinations and stress factors of the natural environment have shown that simple, first-order considerations (with unique stress factors or simplified test coupons) are insufficient to give bankable results about the durability of the module. This is because new designs and materials have sometimes shown unanticipated degradation modes that were not foreseen (PID, LeTID, and some delamination mechanisms are examples from the last decade). Risk of unanticipated failures in new materials or designs limits marketability of such products. This capability based on a multi-stress weathering platform will advance C-AST to examine PV module durability more quickly, reliably, and with fewer samples to accelerate the characterization of truly field-relevant degradation mechanisms that the natural environment causes in all components of the modules. In addition to the evaluation of module materials and components such as the backsheet, encapsulant, frame, glass, grounding parts, and junction box, this work will also include module level power electronics, contacts/switches, and interconnects. This is achieved by applying the stress factors of the natural environment in combination, including light (with partial shading), temperature, humidity, rain, system voltage, and mechanical stress (thermo-mechanical and static loading). Module degradation as it would occur in PV systems in the natural environment can thus be well characterized. DuraMat will therefore focus on accelerating development, bankability, and commercialization of new PV module form factors by approaching PV module durability by design and using combinatorial testing protocols to validate those designs.	Peter Hacke	NL- NREL	4. Module Prototyping and Accelerated Durability Testing	In year one, partnering with industry, mini-modules will be produced at NREL and Sandia so that new materials and designs can be evaluated. C-AST protocols, software, actuation of tests, and metrology will be demonstrated. As an example, degradation by embrittlement, cracking, and delamination of backsheets can be evaluated by C-AST to better distinguish backsheet durability, which is of interest to backsheet manufacturers and module makers. A second example is the determination of key degradation mechanisms of module-integrated electronics leading to corrosion, capacitor, and circuit board failures associated with electrical, chemical, and environmental interactions. At year five, novel module materials, components, and designs will be prototyped, and their durability evaluated with high confidence cost-effectively by C-AST for faster market acceptance and bankability.	
43	Test Coupon fabrication and stress testing for PV module materials	Under the PV module reliability effort, NREL has developed a number of capabilities to construct and evaluate module packaging materials. We have a **laminator** capable of making mini-modules or module components for test with up to 16, 156 mm cells. Frequently we make single cell test specimens because they are easier to manage and enable testing of larger numbers of samples to improve the statistics of an experiment. Alternatively we make coupons without PV cells to evaluate packaging materials alone. This laboratory laminator provides a number of convenient sample sizes for evaluating many aspects of module construction. Our **extruder** creates encapsulant films with customized stabilization packages to elucidate the degradation processes in polymeric materials or creates encapsulants with unique mechanical, moisture ingress, optical, or adhesion properties. This extruder can duplicate vintage encapsulant formulations which are no longer available. Once samples are constructed we have a number of **environmental and weathering chambers** that apply thermal, humidity, voltage, or ultraviolet light stresses to materials to evaluate their long term durability. All these stresses can be applied at the same time, separately, or any combination thereof and at varied set points in different environmental chambers. Comprehensive testing under multiple conditions is needed to be able to evaluate the dependence of degradation on different stressors to be able to extrapolate performance down to the field conditions. With many PV technologies moisture ingress is problematic and must be reduced or eliminated. We have several Mocon permeation measurement instruments useful for determining the diffusivity and solubility of water in packaging materials. We also have a custom built instrument capable of measuring **permeation rates** around 10-6 g/m^2/day. This is a unique instrument based on a patented method where the resistivity of Ca traces changes are used as an indicator for moisture ingress.	Mike Kempe	NL- NREL	4. Module Prototyping and Accelerated Durability Testing	Provides critical, but cost-effective testing platform for module materials in preparation for full-size-module testing. Can compare durabilities with historical formulations.	http://www.nrel.gov/pv/performance_reliability/accelerated_testing.html#components
44	Quantifying Adhesion Within The PV Module Laminate	A fracture mechanics based approach has been developed to quantify the material property of adhesion at every interface within the PV module laminate. The developed metrology may be applied at both the module and coupon level to yield an identical, quantitative measurement. This new capability can even probe the adhesion at interfaces between the cell and front sheet of glass; critical areas for module reliability that, up to this point, have not been evaluated. The metrology involves adhering an elastic beam to the layers of interest and mechanically measuring the energy stored and released from that beam during the delamination process. This stored and released energy represents the material property of the critical strain energy release rate, or adhesion. The metrology was developed with an eye towards its dissemination and adoption within the PV industry. Accordingly it may be conducted with common PV test laboratory equipment and modestly trained personnel. A New Work Item Proposal (the first step for composing an international test standard) for this method has been composed and will be presented at the next IEC working group meeting in October 2016. Once implemented, manufactures, test laboratories and researchers can use this method as a tool to directly and quantitatively compare the adhesion between every interface within the PV module laminate.	Nick Bosco	NL- NREL	4. Module Prototyping and Accelerated Durability Testing	Adequate adhesion is required to maintain the reliability and safety of PV modules. The capability exists presently to quantify adhesion that is a prerequisite to design, develop and test reliable and safe modules. For instance, knowledge of the minimum adhesion required to prevent delamination can guide both optimization during materials development and lifetime prediction through accelerated testing. These efforts can both reduce the cost of materials by preventing over-engineering and their reliability by guiding requirements for reliability testing.	
