DuraMAT "Reliability Forecasting" Lab Core and Spark Projects Request for Proposals (RFP)

Submit proposals adhering to the template and page limits to DuraMAT@nrel.gov by:
11:59 pm MT, Friday, June 2nd[h], 2023

Additional information about the DuraMAT Consortium can be found at: https://www.duramat.org/

DURAMAT BACKGROUND

The DuraMAT Consortium brings together DOE national lab and university research capabilities with the photovoltaic (PV) and supply-chain industries to accelerate a sustainable, just, and equitable transition to zero-carbon electricity generation by 2035 through our five core objectives: development of a central data resource for PV modules, multi-scale and multi-physics modeling, disruptive acceleration science, forensic tools for fielded modules, and materials solutions for more durable, reliable, and resilient modules. DuraMAT leverages the decades of experience, expertise, and world-class facilities at the national laboratories to create a "one-stop-shop" for timely solutions to critical barriers limiting module reliability and durability. In its first five years, DuraMat has become a trusted partner for the US industry.
The core objectives have been defined in partnership with DuraMat's Industry Advisory Board (IAB) along with long-term research objectives that are expected to continue through DuraMat 2.0 (see www.duramat.org).

The program's core objectives are focused on ***the DuraMAT goal of accelerating a sustainable, just, and equitable transition to zero-carbon electricity generation by 2035*** *by addressing these two questions:*

1. *Which materials and module designs will enable sustainable, high-energy yield 50-year modules, and how do we ensure that these new modules are not going to fail prematurely?*
2. *What triggers wear out, defined as a rapid increase in degradation at end of life, and what are the characteristics, rates, and mechanisms of long-term degradation in PV modules?*

The DuraMAT Consortium is currently divided into five core objective areas: Central Data Resource, Multi-Scale, Multi-Physics Modeling, Fielded Module Forensics, Disruptive Acceleration Science, and Materials Solutions. Descriptions of these core objectives are available at https://www.duramat.org/core-objectives.html.

TECHNICAL BACKGROUND FOR THIS CALL

This call is for two types of proposals pertaining to reliability forecasting. Full proposals are intended to be 2 - 3 year efforts, starting October 2023 and ending by the end of September 2026. "Spark" proposals are shorter proposals with a 6-9 month time frame. More information on budget period and expected award amounts for each type of proposal can be found later in this document.

DuraMAT seeks proposals for projects that will enable us to build a capability for **"reliability forecasting", which we define as the ability to predict degradation and failure rates without prior knowledge of how a material, design, interface component, or module performs and degrades.** New PV technologies are evolving so rapidly and being deployed in such widely varying locations that we can no longer rely on historical data as a primary indicator of future reliability. Reliability forecasting differs from standard accelerated testing protocols in several ways:

1. Forecasting is primarily forward looking and focused on recently deployed and newer technologies where historical projections are likely inaccurate.
2. Forecasting efforts start from fundamental research questions about how a material, interface, component or module will change in the use environment over many years. Forecasting does not start with field observations of wide scale problems after deployment.
3. Forecasting studies may focus on whether or not an observed phenomenon is or will become a degradation or failure problem. This includes latent defects from manufacturing and damage during use.
4. Forecasting seeks to quantitatively predict changes over long lifetimes rather than screen out known weaknesses based on prior observations.
5. Forecasting requires the capability to develop scaling relationships between things that have already been studied for longer times and those that are newer.
6. Forecasting requires rapid validation without waiting years for traditional field validation.

This core proposal call focuses on the development of capabilities that enable reliability forecasting. These may include new accelerated testing approaches that can assess new materials and designs and quantitatively predict their degradation/failure rates over time without years of fielded history. Most existing accelerated tests focus on identifying known module or material failure modes that have been previously observed in the field. This has been an extremely effective way to reduce early failures and screen for known weaknesses. However, PV module and cell technology is evolving at an unprecedented rate as the industry scales to meet the demands of energy transition. The industry has already seen multiple issues in newly deployed technology (backsheet cracking, UV-LID, LeTID, PID, thin glass cracking, etc.) that were not detected by accelerated tests based on past observations. We are moving into a world where historical data is an insufficient indicator of present and future performance. The growth rate of the PV industry also motivates us to develop quantitative predictive testing degradation and failure mechanisms, rather than pass/fail detection of weaknesses.

