SAND2021-12670C

Sandia National Laboratories

Exceptional service in the national interest

Relating Photovoltaic Module Stresses to Encapsulant Thermomechanics

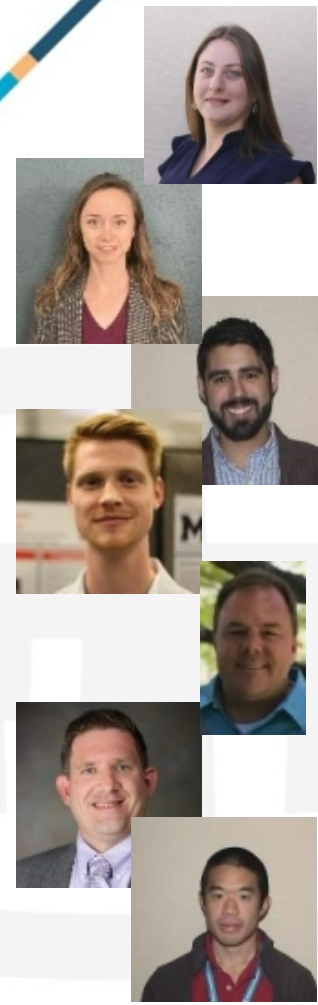
Christine C. Roberts, Ashley M. Maes, Anthony McMaster, Matthew Phillips, Charles Robinson, Scott A. Roberts, James Y. Hartley

ccrober@sandia.gov

October 12, 2021

Society of Rheology Annual Meeting

Virtual Session



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

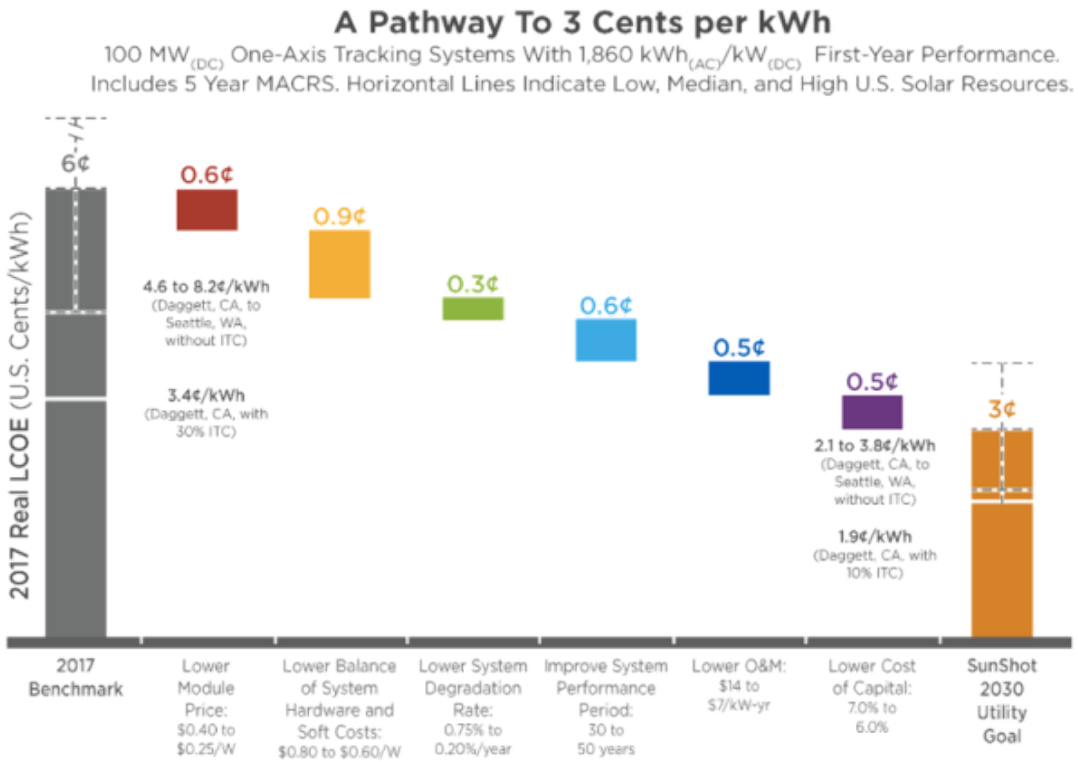
PHOTOVOLTAIC MODULE DURABILITY

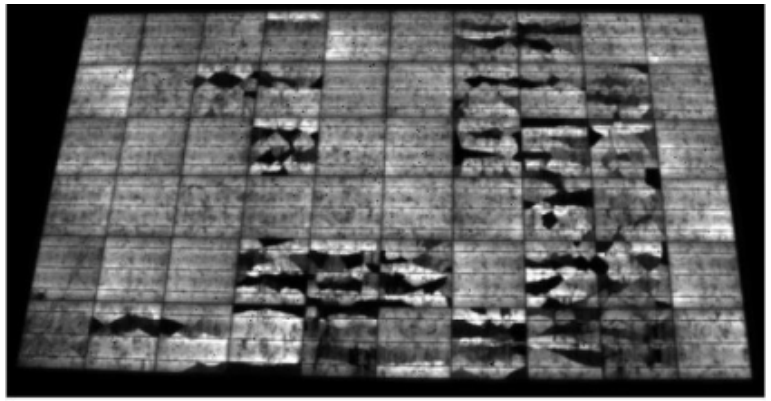
Biden administration memo September 2021:

Solar power can be 45% of nation's energy by 2035

PV Module Economics:

- Industry driven by $/W where ~1/2 cost is in packaging
- Goal: 3¢ / kWh by 2030
- Typical warranty: 80% power after 25 years

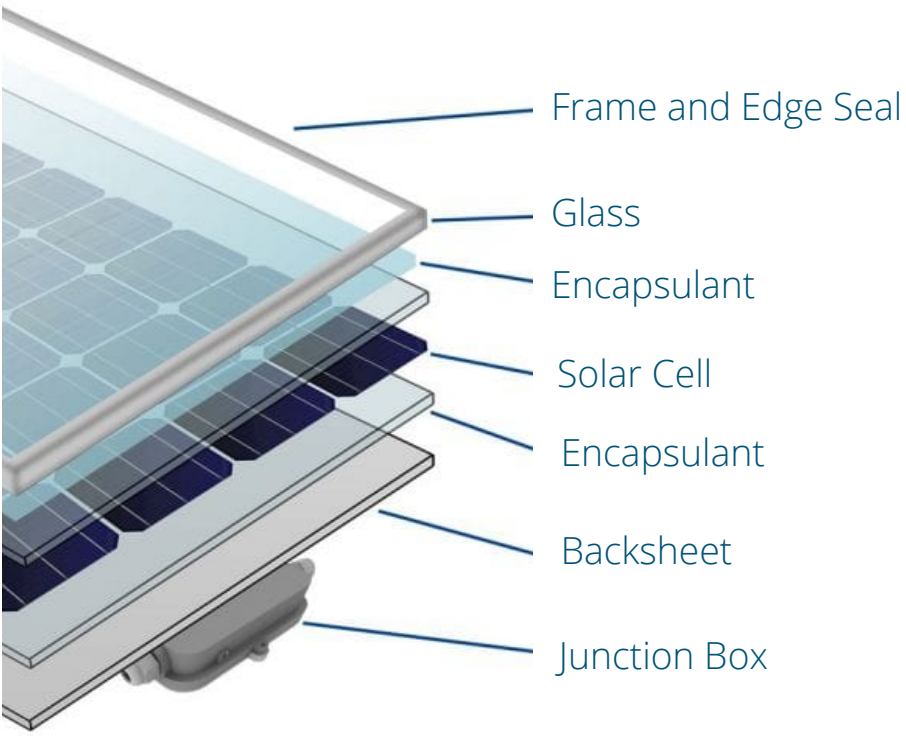




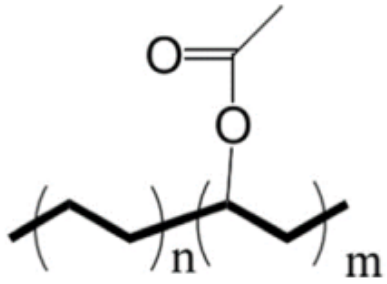
Electroluminescence image of a PV module shows cell damage
Guada, 2020 Energy Science and Engineering