45	Durability testing of materials, components and modules	Capabilities for testing of coupons and modules include multiple environmental chambers that may be used for damp heat, humidity freeze, thermal cycling, etc; with in-situ evaluation by dark I-V methods. Multiple Xe and UV-A based weathering chambers are also available. A salt fog chamber is available for corrosion testing. Light IV, Dark IV, electroluminescence, thermography, photoluminescence, FTIR, mass spectroscopy, and Ramen spectroscopy are available for analyses of degradation mechanisms. Various spectrophotometers, reflectometers, and a gloss meter exist for analyzing optical properties of materials. Static loading, hail ball testing, and other tools are available for examining adhesion, creep, impact and fracture resistance, and other mechanical properties. These include an Instron and a DTS Delaminator. TABER, sand drop, and brush testing equipment are capabilities for testing wear and durability of surfaces and coatings. Equipment and techniques for gas and moisture penetration analyses include calcium-based methods, thermogravimetric analysis, moisture analyzers, and Mocon tools. Equipment for mixing and extruding polymers, as well as a laminator are available for custom coupon and module builds. A goniometer is a capability available for measuring contact angles. Non-destructive analysis tools including acoustic microscopy and X-ray tomography are also available. Mechanical, diffusion, and various other modeling capabilities are available to complement and further understand the key factors for durability. Indoor and outdoor-instrumented performance and durability testing of modules, components, electronics. and coupons are also available.	Peter Hacke	NL- NREL	4. Module Prototyping and Accelerated Durability Testing	These existing capabilities available at the start of and throughout the DuraMat program may be used to understand materials properties for PV modules and electronics on the materials, component, and module levels, both as constructed and after accelerated testing or field testing to evaluate, improve, and fundamentally understand their durability properties.	http://www.nrel.gov/pv/performance_reliability/indoor_testing.html
46	Failure analysis of module-integrated electronics	Module-integrated electronics including bypass diodes, rapid shut-down safety devices recently mandated by National Electric Code, and sub-module power electronic devices embedded in the laminate are increasingly capturing market share. IHS Research projects a US $1 billion market for module-level power electronics by 2019. While there is more than 40 years of experience developing the reliability of conventional PV modules such that 25-year warranties have become commonly expected and to an extent relied upon, experience from other industries tells us that integrated electronic devices are rarely expected to perform for 25 years or more. At this time, the reliability of PV module integrated electronics has not been adequately determined. Failure analysis techniques on these devices must be developed and performed to feedback to quality improvement, reliability and safety standards development, and to achieve lifetimes on par with the modules into which they are integrated. While the NREL Analytical Microscopy group has historically focused on analysis for the performance of cells and absorbers, this group along with the newly forming NREL Virtual Reliability Center is equipped with exactly the toolset required to perform failure analysis on module integrated electronics. These tools include packaging/potting deconstruction, microscopy, electrical testing, acoustic microscopy, X-ray tomography, SEM, EDS, EBIC, and mechanical inspections. We seek to migrate NREL's strong existing capabilities to more rapidly and effectively perform failure analysis of module-integrated electronics. Elucidating degradation mechanisms and performing detailed analyses of the failures will help lift all boats for the burgeoning industry, in which individual players cannot maintain the broad toolset and staff of materials scientists required. The resulting increased durability, safety, and confidence in these devices based on the feedback obtained from failure analysis will improve understanding, reduce costs, and increase penetration of these safety and performance-enhancing devices for the PV industry.	Steve Johnston	NL- NREL	4. Module Prototyping and Accelerated Durability Testing	In year one, we will demonstrate failure analysis capability and root cause identification of one or more failure mechanisms in MIE devices showing effectiveness of our materials analysis capabilities and methods as well as rapid turn around of results to be useful for industry. By year five, we will show the physics and chemistry of interactions of interest to industry. These may include evaluating the nature of corrosion and materials adhesion of the materials in the MIE with respect to flame retardants, potting, conformal coatings, metals, flux, moisture, heat, humidity and bias, and reducing failure rates with proposed solutions.	

