



# Thermal-mechanical-electrical model for PV module-level mechanical failure mechanisms

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**Energy Efficiency &  
Renewable Energy**

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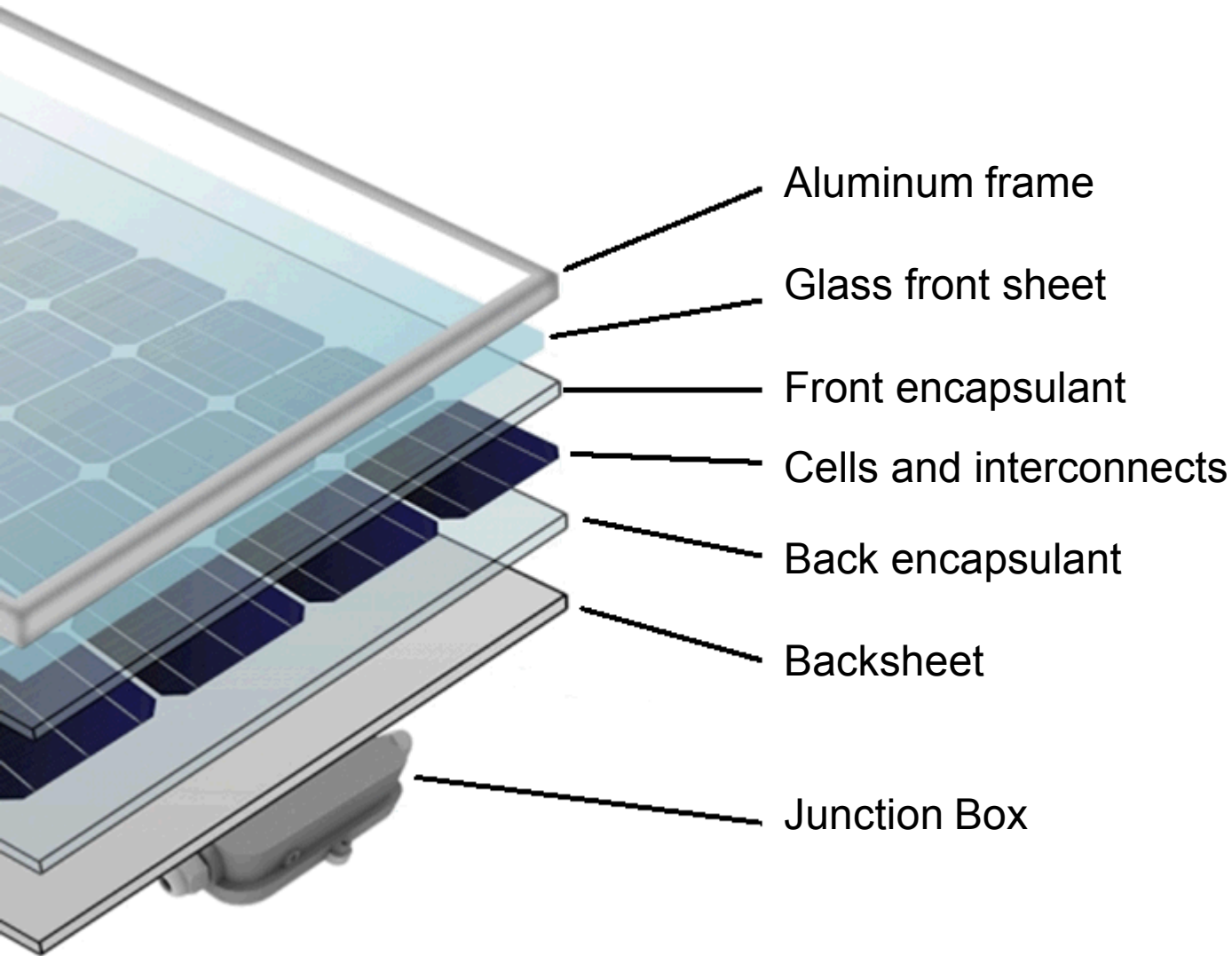
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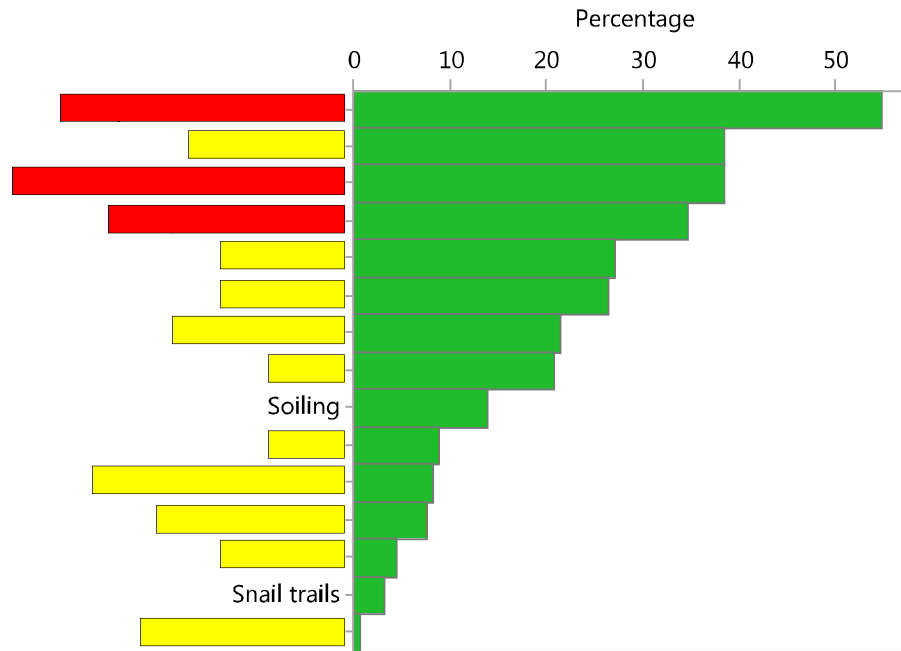
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- PV modules and degradation mechanisms
- Design questions to be answered with modeling
  - Benefits of a module-level model; existing capabilities; previous efforts
- Model validation capabilities
- Capability development plan