DuraMAT is moving towards a "physics of failure" approach based on individual degradation mechanisms, material properties, interfacial properties, climate-relevant stresses, mass transport, and chemical reactions that can be used to build reliability forecasting capabilities. Stated differently, DuraMat is aiming to build mechanistic rather than phenomenological measurements and models of degradation to predict degradation rates, failure rates, and wear out. Example degradation rates over time are shown in Figure 1a, which shows that a product output undergoes a slow, nearly constant, degradation early for the majority of its life, then degrades quickly as wear out sets in. This behavior is shown for a range of product lifetimes, with short service life products shown in red, and long service life products shown in green., Figure 1b) illustrate the same stages in terms of failure rate, rather than output, where failure is defined as the inability of the module to safely produce the expected amount of power. This is frequently described as a "bathtub curve" for a hypothetical PV module. This type of curve is often generated from a combination of two Weibull functions representing early failure and wear-out with some random failure rate throughout the useful life. Wear out is defined as the point in time where intrinsic degradation mechanisms accelerate and failure rates increase sharply. The service life is usually defined as the period of time between deployment and the onset of wear out. Previous successful implementation of reliability standards and testing protocols reduced the "early failure" rate in PV modules, which produces the asymmetrical curve in Figure 1b. Degradation rates are often measured and modeled using individual analytical physical or chemical rate expressions such as Arrhenius (thermal), Eyring, non-thermal stress models, Fick's law diffusion, stress/strain relationships, adhesion energies, photocatalysis, or electrocatalysis. Failure rates are generally described using statistical or probabilistic distributions such as Weibull, hazard curves, mean time to failure, defective parts per million, or T50/T90. Quantifying and understanding degradation and failure require extensive lab experiments, modeling, field data, and characterization. DuraMAT is particularly interested in studies that will lead to quantitative prediction of the fundamental physical degradation processes at all life stages and the onset of wear out, including which degradation phenomena drive wear out.

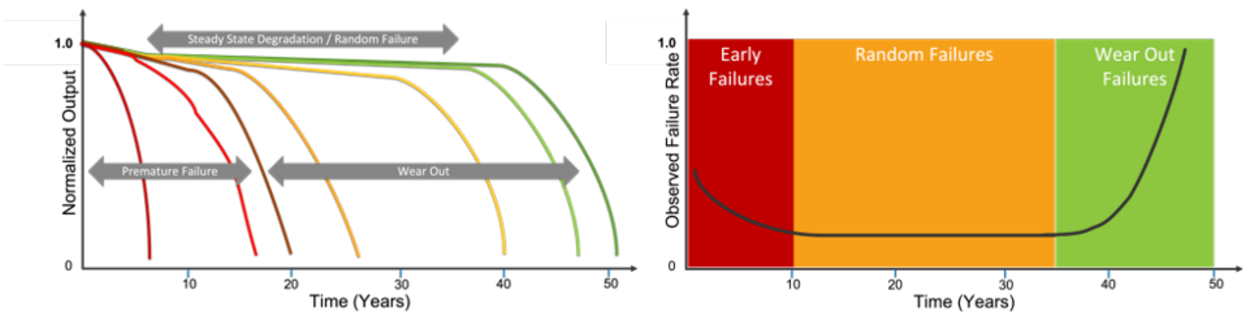

Figure 1: (a) Degradation rate of a hypothetical product output over time with wear out occurring early (red), at current expected PV module lifetimes (yellow), and at targeted 40-50 year lifetimes (green). (b) Observed failure rates for a PV module over time with low early failure rates due to standards testing and sharp wear out curve at 40 years.

Reliability forecasting requires a set of interconnected testing, modeling, characterization, and analysis capabilities that eventually yield an overall prediction. Individual experiments or models may focus on one or several physical, chemical, or degradation mechanisms. Interconnection of the experiments and models allows for the prediction of failure modes and their implication on module performance and/or lifetime. For example, a testing and characterization project focused on metallization corrosion may consist of experiments that are capable of measuring moisture ingress, reactant transport, reactant formation, corrosion reactions, and eventual metallization failure mechanisms. A complementary project may focus on modeling these processes at different time and length scales. Experimental and modeling results could then be validated with "top-down" approaches by comparing the prediction results with field observations, modeled predictions, and other data. DuraMAT expects a mixture of "top-down" studies and "bottom-up" studies in the portfolio. Each can focus on either a specific stressor, material or interface property, mechanism, or failure mode, but when incorporated into a larger forecasting capability needs to contribute to a more complete understanding of degradation and failure rates over time.