Animals are used to control weeds around PV installations
https://www.youtube.com/watch?v=R0F7JYAr8IU

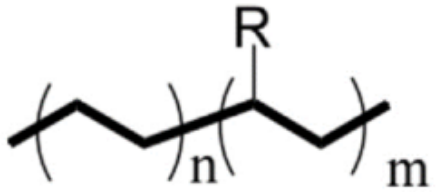
POLYMERS PROTECT PV MODULES



Layers of a typical silicon PV module



EVA (Ethylene Vinyl Acetate)
~30% vinyl acetate
Crosslinked - peroxides



R= -CH_3 ,-$(CH_2)nCH_3$, others

POE (Polyolefin)

Encapsulants

Laminated under heat, vacuum

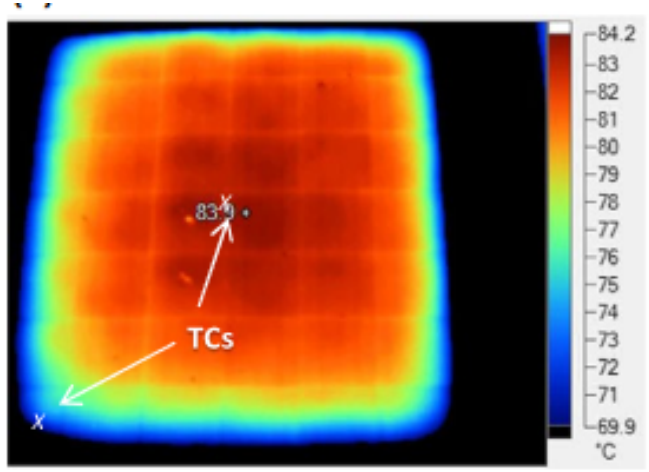
New design concepts: glass-glass, frameless, thin-film, bifacial, glassless
Reduce $/W through advances in packaging

FAILURES OCCUR IN PACKAGING

Polymers provide adhesion between layers, protection from water, and electrical isolation

Transparency critical for function

Stressors: Water, Wind loads, Temperature, Electric Fields, Animals, UV aging…



IR measurements of modules installed in Arizona show internal T's can reach >90C
Kempe *et al.* 2015

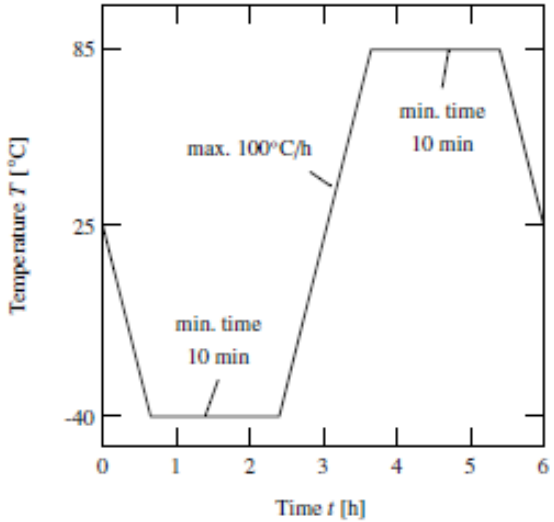
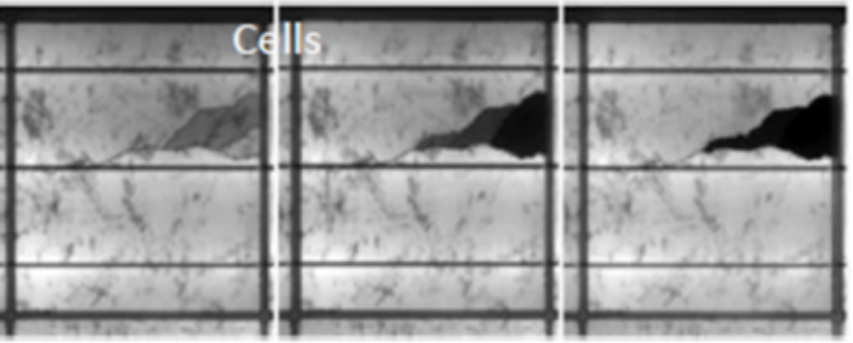
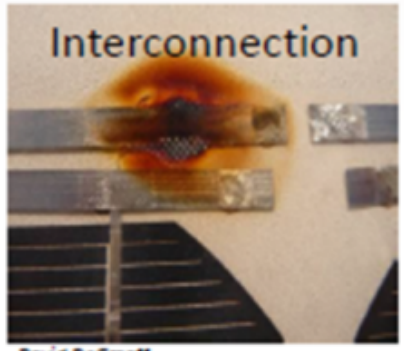


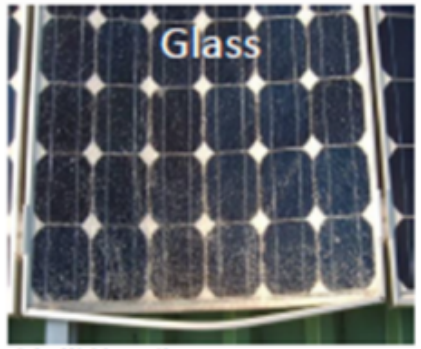
Fig. 29.2 One cycle of the temperature cycling test according to IEC 61215