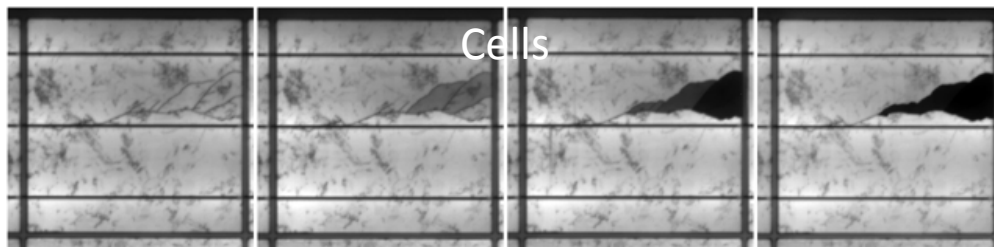
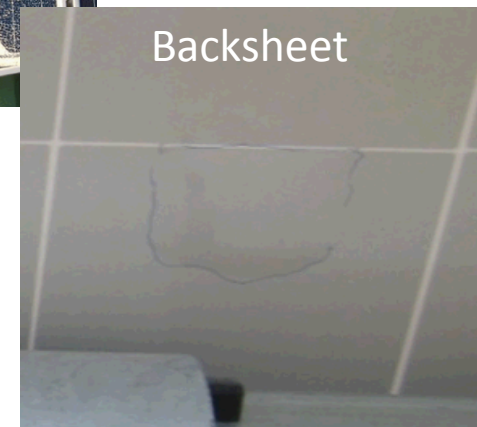
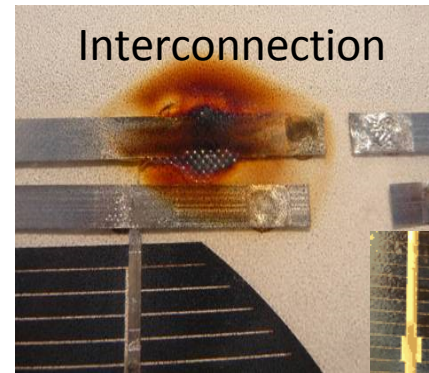
## **DuraMAT Capability Area 2: Predictive Simulation**