DuraMAT is not requesting complete service life prediction models under this budget and timeline. Instead, we are requesting proposals for accelerated testing, materials and module forensics, advanced data analytics, and/or models that can be integrated with model chains to leverage work done by multiple groups and institutions to collaboratively build reliability forecasting capabilities. The proposed projects may follow the "model chain" approach used for Predictive Modeling[1] where individual mechanism-based

[1] https://doi.org/10.1002/pip.3645

models are linked in a larger modeling framework for a holistic assessment of PV module reliability.

Individual mechanistic studies can be difficult and time-consuming, therefore it is essential to develop such capabilities in parallel and to include methods to effectively collaborate and share results between projects so that they can be interconnected in the future. More specifically, proposers should describe how their work addresses a key question in accelerated testing that is currently missing from standards and existing tests, develops predictive testing capabilities derived from field relevant conditions, provides and leverages predictive modeling data, or contributes to material, stress, or mechanistic property libraries. This does not mean that projects must use the same accelerated testing approach or samples, but it does encourage researchers to develop connections between projects where useful.

Proposed work should drive toward long-term forecasting of degradation and failure rates. Proposals including experimental studies including accelerated testing and test development, characterization of degradation mechanisms, and material/module characterization are encouraged. Supporting modeling and data analytics components may include rate modeling, probabilistic failure models, mechanical models, chemical reaction models, development of non-thermal rate equations, and field data analytics for validation. Proposed work may also include equipment design/development, forensics technique development, software to make data publicly available and human readable, and creation of publicly accessible dashboards or calculations tools or open source software.

Examples of this kind of work from previously awarded projects include:

1. Correlation of Advanced Accelerated Stress-Testing Procedures with Field Data through Advanced Characterization and Data Analytics, https://www.duramat.org/accelerated-stress-testing-procedures.html
2. PV Module-Level Solutions for Degradation by Ionization Damage, https://www.duramat.org/ionization.html
3. Rapid Reliability Prediction of Emerging Module Interconnect Technologies With Combined-Accelerated Stress Testing https://www.duramat.org/rapid-reliability-prediction-cast-testing.html
4. Degradation Pathways in Glass/Glass Bifacial PV With Emerging Encapsulants and Half-Cut Cells, https://www.duramat.org/degradation-pathways-bifacial-pv.html
5. Direct Imaging of Stress in Crystalline Silicon Modules, https://www.duramat.org/direct-imaging-stress.html

Aspects of reliability forecasting other than those listed above may be in scope, provided that such work represents a clear step towards a capability for reliability forecasting.

PROPOSAL SCOPE AND AIMS

Degradation or failure in a complex system can result from multiple physical processes, which may be independent or may interact. A failure mode is the physically apparent product of a failure. For example, in a PV module, delamination, grid corrosion, or voltage loss are failure modes. A failure mechanism is the underlying physical cause that produces failure modes a failure mode. For example, formation of a boron-oxygen defect is a degradation mechanism that causes voltage loss. A failure mode, can be the direct result of a single or a combination of degradation mechanisms. Degradation mechanisms are described by physical, chemical, thermodynamic or other processes that ultimately result in a failure mode, e.g., creep, fracture, corrosion and so forth. **Proposals under this call should focus on degradation mechanisms rather than previously observed failure modes.** Observed field failures may be a useful validation tool, but they should not be the focus of the proposal. Proposals may also take a proactive approach, such as investigating potential reliability risks and packaging needs of new technologies before large scale deployment.

Figure 2 summarizes some common themes from recent workshops, publications, presentations, and discussions with the DuraMAT Industry Advisory Board about reliability forecasting research needs. The crux of the problem is that we have a lot of lagging indicators in the form of field failure, but very few leading indicators that modules or materials will perform well in the field. Related to this problem is that lagging indicators may not translate to new materials or module designs as readily as mechanism-derived leading indicators. DuraMAT is interested in studies that can help reduce that "lag" by developing leading indicators which provide quantitative information on degradation and failure before deployment. Examples of leading indicators are understanding multi-step, multi-physics degradation/failure mechanisms and developing scaling relationships that enable extrapolation from mechanisms we currently understand to new module technologies we plan to deploy.