Eitner, 2011

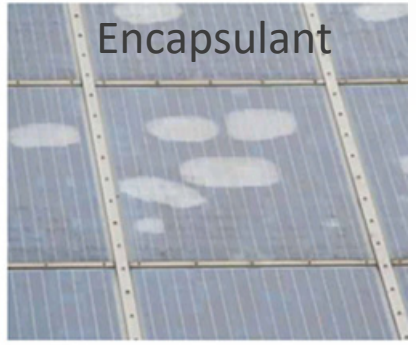




David DeGraaff



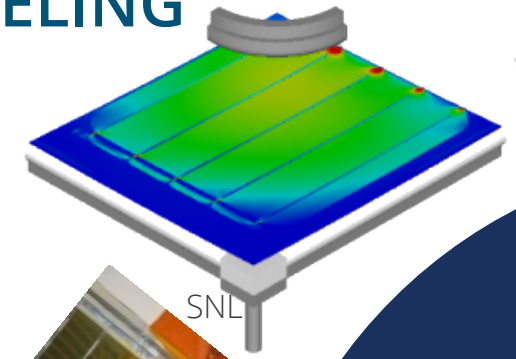
John Wohlgemuth



DuPont

DOE DuraMAT consortium established between NREL, SNL, LBNL, SLAC, others

ACCELERATE DESIGN CYCLES THROUGH COMPUTATIONAL MODELING

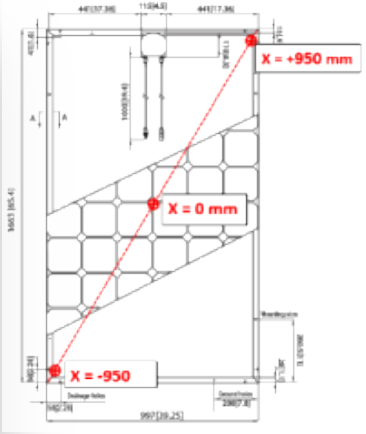


SNL

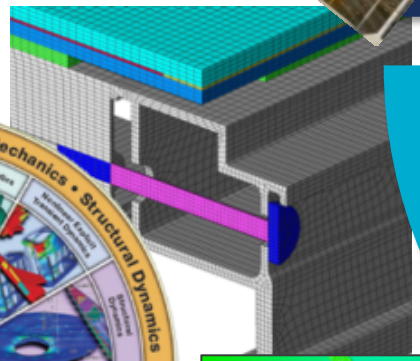
NREL

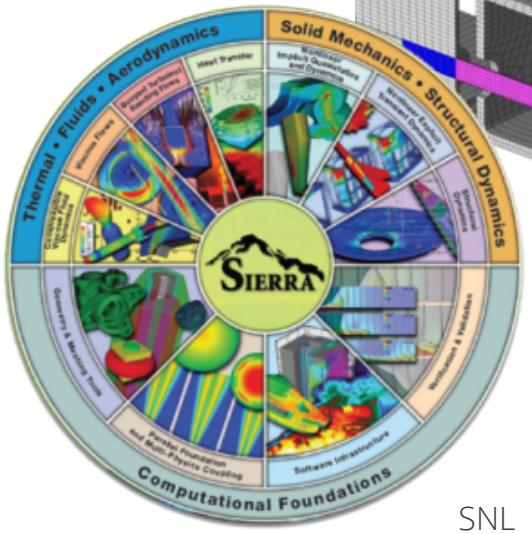
Validate

Design