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47	Material/representative coupon weathering, optical characterization, and failure analysis of PV materials/components.	There has been much recent interest in the development of weathering tests for materials and components used in PV modules. For example, Task Group 5 within the PV Quality Assurance Task Force has organized an interlaboratory study at 14 institutions regarding the UV aging of encapsulants. Similarly, 12 institutions are collaborating on a weathering experiment for backsheets, in support of the IEC 62788-7-2 standard. Equipment capability unique to NREL includes many Xenon-lamp Weather-ometer chambers (including a chamber customized for high irradiance aging). These chambers have proven useful for determining key weathering parameters like activation energy. Future studies would benefit from improved automation. Parameters like optical transmittance could be more rapidly measured in a custom instrument (rather than a spectrophotometer), with the specimens handled in a cartridge carrier. Regarding failure analysis, Raman spectroscopy could likewise be performed using a cartridge carrier to allow stepping between specimens or mapping within specimens to analyze their degradation. Recent work has focused on steady state weathering. Future work might apply conditions in an aging cycle (to better cover diurnal variation or most severe circumstances) and/or a sequence of different weathering tests, like used in module qualification. Present efforts have not emphasized failure analysis to understand the underlying mechanism(s), which will become important for emerging materials with no PV legacy. Future studies might also leverage the Design of Experiments method to quantify the most significant parameters affecting weathering and the interdependence between those factors. Weathering tests have been traditionally applied towards safety and qualification of materials. The advent of veteran or decommissioned installations now allows the industry the opportunity to study the component materials to determine what is truly required for the application and avoid costly overdesign. This may allow a reduction in the quantity or number of materials used. Future studies will also need to more accurately assess material lifetime, in the event of longer required module lifetime.	David Miller	NL- NREL	4. Module Prototyping and Accelerated Durability Testing	Near term 1 year goals would be to identify topics/materials that would benefit from improved study. Long term 5 year successful use of the capability would demonstrate new instrumentation, methods of experiment, and the related industry infrastructure If we can demonstrate new instrumentation, methods of experiment, .	
48	ASU-PRL: Arizona State University Photovoltaic Reliability Laboratory	In the past four years alone, ASU-PRL has published more than 40 papers in the peer-reviewed photovoltaic conferences and journals, and most of these papers are related to PV reliability and durability. ASU-PRL has more than 20 years of track record to secure and successfully execute sponsored projects funded by DOE, NREL, Sandia, EPRI, electric utility companies and private companies. ASU-PRL has over 20 years of reliability testing expertise and capabilities to perform accelerated tests, to perform outdoor field tests, to characterize modules, cells and materials, and to develop stress and statistical models predicting lifetime of PV modules. **Accelerated testing** capabilities include: Three walk-in environmental chambers; one walk-in UV weathering chamber for UV weathering of commercial size PV modules; one small weathering chamber for UV weathering of coupons; two PID test setups; four ovens for static temperature stresses; one indoor soiling chamber. **Outdoor testing** capabilities include: Two 2-axis trackers; one 1-axis tracker; several fixed tilt racks; weather stations; three soiling stations; mock rooftop; several data acquisition systems with online monitoring capabilities; power quality analyzer; two multi-curve I-V tracers; three single-curve I-V tracers; AOI identifier; SunEye. **Module characterization** tools include: Cell QE at the module level for QE loss determination after repeated accelerated/field stresses; electroluminescence; infrared; handheld reflectance/transmittance spectrometer (350-2500 nm); handheld FTIR for indoor and outdoor; dark I-V; module laminator; semi-automated cell tabber and stringer; dryhipot and wet-resistance testers. **Cell characterization** tools include: Indoor solar simulator for dark and light I-V; cell QE; four-probe resistance tester; cell component extraction (mechanical and chemical). **Materials characterization** tools include: Differential scanning calorimeter (DSC); thermogravimetric analyzer (TGA); water vapor transmission rate (WVTR); universal mechanical/peel tester; thermal conductivity tester for polymeric materials/sheets. **Stress, statistical and image processing models/tools** development includes: full suite of ReliaSoft software; Minitab, Tableau, SAS, JMP, MATLAB and OriginPro.	