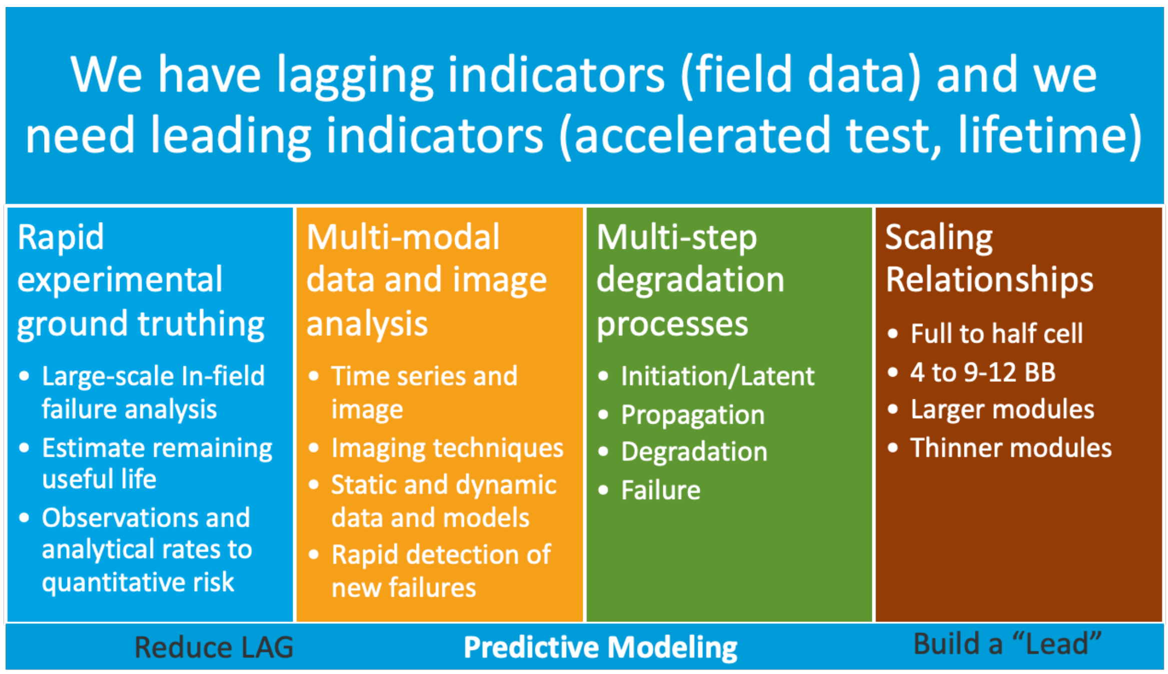

Figure 2: Research needs for reliability forecasts based on input from the DuraMAT Industry Advisory Board and workshop participants

DuraMAT is open to studies at different scales as shown in Figure 3, which shows the range of samples that could be relevant and some of the scaling relationships between different sample/test article types that could be used for experimental studies, modeling, and validation. Material coupons may be used to study bulk degradation rates under individual or combined stresses. Coupon testing has very high throughput at low cost, but the data can have low fidelity or direct relevance to fielded module performance. Some mechanisms may require custom test structures (e.g. a solder bump test)[2] to get field relevant combinations of stresses and interfaces. Single encapsulated cells or mini-modules can be used for studies that use cells as "sensors" of degradation or of complex heterogeneous reactions. Increasing

[2] M. Kempe, T. Lockman, J. Morse, "Development of Testing Methods to Predict Cracking in Photovoltaic Backsheets," Proc. of the IEEE PVSC 46, 2019

sample complexity to mini-modules and full-size modules increases the fidelity of the test results to commercial product performance, but at higher cost and much lower throughput. All of this can be done before commercialization and purchase/deployment. At the opposite extreme, huge PV system and fleet datasets are available, occasionally with additional imaging and characterization. However, learning from these complex and noisy datasets is challenging. Proposals for this call are encouraged to have substantial efforts at the sub-module (coupons, test structures, encapsulated cells, min-module) or module levels, shown in Figure 3, with system and fleet data used for validation.