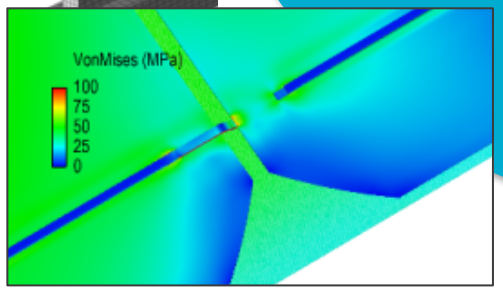


SOLARTECH UNIVERSAL



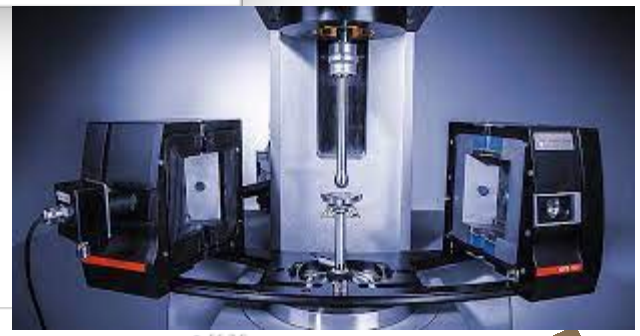


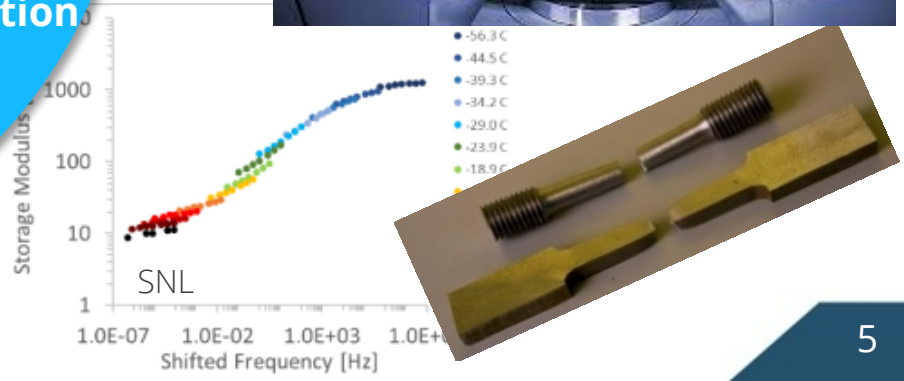
Computational Model



SNL

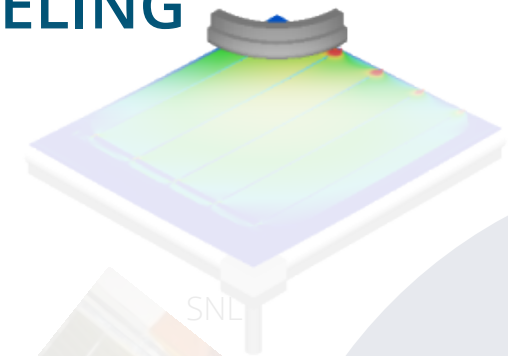
Materials Characterization



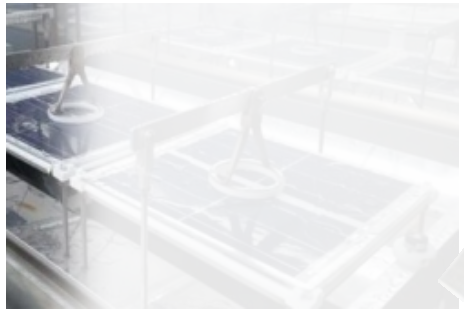


SNL

ACCELERATE DESIGN CYCLES THROUGH COMPUTATIONAL MODELING

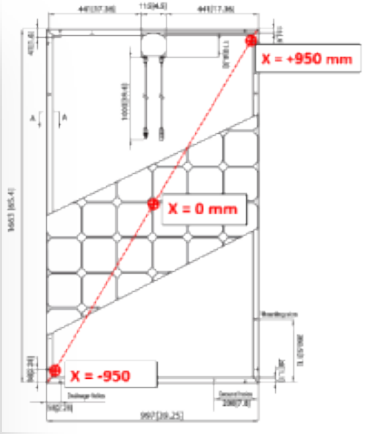


SNL

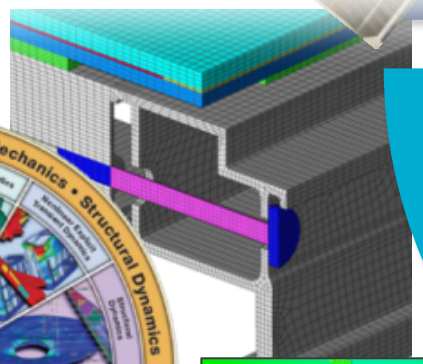