Dr. "Mani" Govindasamy TamizhMani; Director, ASU Photovoltaic Reliability Laboratory, Email: manit@asu.edu; Cell phone: 480-528-4967	AI- Arizona State University	4. Module Prototyping and Accelerated Durability Testing	Near term usefulness of ASU-PRL: Key accelerated qualification and safety testing of newly packaged PV modules before the modules are submitted to certification testing with certification labs; Key accelerated testing of new packaging materials to be included in the new or existing design of PV modules; Characterization of new PV modules and module materials for various issues including LID, PID, encapsulant browning, QE loss, soiling loss, AOI loss. Long term usefulness of ASU-PRL: Lifetime prediction of packaging materials and PV modules; reducing warranty claims; passively lowering the operating temparatures of the modules using innovative encapsulant and backsheet materials.	https://Pvreliability.asu.edu
49	Solar Power Laboratory	The Solar Power Laboratories at Arizona State University consists of more than 6,000 ft² of laboratory space for fabrication and testing of solar cells and photovoltaic modules. These capabilities include a silicon pilot line fabrication facility, which enables fabrication of full 6" square wafers using a variety of silicon substrates and technologies. The technologies and processes include: diffused Si solar cells (averaging 18% efficiency); heterojunction solar cells (showing > 22% on full 6" wafer and > 24% peak); process for plated Cu metallization (including reliability and pull-testing measurements); thin silicon flexible solar cells both free standing and bonded to a glass substrate (20% efficiency); silicon laser processing for advanced processes; full range of passivation approaches including tunnel contacts, atomic layer deposition of Al_2O_3 among other materials, silicon nitride, and new carrier selective contact materials; complete suite of modeling and simulation capabilities, ranging including advanced transport mechanisms, 2D and 3D simulation and cell-to-system modelling capabilities; characterization of silicon solar cells and modules; and full-size module lamination.	Stuart Bowden / Christiana Honsberg	AI- Arizona State University	4. Module Prototyping and Accelerated Durability Testing	Use of the cell processing line and module assembly to evaluate the impact of materials and processesin the performance of modules	http://pv.asu.edu/
50	PV module rapid prototyping line	This capability provides a customizable prototyping line for rapid assembly of new PV module configurations (optical, electrical, physical size, etc). Developed capability at SNL is large-scale module prototyping capability, including combined tabbing/string tool (customized Solar Automation model CTS20) , PV laminator, as well as light soaking and environmental chambers. This will enable the consortium's capability to prototype and test full size PV modules. While the basic PV module configuration (35 vs 60 vs 72 cells in series, with a standard cover-glass) remained mostly unchallenged for a long time, it may be beneficial to experiment with other novel PV module configurations. Several varieties of glass (tempered vs non-tempered, various light-trapping and coatings, etc), plastics and polymers can be incorporated. Rapid prototyping can concentrate on establishing durability of a single component or single point of failure (such as solder joints fatigue or interconnects) or durability of the whole assembly. What's more important, to be competitive, each potential product needs to be scrutinized for scalability and manufacturing. Our rapid prototyping line can quickly provide such assessment Using Design-for-Manufacturing and Design-for Automation principles. Coupled with the predictive simulation capability for manufacturability (which can provide modeling of how individual manufacturing stresses can impact durability and lifetime of a product), both of these capabilities can provide rapid assessment of manufacturing yields and long-term profitability of a new product. The prototyping line can also emphasize low cost, a unified form factor and connectivity, and easily recycled components.	Olga Lavrova	NL- Sandia National Laboratories	4. Module Prototyping and Accelerated Durability Testing	In year one, partnering with industry, Sandia will apply Design-for-Manufacturing (DfM) and Design-for Automation (DfA) principles to partner's new products and ideas. Mini-module coupons (and if theTRL of a new product allows, full scale modules) will be produced at Sandia so that DfM and DfA can be validated. Coupled with the predictive simulation capability for manufacturability at SNL, as well as Module prototyping and combinatorial-accelerated stress testing at NREL, partner's products can be evaluated and assessed for multiple performance metrics (manufacturability, yields, durability, lifetime, etc). In 5 years, this partnership with industry is expected to produce new types of PV modules at lower costs, therefor leading to better LCOE.	