“This capability will be a suite of modeling and simulation tools, model workflows, and a community of experts who work in concert with experiments and data analytics... to help interpret and enrich existing test/experimental data, design durability-testing experiments, and help create design rules for Materials Discovery”





PV failures and degradation modes reported in literature





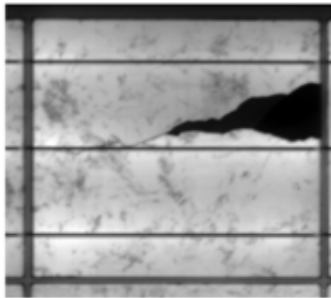
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What is the driving force for delamination between layers?



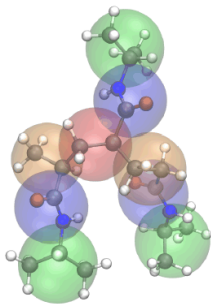
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What environments are most damaging?

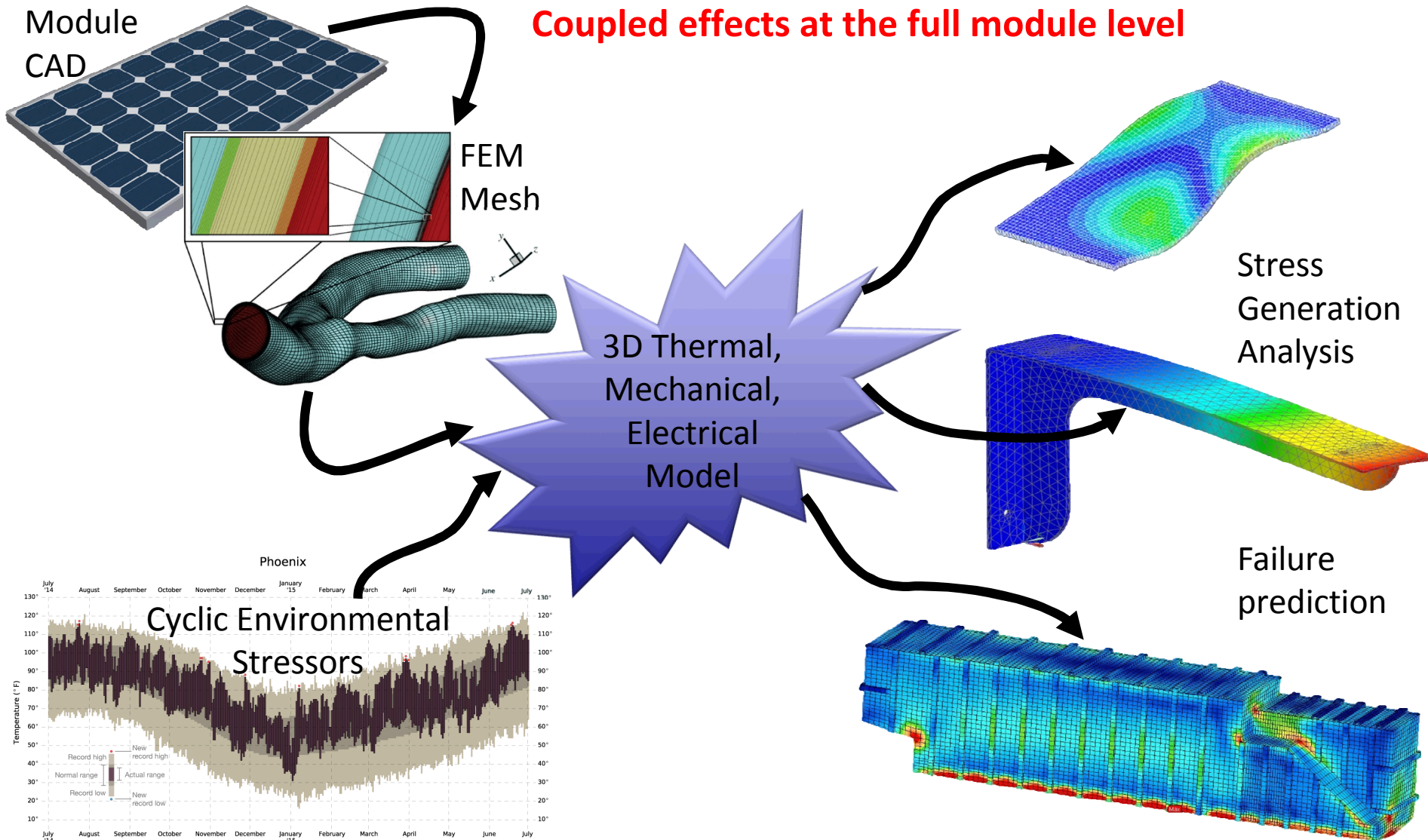
What would the ideal material properties of an encapsulant be to avoid cell cracking and delamination?