NREL

Validate

Design

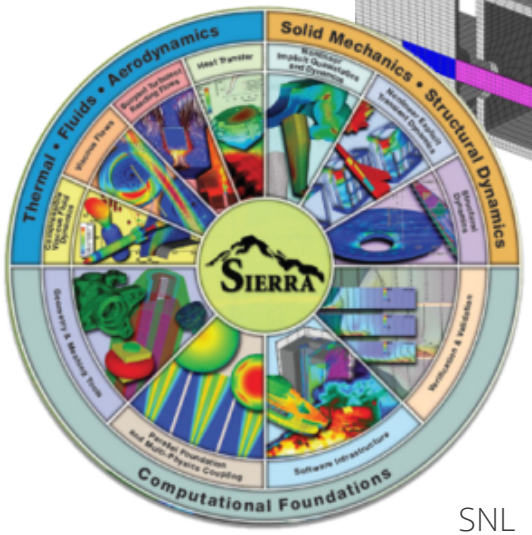


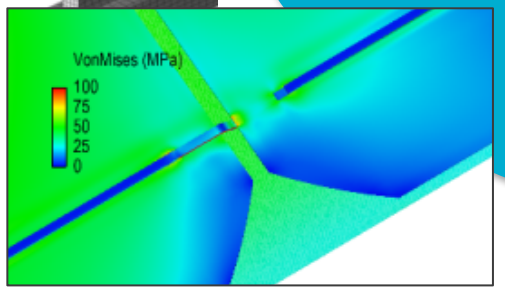
SOLARTECH
UNIVERSAL



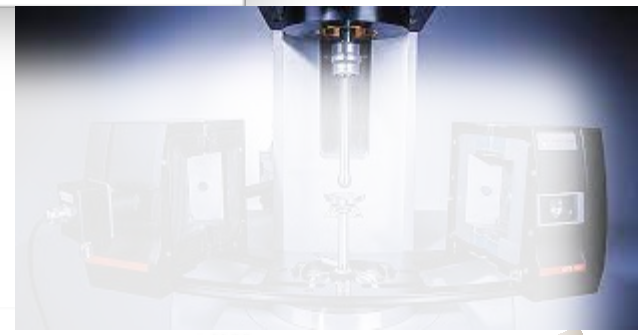
Computational Model

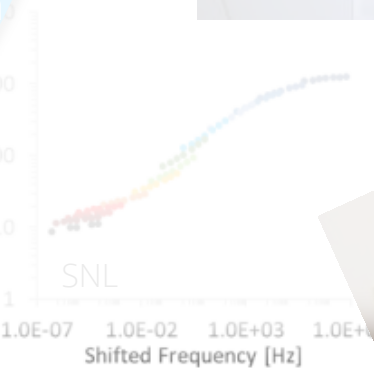
Materials Characterization





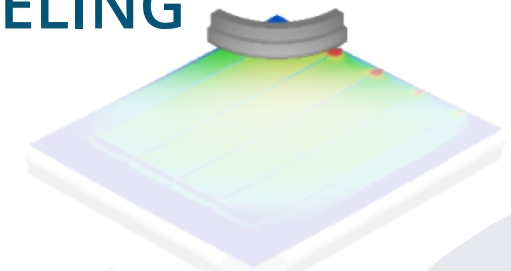
SNL



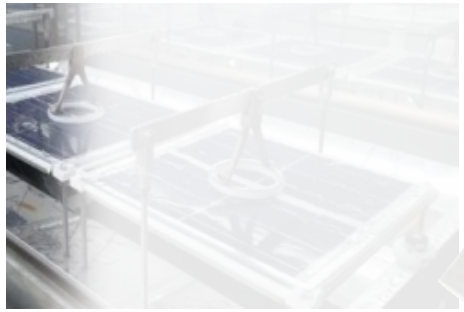


SNL

ACCELERATE DESIGN CYCLES THROUGH COMPUTATIONAL MODELING



SNL