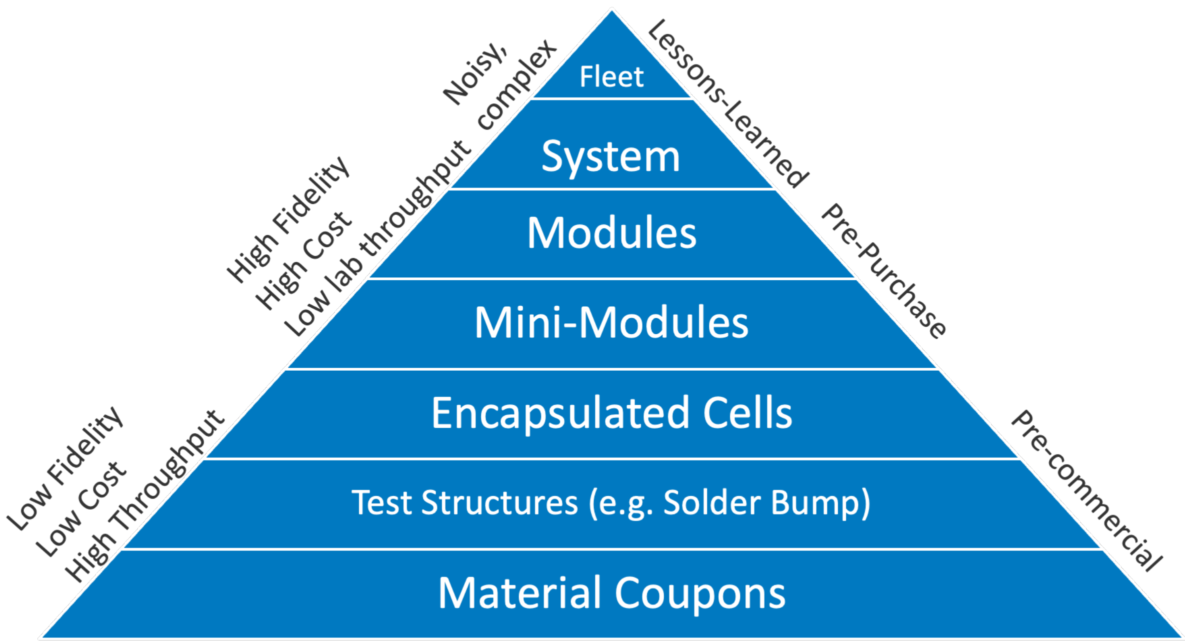

Figure 3: Scaling relationships between sample sets used in reliability studies. Sample sets can vary from isolated material coupons to packaged devices and mini-modules to commercial products and systems. Forward looking work is concentrated towards the lower portion of the pyramid. .

Successful proposals will identify relevant modes and mechanisms that can result in degradation and describe which mechanisms, physical/chemical properties, or stresses will be studied. They should describe how the proposed work will result in an improvement in our abilities to predict degradation and failure indicators, including the onset of wear out, or indicators that materials, designs, or modules will be reliable in the field. Proposals should describe how results could eventually be used to address the DuraMAT goal and key questions on page 1 – include existing and missing pieces. They will also include a plan to use the DataHUB to store and share data.

PROPOSAL ELEMENTS (see proposal template for formatting details and page limits)

PROPOSAL TYPE

DuraMAT is soliciting two types of proposals during this call: full project proposals (2 – 3 year efforts) and "Spark" projects (6 – 9 month efforts - $65k). The Spark projects are expected to have a well-defined final project deliverable. These efforts are expected to support the larger DuraMAT reliability forecasting goals, but they may address the topic tangentially. Examples of Spark projects include, but are not limited to:

- Building a publicly accessible web, DuraMat data hub (https://datahub.duramat.org), or Github-based tool from an existing study that is currently proprietary or inaccessible (*e.g.*, exists only in a desktop spreadsheet).
- Creating a simple material, stress, or reaction model that is needed quickly
- Experimental or data driven validation work
- Extending an existing model, test, or characterization approach to include a new material, stress, interface, etc.

FORECASTING PROBLEM STATEMENT

- Define your project in terms of the specific degradation mechanism your work will address and briefly describe the materials and stresses involved in the mechanism. Be specific about which materials and stresses will be addressed in your project.
- Document the relevance of this mechanism in current and emerging commercial modules. DuraMAT prioritizes research on issues relevant to high energy yield modules for utility commercial, and residential applications.
- Describe the effect of the degradation mechanism on future fielded performance, including the risk factors that make modules susceptible to this mechanism, probability or frequency of occurrence, ability to detect, and impact on performance. DuraMAT prefers proposals that address the degradation rates or failure probabilities shown in Figure 1 and show how the study improves our ability to quantify lifetime, degradation, or failure more quickly.