?



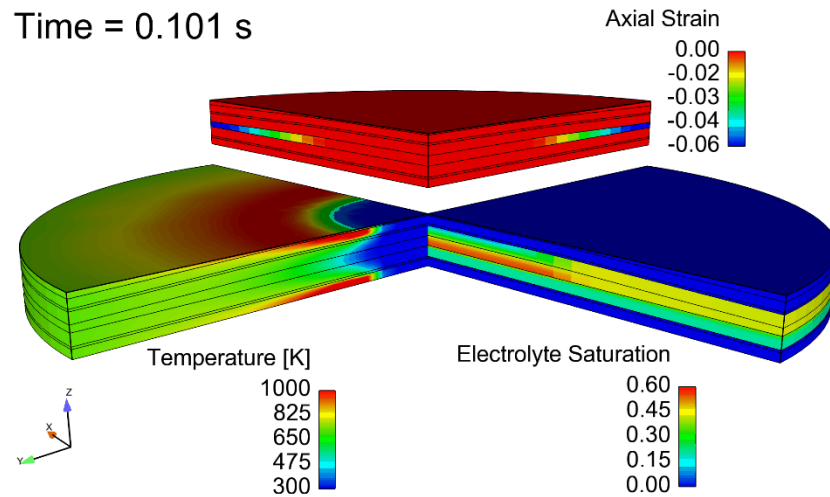
Are we *really* capturing a lifetime of exposure in accelerated tests?

?

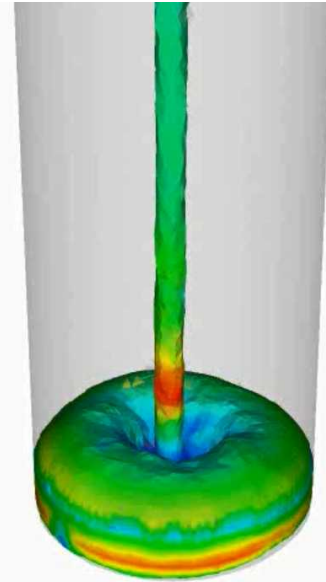


# 3D thermal-mechanical-electrical modeling capabilities

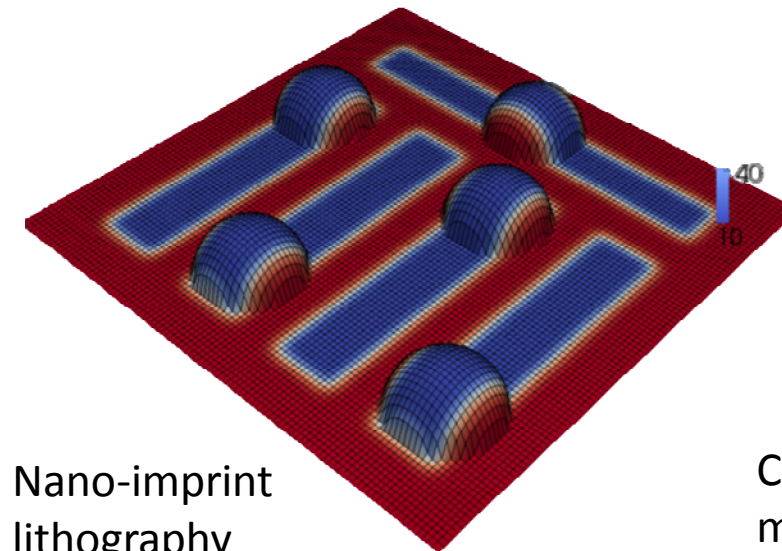
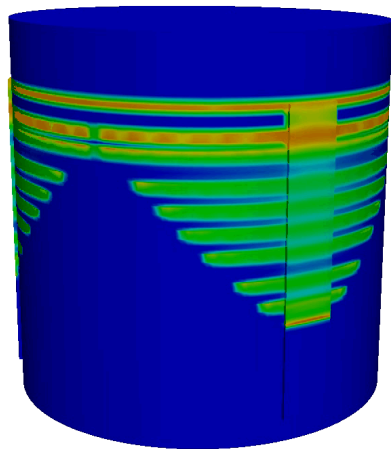
Time = 0.101 s