51	PV Module Durability Testing	CFV Solar Test Laboratory, located in Albuquerque, NM, is a 27,000 square foot state-of-the-art photovoltaic (PV) test center, accredited to ISO 17025. CFV is jointly owned by the world-renowned standards and research organizations: CSA Group, Fraunhofer ISE, and Fraunhofer CSE. CFV performs certification, performance and durability testing on all types of solar technologies – Silicon, CdTe, CIGS, CPV and BiPV. We tend to specialize in new and evolving technologies and we work closely with many of the world's leading solar manufacturers as well as national labs like NREL and Sandia. Because of our location in the Southwest we do quite a bit of outdoor performance and long term exposure testing in our outdoor test yard. We do substantial amounts of module durability testing with our Environmental Chambers, UV Exposure Chambers and Mechanical Load testing equipment. We have done testing in the past for Fraunhofer for their PVDI program and have completed several rounds of NREL Qualification Plus testing for a DOE Sunshot program on next generation lightweight modules. Of course we also do custom testing protocols. We are known for our fast turn-around times and reasonable costs on all types of chamber protocols. Our temperature chambers have overbuilt heating and cooling systems and are capable of a minimum of 8 cycles per day and can be run up to 12 cycles per day to decrease testing times. Our large UV chamber runs at 3x ambient exposure (150w/m2) and can accommodate (8) 60 cell modules or (4) 72 cell modules. Our PSE MLT stand can run static MLT protocols and also dynamic MLT at up to 4 cycles per second and can be placed in one of a large environmental chambers. Our directly attached outdoor test yard has dual axis trackers, single axis trackers, fixed racks and simulated roof decks. Combined with our indoor capabilities this creates capabilities for comparison performance testing and many types of exposure tests	Jim Crimmins, 505-998-0102, jim.crimmins@cfvsolar.com	C- CFV Solar Test Laboratory, Inc.	4. Module Prototyping and Accelerated Durability Testing	One year - qualification and durability testing of new module materials and designs, possibly with integrated mounting features. Five year - commercialization of new module technologies with reduced cost, streamlined installation, improved performance and better durability.	www.cfvsolar.com
52	Static and Cyclic Mechanical Load Testing with simultaneous Electroluminescence and IV measurements for improved imaging of cracks and predictions of future degradation once closed cracks open up in the field	Mechanical Load Testing is required for IEC module certification and is linked to a variety of materials and module design issues related to durability including cracking of solar cells, integrity of edge seals and metallization interconnects, adhesion of encapsulants and backsheets, and anything that relates to or affects the stress/strain vs load characteristics of the mounted modules. There is a need for tools that can meet both the specified durability tests as well as well as highly accelerated version of these tests to aid product/materials development. The LoadSpot Mechanical Load Tester installed at the Florida Solar Energy Center can perform such tests and adds significant additional capability with respect to measuring the formation and impact of cracked cells as a function of load, and predicting the crack-related degradation that would occur in the field in a matter of seconds as opposed to weeks in a climate chamber. The LoadSpot is fast and easy to use, is flexible for a variety of module shapes and sizes, and is more uniform than suction-cup based systems as the tool uses vacuum and air pressure applied to the rear side of module. Since the front side of the module is unobscured during loading, it is uniquely able to perform IV/EL and other optical based measurements during loading. Series resistance monitoring can potentially detect failure modes such as wire fatigue during cyclic loading. Many degradation phenomena are a function of module temperature, especially when going below the glass transition temperature of encapsulants, and future enhancements to the LoadSpot platform may include the ability to perform loading under controlled temperature.	Andrew Gabor - BrightSpot Automation	C- BrightSpot Automation	4. Module Prototyping and Accelerated Durability Testing	Over a 1 year horizon, load testing of modules with experimental materials and designs can be performed on the LoadSpot tool at the Florida Solar Energy Center to help improve the durability of modules with respect to cracked cells and other load related problems. This can accelerate and lower the cost of development cycles, provide confidence to investors, and help bring new materials and designs to market. BrightSpot can design customized clamping hardware and software to aid these efforts. Over a 5 year horizon, new capabilities will be added to the LoadSpot and it will be interfaced with additional characterization tools during load as is requested by the community of users.	www.brightspotautomation.com