TECHNICAL APPROACH

- Clearly describe the experimental, modeling, and/or characterization aspects of the work and how they will add to our understanding of lifetime and degradation.
- Describe how your approach addresses your problem statement or key research question and how it addresses the challenges identified in Figure 2.
- Document the expected results – Is this a new test, an interfacial adhesion model, reaction mechanism, validation study, etc? How can the results be used?
- Document available input data from other projects and how your output data could be used in a future lifetime prediction effort. Include references to complementary or related work.
- Describe the specific mechanisms under investigation and the relevance current and emerging commercial modules. How can your work be leveraged for future technologies?
- Describe why you have chosen your test samples, stress testing, or characterization approach and how they are relevant to current and emerging module technologies. Does this experiment answer your research questions?
- Describe how you will make your results publicly available including material, mechanism, or stress libraries, test data, or documented code libraries and APIs if applicable
- Describe the data that will be included in the datahub
- Describe how your work will help DuraMAT meet its goal of developing confidence in 50 year modules by forecasting early failure, useful life, degradation, or the onset of wear out related to the phenomena you study.

DATA SHARING

All project proposals are required to include a plan to submit FAIR-compliant data to the DuraMAT datahub[3]. Periodic data submissions to the data hub are a requirement for DuraMat funding. Proposals for development of new software tools must include open-source development and release with full documentation and an example or demonstration data set for use. Modeling aspects of proposals relying on proprietary or commercial software packages must commit to sharing methods, input data, boundary conditions, output data, *etc.* so their work can be replicated using alternative software packages to the extent permitted by license conditions. For example, projects using commercial finite element analysis software may opt to use tools such COMSOL Application Builder, PyAnsys, or similar packages.

EXTENSIBILITY/DISSEMINATION PLAN

Successful proposals will be expected to have a mid- to long-term impact on addressing the DuraMAT goals by answering the DuraMAT questions, leveraging the results and capabilities of DuraMAT to date, and creating effective links between core objectives at the national laboratories. The proposed approach and problem statement should be clearly justified (e.g. how/why was this problem chosen). A dissemination plan for the project should be described in the proposal, including a description of how others can use your work, model, or data without working with you. Studies are expected to be foundational with a clear path for next steps. Proposals must have a well-defined work plan with clear yearly milestones and deliverables. Proposals are encouraged to include industry participation and should address problems or challenges identified as longer-term research needs by the PV industry.

Proposals should include a short description of how their work could be used in a larger lifetime prediction effort or combined with other work to study more complicated questions requiring sequential or combined stresses, validated material models, or additional degradation models.

CURRENT STATE OF THE ART & DURAMAT CONTEXT

Describe the current state of the art in the area of your proposed work and the current state of this field in DuraMAT. Is this a new area for the consortium or is it a continuation of or complement to existing work? Describe how the proposal will leverage the DuraMAT Network, the strengths of your project team, and how feedback from workshops or the IAB have informed the proposal.

If needed describe how this proposed effort is differentiated from the research in other current or past SETO-funded projects (e.g. SETO Lab Call/Core, PVRD, PREDICTS, etc.).

Eligibility

Proposals must have a National Lab PI from a DuraMAT core partner lab (NREL, Sandia, or LBNL) or core participant lab (SLAC) and are strongly encouraged to consider partnerships with DuraMAT core participant Universities (Stanford University (SU) and Arizona State University (ASU)). Proposals may include team members from industry, national labs, academia, etc. as subcontracts, but at least 70% of

[3] FAIR Principles at GO FAIR https://www.go-fair.org/fair-principles/

the funding must stay within the DOE national laboratories. More information on working with DuraMAT can be found at https://www.duramat.org/working-with-us.html. Cost share is encouraged, but not required for this proposal call. Collaboration or coordination with other SETO programs (e.g. reliability core, PV proving grounds) is encouraged.

Proposal Format

Proposals must be submitted using the appropriate Word and 2-slide summary templates attached to this email and available at www.duramat.org.

Full Proposals:

Full proposals are **strictly limited to six pages, not including the cover pages and appendix, plus a 2-slide summary using the attached templates**. The first four pages should describe the project goals, approach, dissemination plan, and impact on the current state of the art. The final two pages should include the technical workplan, milestones, and industrial relevance. All proposals should have an appendix that includes references, 2-page resumes, letters of support, and current/pending support info, which do not count towards the page limit. A template for current/pending support can be found at the end of the template document. **No technical or project information outside of the page limit will be considered. Any proposal content in excess of the page limit will be removed before the proposals are sent to review**.