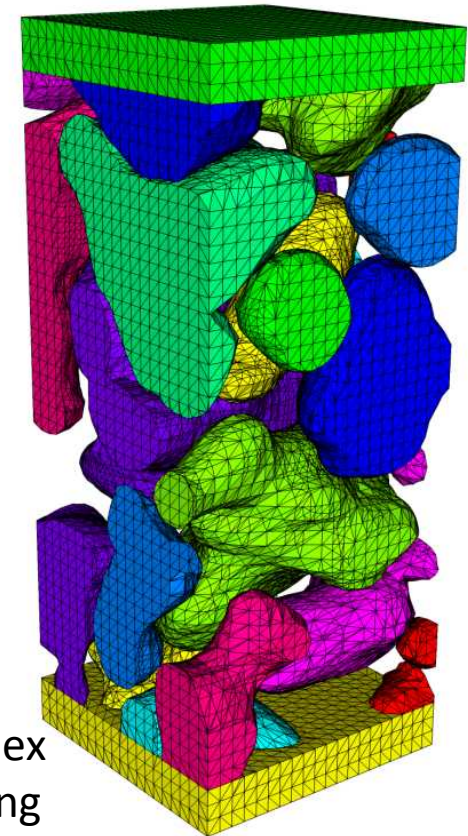
Molten salt  
batteries



Constitutive  
modeling:  
non-Newtonian,  
visco-plastic,  
elasto-plastic

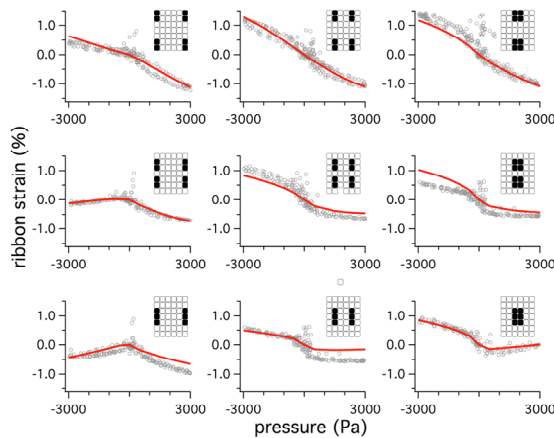


Nano-imprint  
lithography

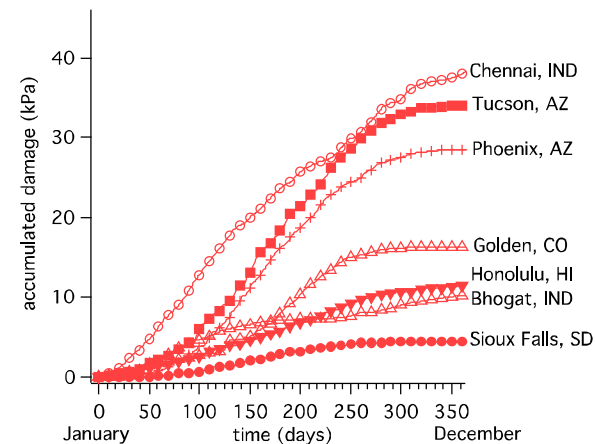


Complex  
meshing

- 3D model of a flat plate PV module to simulate interconnect ribbon strain for module level loading
- 2D model of a flat plate PV module to simulate accumulation of solder thermal fatigue damage through outdoor deployment