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53	Arc fault and Fire hazards testing and mitigation technologies	With the increased deployment of PV, there is a very real need to address the hazards of PV-related fires, such as those resulting from arc-faults in these high voltage systems. Reducing and eliminating potential safety hazards which may be associated with PV modules, their packaging and othe BOS components, are critical objectives if SunShot targets for LCOE ($0.06/kWh by 2020), PV reliability, and system safety are to be achieved. Sandia National Labs has established a significant capability around research of fire dangers associated with PV modules, has created a designated lab setup to simulate various types of arcs and ignition conditions, and ways to mitigate such fires or completely eliminate the possibility of ignition or combustion. The arc-fault research program at Sandia National Laboratories performed R&D on methods of arc-fault detection in DC systems, which has led to DC arc-fault detection systems that leverage time-based or frequency-based methods. Sandia National Laboratories has also been highly active in the development and revisions of the PV AFCI certification outline of investigation, UL 1699B. Extensive experimentation and modeling of arcs in proximity to multiple polymers produced and confirmed UL 1699B trip times what would be effective at preventing fires in PV systems. Additionally a low power (100 W) test was recommended to be added to the standards. Sandia has also offered suggestions to industry and standards boards on the type of tests, along with the difficulty in passing them, based on a number of experiments with 10 arc-fault detectors and AFCIs to determine their ability to withstand unwanted tripping scenarios. Sandia researched a range of prognostics and health management (PHM) concepts to find arc-fault 'canaries' that could indicate the PV array was degrading and at risk of experiencing an arc-fault. Some of the methods that were investigated for arc-fault PHM were impedance spectroscopy, where impedance increases in solder joints and connectors, and temperature increases from Joule heating. The idea of using learning algorithms to detect when PV arrays were experiencing unexpected degradation was also studied. Additionally, significant activity took place in the development of a novel, automated and highly-instrumented arc-fault generator has garnered much development in the area of plasma physics and provided new capabilities for thermal plasmas characterization and mitigation strategies. The research has promoted the development of a new optical spectroscopy technique for measuring the electron and bulk temperatures of plasmas, and the impacts of polymer off-gassing on ionization potentials that facilitate arc plasma discharges. Additionally, recent work has also discovered new classes of nano-ceramic polymers which self-extinguish arcs and abate the resultant fire.	Olga Lavrova (olavrov@sandia.gov)	NL- Sandia National Laboratories	4. Module Prototyping and Accelerated Durability Testing	Within one year, Sandia will work with interested collaborators to analyze and test fault and/or fire risks in their products. Within 5 years, Sandia will be able to help partners design solutions which reduce or emilinate fault and fire risks from their products.	
54	Fracture Mechanics in Highly Controlled Environments	This advanced testing capability, presently utilized to facilitate the qualification of nuclear materials under strict NQA-1 standards, enables elevated temperature fatigue, creep-fatigue, and crack growth testing as well as static exposures of materials in highly controlled environments to study the cyclic failure resistance, fracture mechanics, stress relaxation, and corrosion behavior of materials and components. Servo-hydraulic and a servo-electric frames have been equipped with gas-tight chambers, in some cases with integrated precision gas delivery systems, to feed a simulated environment at specific partial pressures. Mass flow and pressure controllers regulate the gas flow and pressure, respectively. This allows the ability to perform cyclic and stress relaxation tests while operating in several control modes including strain-, load-, and stress-control and to test specimens at highly accurate temperatures of up to 1000 °C. It has a gas chromatograph and two solid-state hygrometers to record the gas chemistry at the inlet and outlet of the chamber and continuous feedback of the partial pressure of water is employed at the inlet hygrometry. The gas delivery system combined with the continuous feedback allows the water content to be controlled at various levels to ppm accuracy. Similarly, the test environment in the crack growth servo-electric frame can be precisely controlled at temperature as high as 1100 °C. An inert gas flow loop is also part of this suite of equipment and is used to study the static corrosion behavior of materials in a variety of environments. Materials can be exposed to oxidizing, carburizing, reducing, and decarburizing environments for long periods of time at temperatures as high as 1000 °C in a closed-loop, feedback controlled system that pre-mixes the gas composition.	Mark Carroll - (208) 526-8104, mark.carroll@inl.gov	NL - Idaho National Laboratory	4. Module Prototyping and Accelerated Durability Testing	Materials and component selection in demanding environments requires accurate screening and evaluation methods in order to facilitate both advanced modeling and simulation capabilities and eventual deployment in commercial systems. An analysis of the underlying degradation mechanisms are often highly dependent upon accurate test protocols and approaches that can simulate not only complex stress states, but also highly controlled environments that can have crucial effects on mechanistic response. Specialized fixturing setups for component-level testing of multi-material systems would provide a powerful capability when coupled with the advanced systems at INL that were devised for qualification of candidate nuclear materials.	