Spark proposals:

These abbreviated proposals are strictly limited to 3 pages (including references), plus a 2-slide summary using the attached templates. No additional supporting documentation is required (e.g., please do NOT include separate References, 2-page resumes, letters of support, or current/pending support info).

Proposal Evaluation

Submitted proposals will be screened for adherence to the above guidelines and relevance to the targeted DuraMAT critical outcomes. Proposals that meet these criteria will be reviewed by technical experts on the DuraMAT Industry Advisory Board using the following criteria. Any members involved in a proposal will recuse themselves. Each proposal will be considered based on the following metrics:

TECHNICAL MERIT (70%)

- How effectively does the proposal address the **DuraMAT goal** of *accelerating the transition to zero carbon electricity generation by 2035* by answering one or both of these questions:
    - Which materials and module designs will enable sustainable, high energy yield 50 year modules, and how do we ensure that these new modules are not going to fail prematurely?
    - What triggers wear out, defined as a rapid increase in degradation at end of life, and what does long term degradation look like in PV modules?
- What is the potential impact of this work on the **DuraMAT Goal** identified above if it is successful?
- Which mechanism(s) does the proposal address and what is the relevance of the mechanism(s) in forecasting the reliability of high energy yield modules?
- Does the proposal clearly identify a research question or problem statement and its relevance?
- Does the proposal clearly identify a method to address that research question or problem statement and expected results?

- Does the proposal improve our ability to quantify degradation rates, failure probabilities, or identify "successes" in the form of more durable or reliable modules?
- Does the proposal clearly describe the current and future field relevance of the work?
- How will the results be made publicly accessible? Is this sufficient for industry adoption?
- Which public data sets or tools will be made publicly available?
- What is the likelihood that this research would be effectively leveraged by DuraMAT collaborators in the solar industry?
- What is the plan for stakeholder engagement to use this research or build on the results from this work?
- If the proposed work is unsuccessful, what can DuraMAT or the PV community learn?

ORGANIZATION AND EXECUTION (30%)

- Is the work plan clearly articulated and effective in achieving the goals of the project?
- Are the milestones and deliverables clearly articulated and appropriate?
- Does the proposal describe how the project leverages or engages ongoing or previous work and progress towards the DuraMAT goals? How does it fit into the DuraMAT ecosystem?
- Does the proposal include a data plan that includes providing data meeting FAIR standards (www.go-fair.org/fair-principles/) to provide data sets and/or analysis tools to the DuraMAT datahub?
- Does the proposal include an effective dissemination plan to ensure that the results reach appropriate stakeholders?
- What is the likelihood of the proposed work to succeed based on the budget and work period proposed?
- Does the team have the skills and resources necessary to build this capability?
- For proposals including characterization does the proposal provide a clear plan for obtaining relevant samples. This might include a plan to fabricate samples from available materials, in-kind partnerships, or sourcing commercial modules or materials.
- Does the proposal complement current DuraMAT work? How is it differentiated from existing SETO projects and how does it compare to the current state of the art?

Proposal Selection

The DuraMAT industry advisory board (with additional technical experts approved by SETO If needed) will review proposals according to the merit criteria above. The DuraMAT Leadership Team will make programmatic recommendations based on those rankings to SETO, and the DOE SETO program manager will have final selection authority. DuraMAT anticipates making selections in Summer 2023 for work starting in October FY24.

Total Award Funding for this up to: $2,600,000 for 1-2 full projects and 1 – 3 Spark projects.

Estimated project funding: Full projects: $825,000 per year for up to 3 years. Spark projects: $65,000 for up to 9 months.

If selected for award PIs will be responsible for submitting a budget package, completed website template, and 2 slide project summary.

Reporting requirements include quarterly reporting slides, quarterly milestone/accomplishments tracking, reporting of data and/or analysis tools to the DuraMAT datahub, and participation in one (for spark projects) and two (for full projects) DuraMAT workshops per year for the duration of the project.

Travel to the two annual workshops is required for full proposals. Travel to workshop is required for sparks. All projects are required to upload data to the DuraMAT DataHub and work with the data team to ensure full compliance with open data requirements.

Please plan for these requirements in your budget.