Cell-to-cell ribbon strain vs. position in module



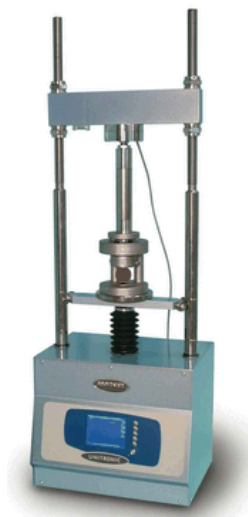
Damage rate vs. Geographical Location

- Results have elucidated:
  - Equivalency between mechanical test conditions and a 30 year exposure
  - What climate conditions drive fatigue damage rate

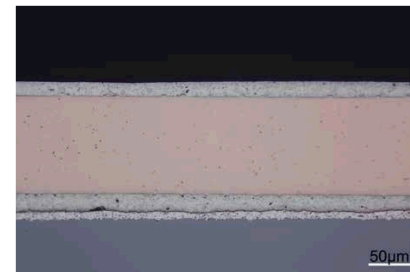
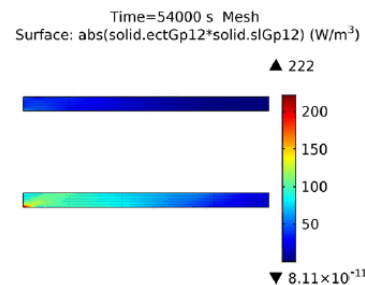
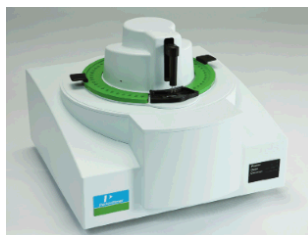
**With existing modeling capabilities, much more is possible!**

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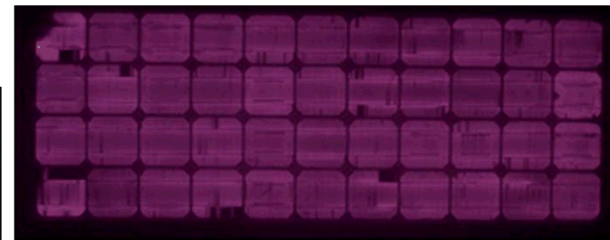
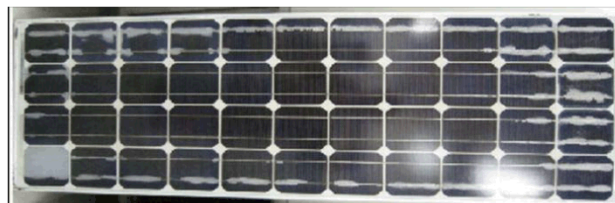
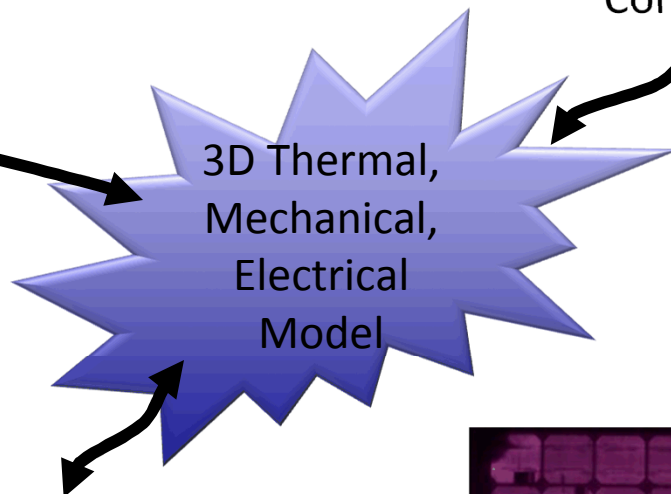