55	Accelerated Ageing Reliability Models	PV Systems and Module Materials Reliability: Accelerated Ageing Experiments Combined with Physics-Based Predictive Models Sandia has developed universally recognized models to predict the effect of materials degradations on PV component reliability and performance. For example, TurboSiP, a thermal mechanical fatigue model predicts degradation and failure of solder joints (e.g. electrical components, module conductor ribbons, junction box interconnects, etc.). Combined with accelerated ageing protocols, failure analyses, and data from partners, the tools can be expanded to study a variety of degradation modes in connectors, micro-inverter components, TCOs, and EVA. TurboSip is finite-element based, includes mesh generation, and predicts solder joint ageing and crack propagation based on package geometry, materials properties, and thermal cycling conditions. Models used to predict reliability must be easy to implement, and they must be at least physics-informed. They are often empirical or phenomenological rather than first principle models, and are often applicable only to a specific situation. To develop a model, we first determine the appropriate failure mechanism and stresses that activate that particular mechanism. Accelerated testing using those stresses provides degradation information that can be incorporated in the model. Often the contributing stresses include elevated temperatures (85oC), damp heat (85% RH), and thermal cycling. Additional stresses could include vibration, shock, electrical stresses, and corrosive species, requiring special test capabilities such as mixed-flowing gas atmospheric corrosion capabilities. We would work in close collaboration with partners to ensure the identification of correct failure mechanisms, which are investigated (with actual hardware when available) using appropriate forensic analysis tools such as electroluminescence spectroscopy, Scanning Electron Microscopy (with Electron Back Scattered Diffraction and Energy Dispersive Spectroscopy), and Multi-STEM to obtain microstructural/atomistic information about the degradation phenomena. The end product is understanding and models that can be used to characterize and predict reliability of specific hardware.	Rob Sorensen	NL- Sandia National Laboratories	4. Module Prototyping and Accelerated Durability Testing	1 Yr.: Develop partnerships that provide initial data on package geometry, materials properties, and environment conditions in order to populate model parameters and generate finite element meshes. 5 Yr.: Successfully predict degradation and failure modes that suggest next-generation geometries and materials for increased durability.	
56	Comprehensive loss analysis for PV cells	PV cell characterization is a critical step that bridges cell and module manufacturing. It is an opportunity to detect problems, quantify losses, and learn more about the part of the module that actually produces energy. Our measurement and analysis capabilities enable researchers to locate where losses occur, quantify their impact, identify root causes, and offer possible corrective actions. In industry, the illuminated current-voltage (I-V) curve of all cells is collected. While this remains the most important measurement one can do, it only tells so much. Our approach relies on a suite of metrology techniques, including: illuminated and dark I-V; Suns-Voc; external and internal quantum efficiency; electroluminescence (EL) and photoluminescence (PL) imaging; TLM-based contact resistivity; and optical imaging. Our team has developed innovative methods of performing spatially-resolved measurements of numerous device parameters (e.g., short-circuit current, open-circuit voltage, series resistance, saturation current density, ideality factor, cell efficiency) and the ability to decouple specific loss mechanisms based on spectral or spatial signatures. And more important, our team has experience working with numerous PV cell architectures and has developed the analysis tools to interpret these complex data sets.	Kristopher O. Davis, Ph.D.	AI- Florida Solar Energy Center	4. Module Prototyping and Accelerated Durability Testing	For PV cells, a near term success would be to create better procedures for detecting potential reliability and/or durability defects during cell testing/sorting (i.e., before module manufacturing). A longer term success would be to implement these procedures on a host of different cell featuring alternative wafers, cell process steps, materials, and cell architectures. This could help accelerated cycles of learning and speed up the adoption (or rejection) of novel technologies.	