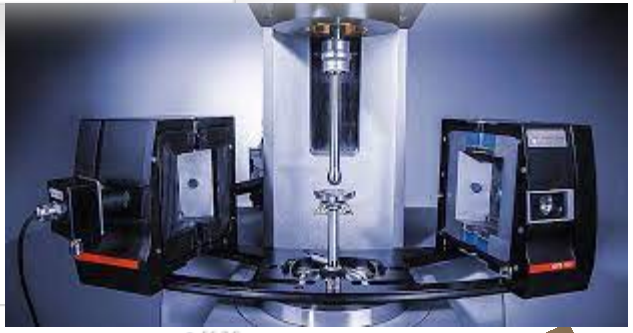
NREL

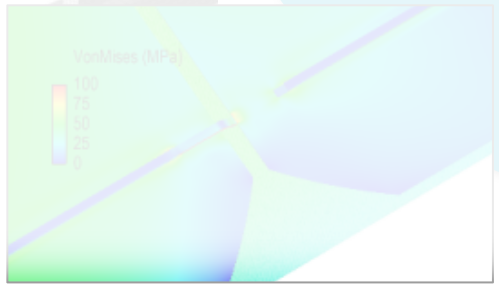
Validate

Design

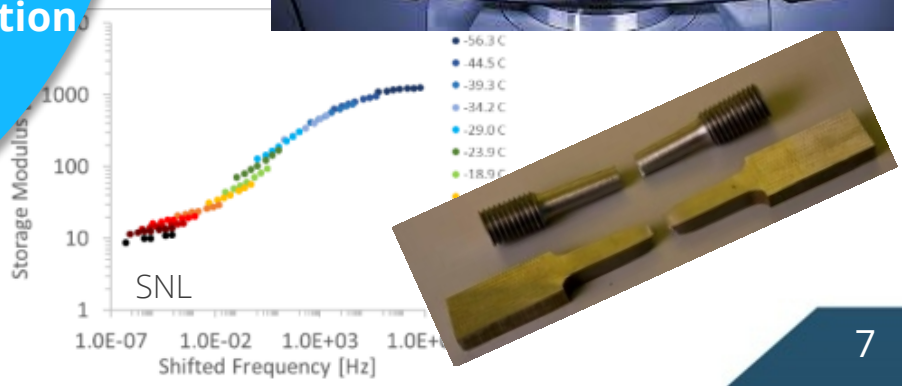
Computational Model

Materials Characterization



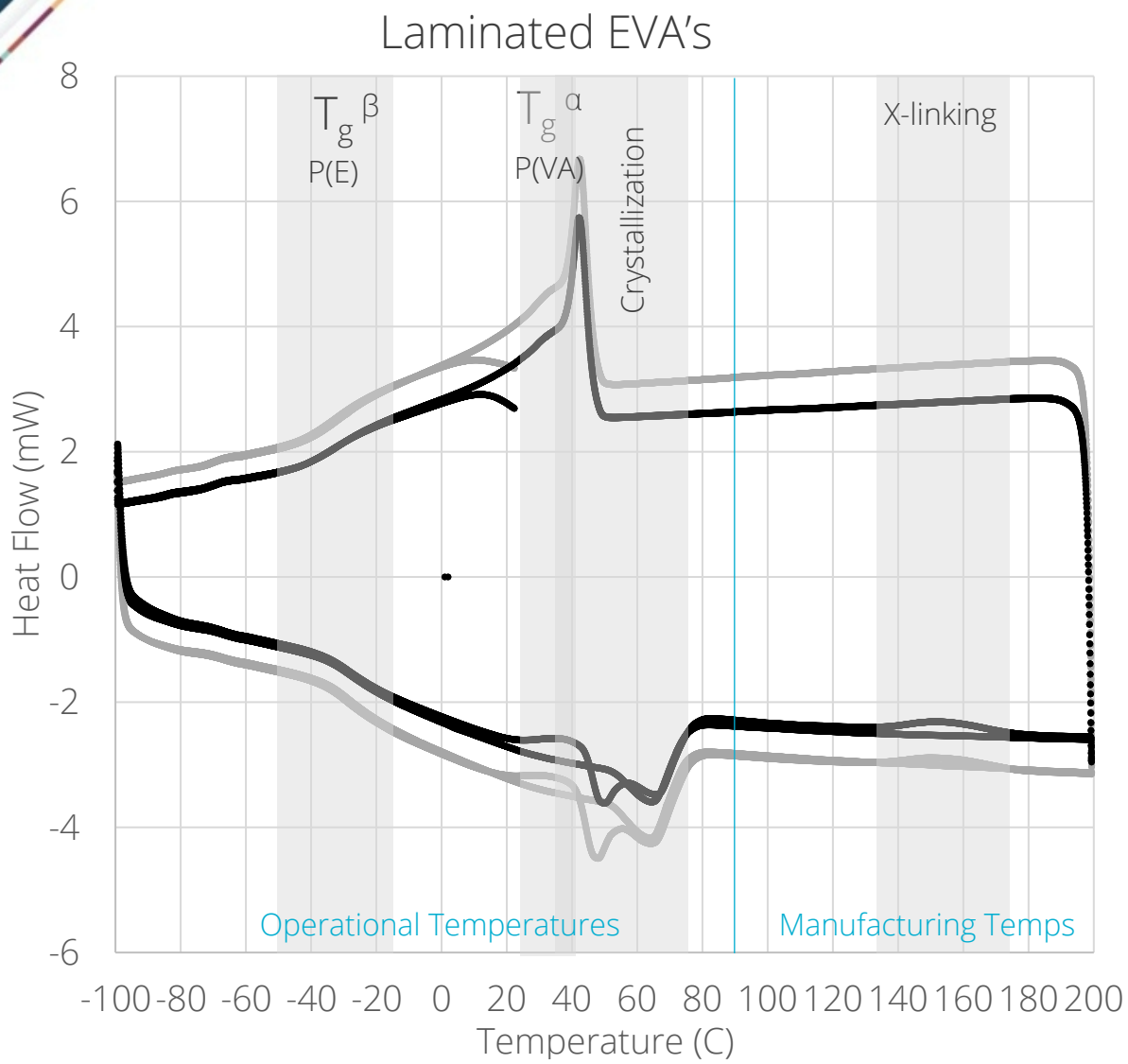


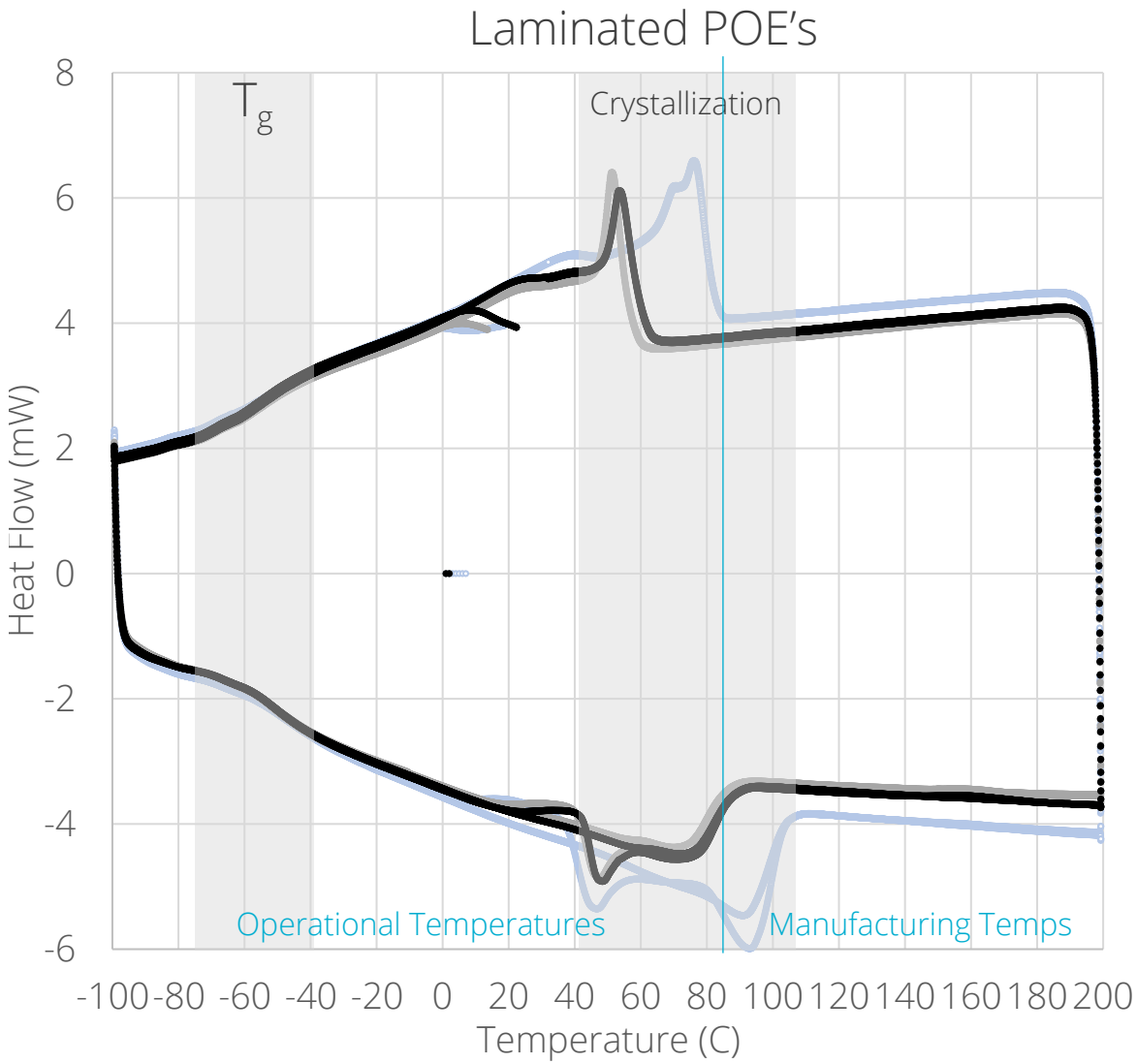
SNL



SNL

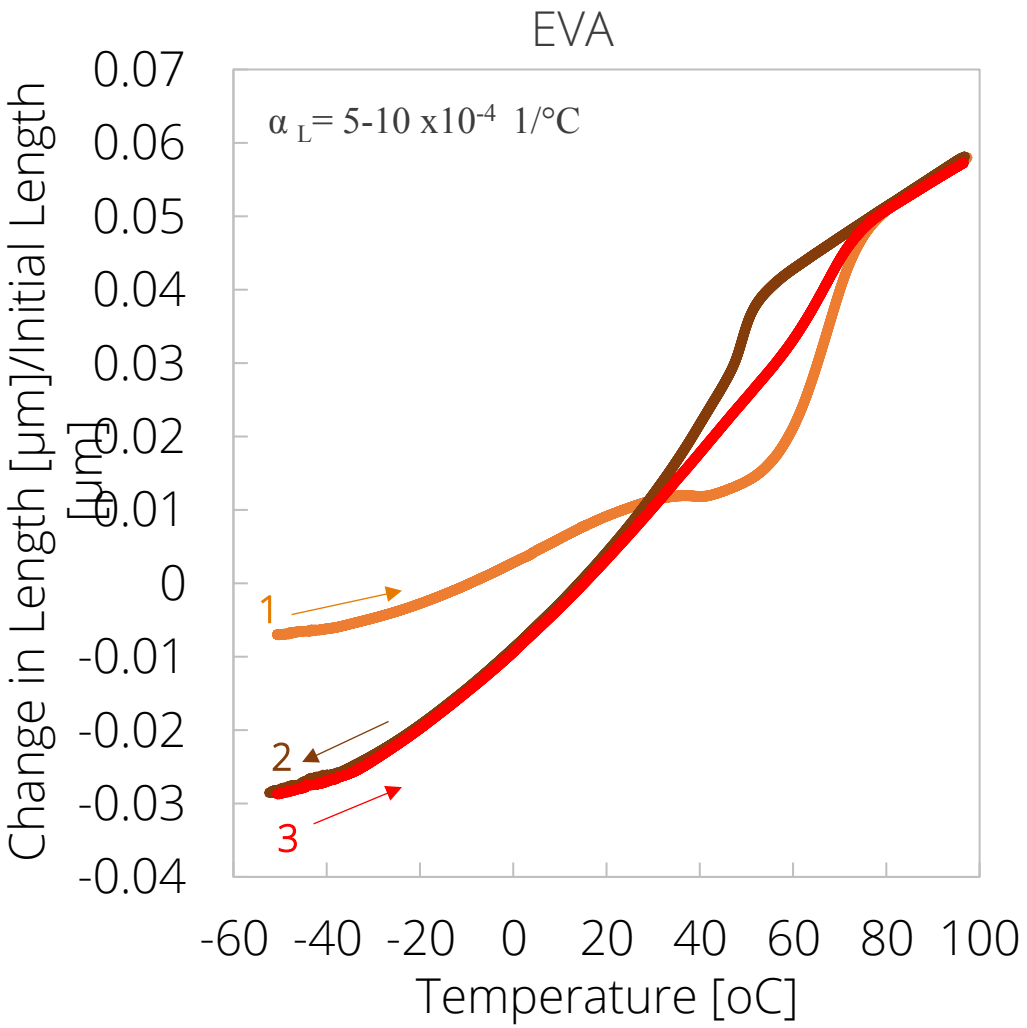
THERMAL TRANSITIONS IN ENCAPSULANTS

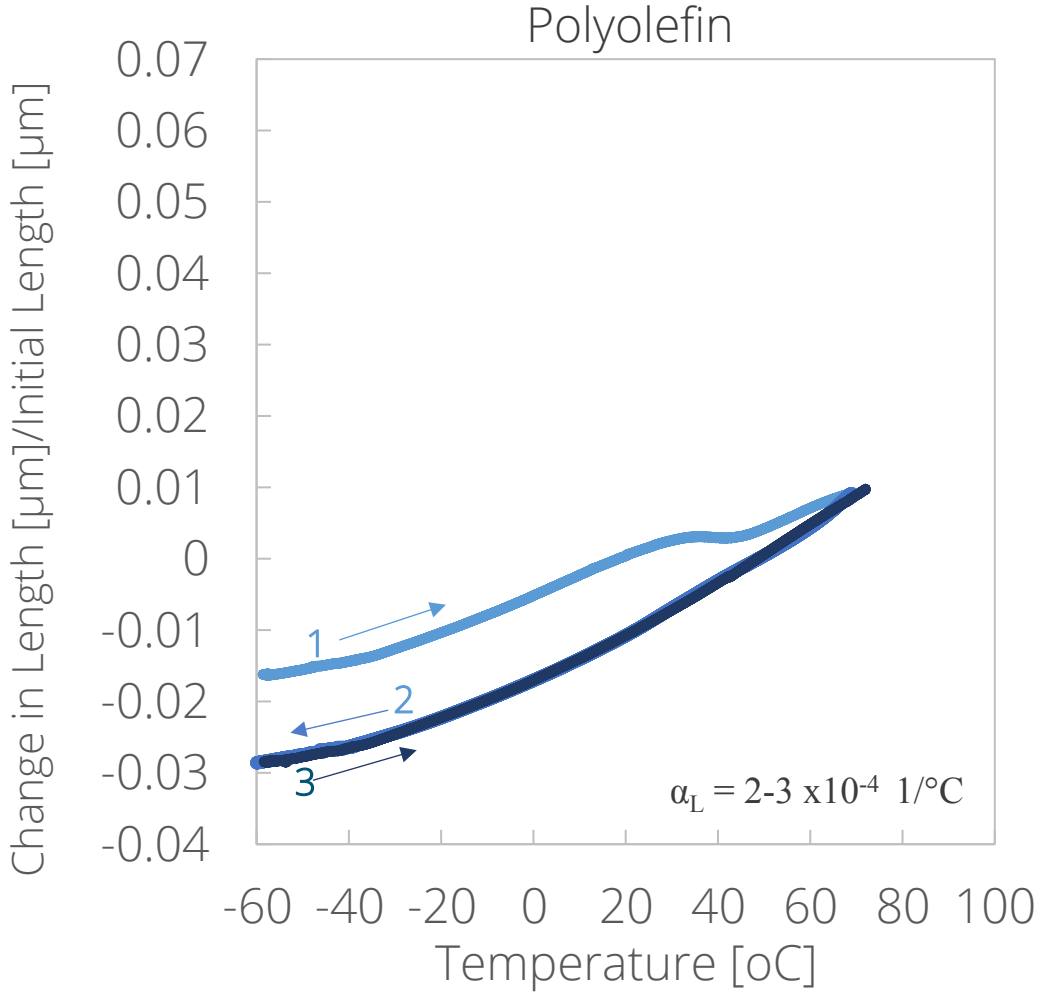




DSC data show key polymeric transitions in PV day/night cycles