Materials characterization



Component scale validation



Module-level test data



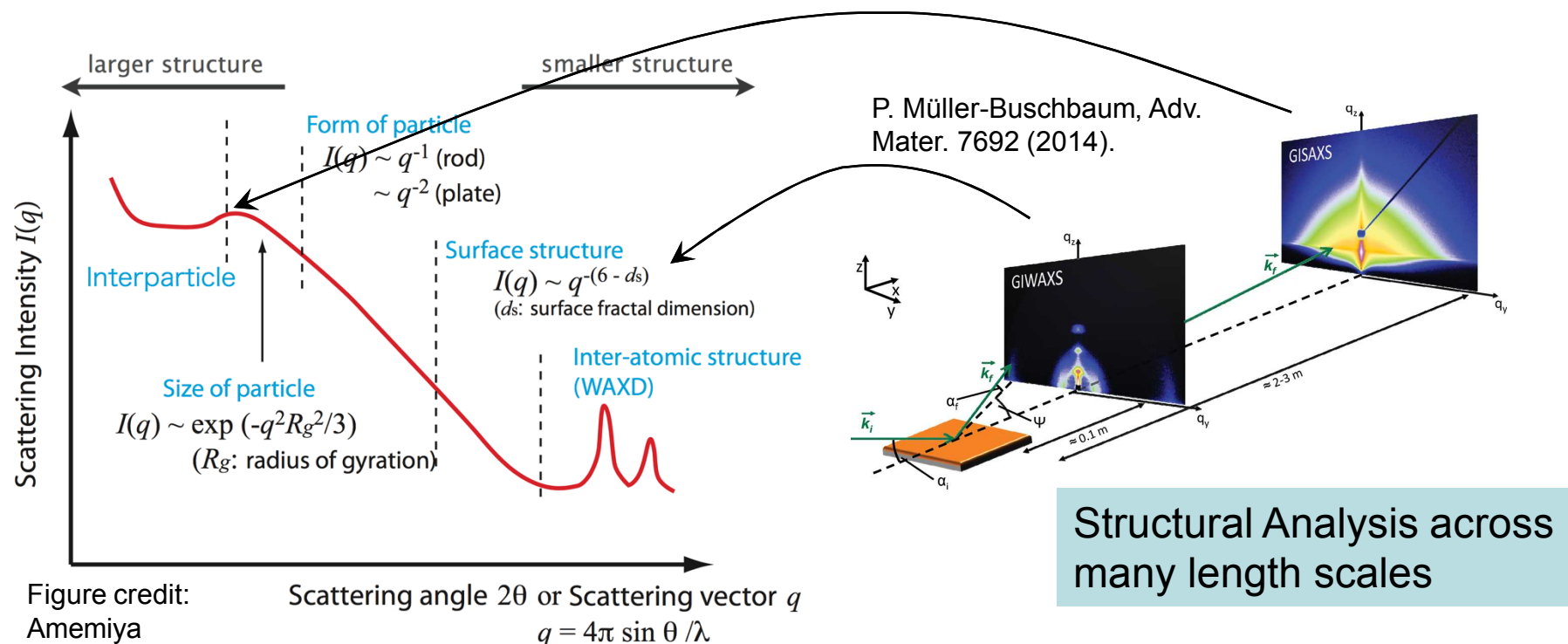


Figure credit:  
Amemiya

## Operando Structural & Microstructural analysis

- Understand the effects of aging & thermal cycling
- Applied stressors:
  - Atmosphere
  - Humidity
  - Temperature
  - Light
  - Electric field bias
  - Mechanical loading

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- Scope problem
  - Define the problem (nominal geometry and materials, types of stressors to include)
  - Scope the simulation (single model or coupled workflow? What are key degradation mechanisms to target?)
  - Identify property needs
- Build constitutive models
- Component-level modeling
  - Build model capability for critical components
  - Validate component-level models
- Module-level modeling
  - Combine component concepts into module-scale model workflow
  - Validate against real-world module data

- Capability Area goal is “[a suite of modeling and simulation tools and a community of experts, available to DuraMAT partners and industry/academia teams]”
  - Sandia will stand up and maintain the simulation code and capability
  - Intermediate results to be published and disseminated to the community of practice
  - Intent is for all Sandia modeling expertise to be available to the DuraMAT network
  
- Collaboration opportunities exist:
  - DuraMAT Solicitation of Letters of Interest
  - Sandia-specific avenues
    - Cooperative Research and Development Agreement (CRADA)
    - Strategic Partnership Programs (SPP); Work For Others (WFO)



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