57	Comprehensive loss analysis for modules	The Florida Solar Energy Center (FSEC) provides a unique opportunity for partners to combine outdoor field testing of PV modules with periodic indoor characterization utilizing our advanced module characterization facilities. Along with industry standard measurement techniques such as flash testing at standard test conditions, our module characterization lab is focused on providing a comprehensive loss analysis for module performance. This involves high-resolution, calibrated electroluminescence techniques that provide quantitative results on cell and module performance. A Sinton FM-350 module flash tester provides detailed module performance metrics over a wide range of irradiance conditions, while also enabling accurate measurements for high efficiency module types. A LoadSpot™ tool from BrightSpot Automation enables dynamic mechanical loading capabilities while leaving the front side of the module free from obstruction to allow for in-situ electroluminescence imaging and I-V characterization. Our partnerships with Sinton Instrument, BrightSpot Automation, Tau Science and others allows for the flexibility to tailor existing infrastructure and to develop novel techniques to accommodate the needs of partners within DURAMAT. Our outdoor testing facility also provides partners with the opportunity to deploy samples in the hot and humid climate of Florida with detailed monitoring of electrical performance and relevant meteorological data, including a full range spectroradiometer. Advanced monitoring through in-situ I-V curve tracing could also be utilized. Recent efforts at FSEC have focused on the ability to process in-situ I-V data to provide real-time feedback on module degradation. Our comprehensive module test facility is intended to provide partners with infrastructure and expertise to quickly evaluate module design modifications in terms of electrical, mechanical, and optical performance and reliability	Eric Schneller	AI- Florida Solar Energy Center	4. Module Prototyping and Accelerated Durability Testing	Module - mechanical testing - creating mechanically robust module design, contribution to testing standards, advancing quality assurance in the manufacturing line,	
58	Spherical Indentation Stress-Strain Curves	Our research group has pioneered novel analyses protocols that reliably and consistently extract highly meaningful indentation stress-strain curves from the raw datasets measured in instrumented spherical indentation experiments at length scales ranging from ~50 nms to ~500 microns. These indentation stress-strain curves have produced highly reliable estimates of the local indentation modulus and the local indentation yield strength in the sample, as well as certain aspects of their post-yield behavior, and have been critically validated through numerical simulations using finite element models. Much of this progress was made possible through the introduction of a new measure of indentation strain and the development of new protocols to locate the effective zero-point of initial contact between the indenter and the sample. This has led to an important key advance in this field where it is now possible to reliably identify and analyze the initial loading segment in the indentation experiments. Major advances have also been made in correlating the local mechanical response measured in nanoindentation with the local measurements of structure at the indentation site using complementary techniques such as orientation imaging microscopy (OIM) and Raman spectroscopy. These new research tools are expected to provide the critically needed microscale information for the maturation of physics-based multiscale models for the mechanical behavior of most advanced materials in an unprecedented high throughput manner.	Prof. Surya Kalidindi, surya.kalidindi@me.gatech.edu & Kevin Strong ktstrong@sandia.gov, Sandia	AI -Georgia Institute of Technology NL- Sandia National Laboratories	4. Module Prototyping and Accelerated Durability Testing	In the near term, this project will help establish essential tools for measuring reliably and consistently local properties of various metallic interconnects and packaging materials. In five years, tools developed will devleop and implement improved diagnostics and quality control systems for PV systems.	

59	Quantitative Fracture Mechanics Based Experimental Results for Lifetime Predictability	Sandia National Laboratories has a successful history of designing laboratory experiments and applying their results to long term predictive reliability of complex components. These experimental designs include both material testing to establish a database of material properties, but also designed experiments that represent failures that occur in real components, such as interfacial failure (e.g. glass-to-metal seals, ceramic brazes, and polymer films on brittle materials). Unexpected failures in photovoltaic (PV) devices typically occur at similar types of interfaces, in particular the tempered glass sheets delaminating from the underlying PV cell layer. This project aims to develop laboratory experiments that provide quantitative fracture mechanics based results to understand failure modes that occur during Accelerated Durability Testing. Accelerated testing allows for a qualitative approach to determine statistically how long a PV device will last. Thermo-mechanical simulations can also aid in understanding the stresses that are occurring prior to failure during accelerated testing; however, in order to truly predict the lifetime of a device it is necessary to have quantitative fracture mechanics based data that can assess whether 1) will a crack form under specific conditions and 2) if a crack already exists how long until it causes failure in the device. In addition, results from the proposed experiments will also feed into the data analytics library and provide necessary data to calibrate predictive simulations. The outcome of this project will provide insight into the long term reliability of a device and module design to achieve 30+ year service life.	Kevin Strong	NL- Sandia National Laboratories	4. Module Prototyping and Accelerated Durability Testing	The near term goals for this project would be to provide a quantitative and observational assessment on how and where cracks initiates representative of a real failure in a PV device. In addition, valuable material property and quantitative interfacial mechanics data will be provided to the PV module database. The long term goals would be to have experiments that would aide in predictive lifetime reliability. This will aide in the design and material selection of the PV module to prevent fracture from occurring and in production, as to determine what is the failure criteria during inspection.	