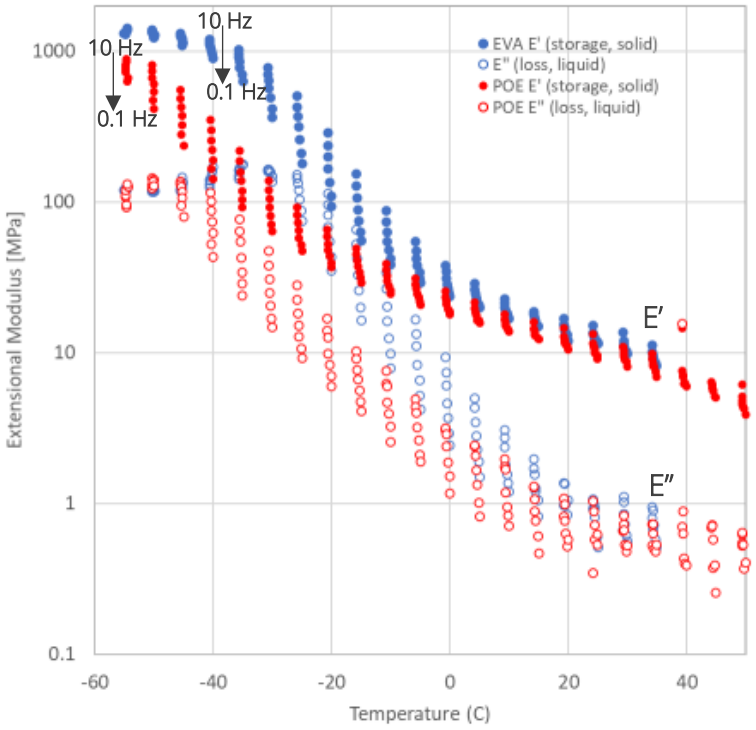
THERMAL EXPANSION COMPLICATED BY CRYSTALLIZATION



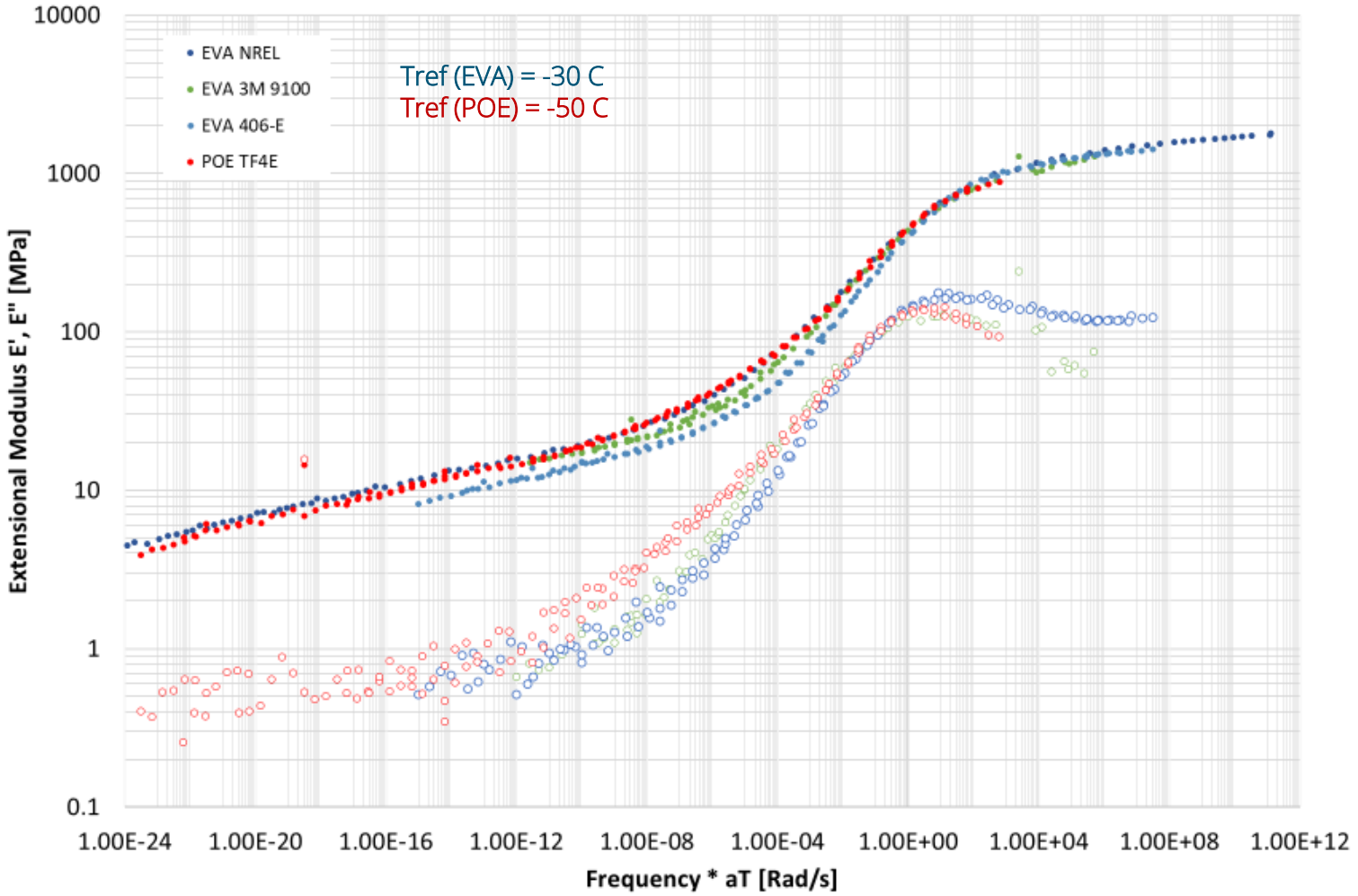


1°C/min, TA Instruments Thermomechanical Analyzer

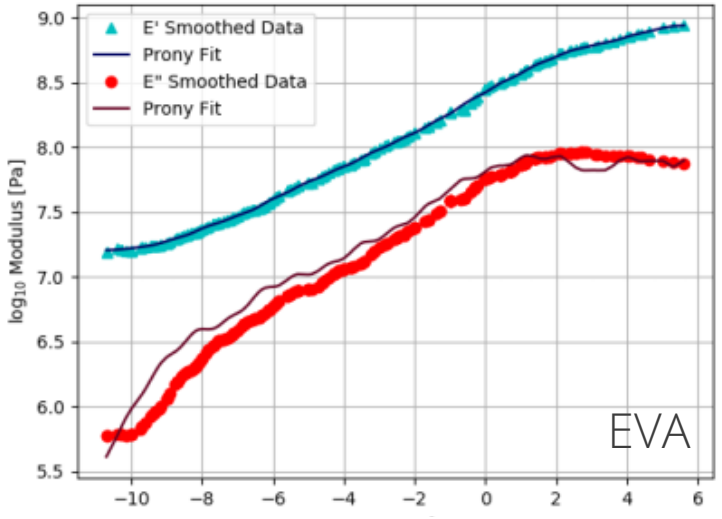
MODULUS OF ENCAPSULANTS

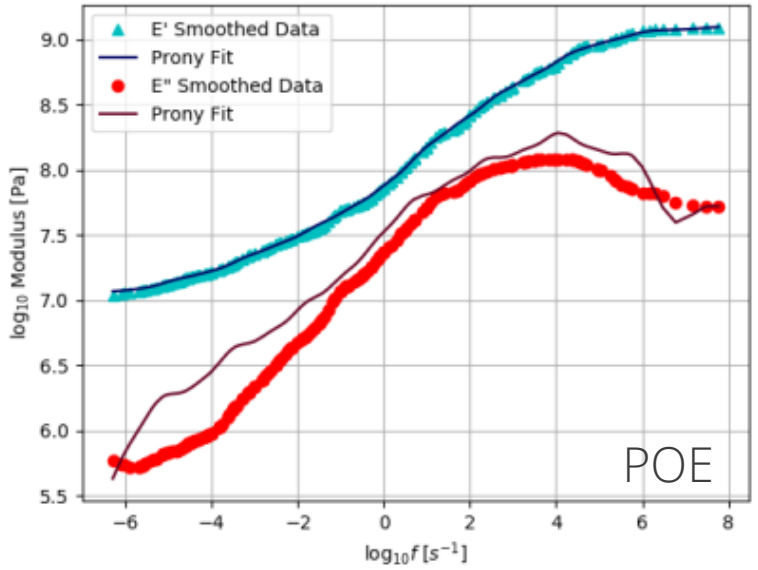


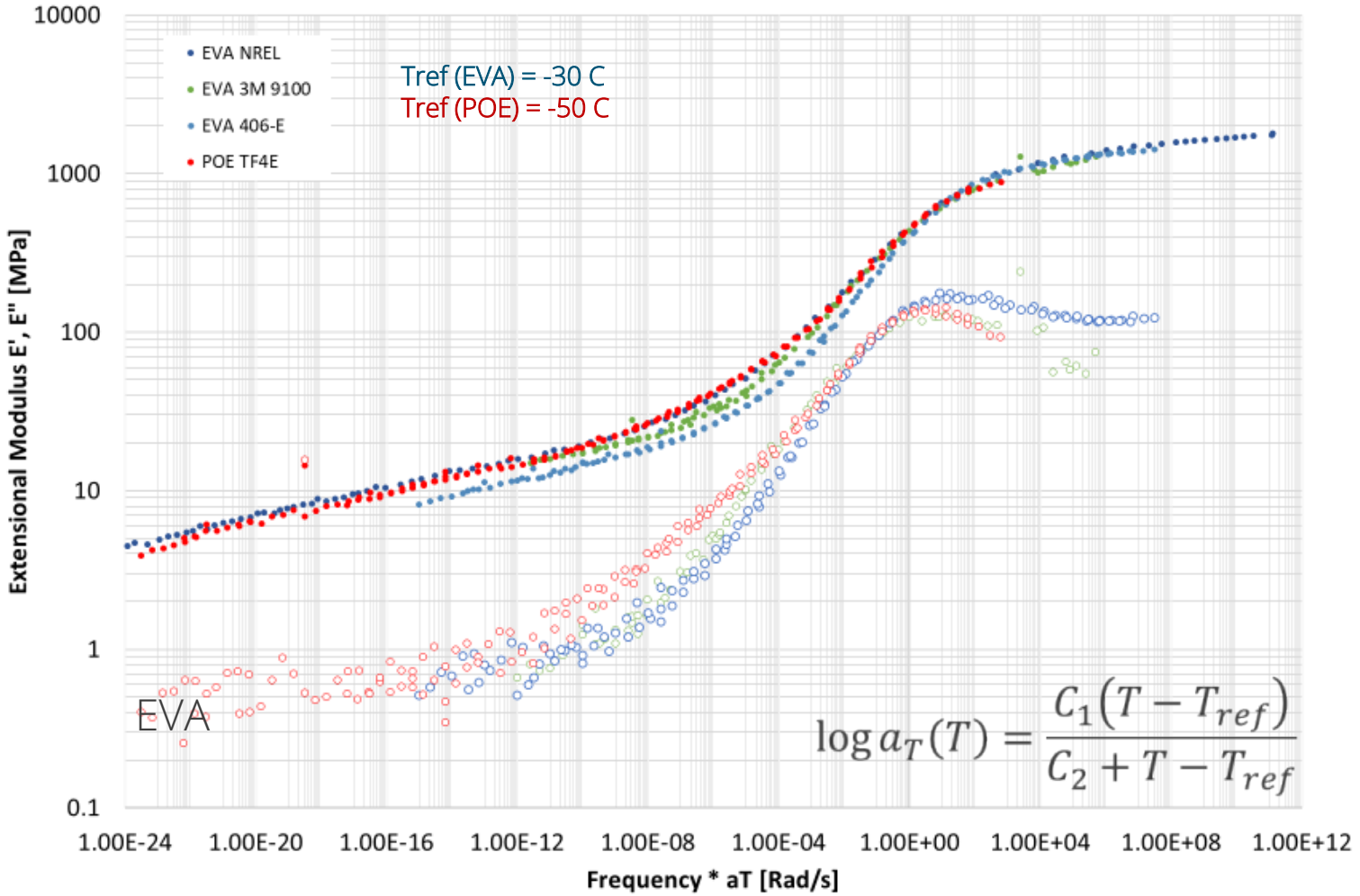
Isothermal frequency sweeps 10 Hz – 0.1 Hz
Netzsch DMA in extension



MODULUS OF ENCAPSULANTS

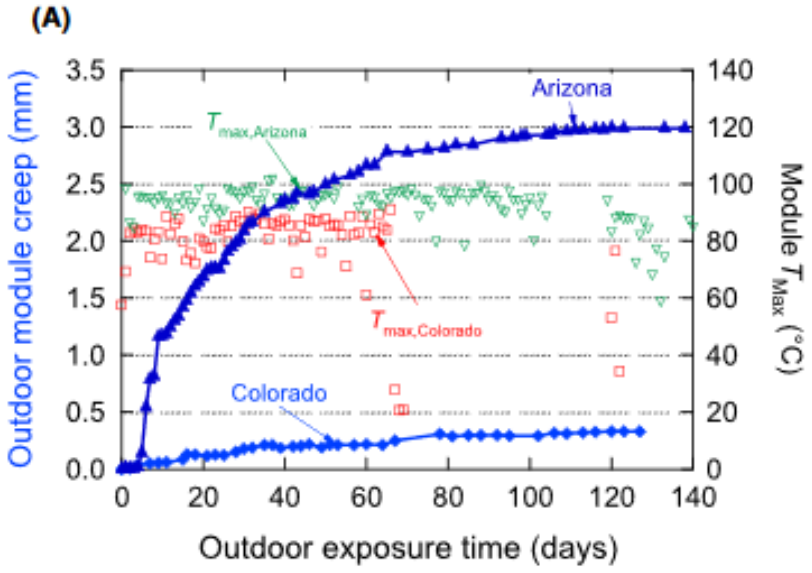






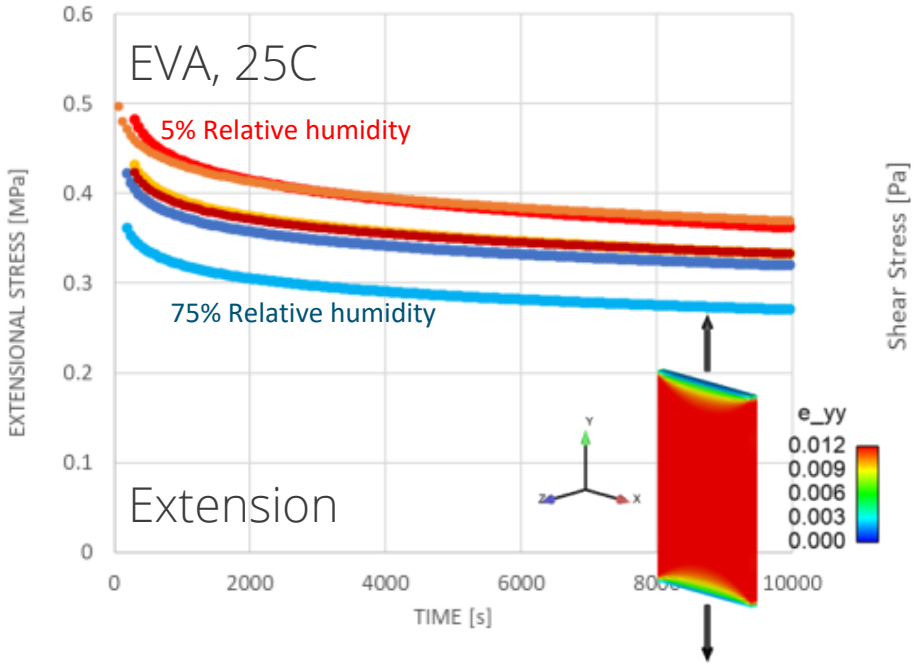
WLF shift, Generalized Maxwell model fit to each dataset
25 terms found to give acceptable error

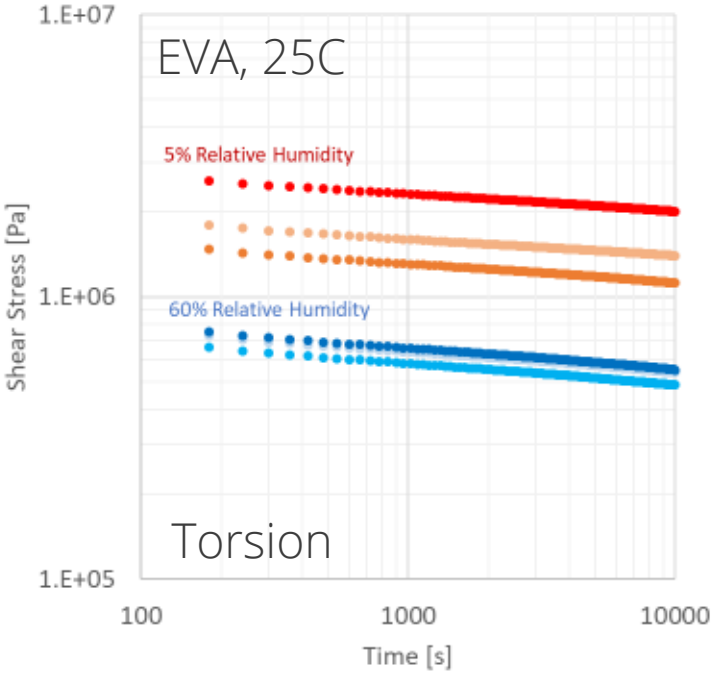
CREEP AND STRESS RELAXATION IN ENCAPSULANTS



Creep is observed in modules, depending on operating temperature

Kempe *et al.* 2015

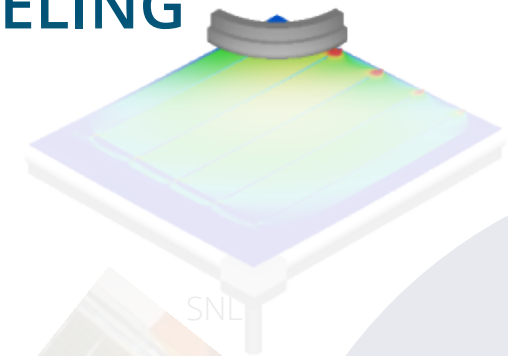




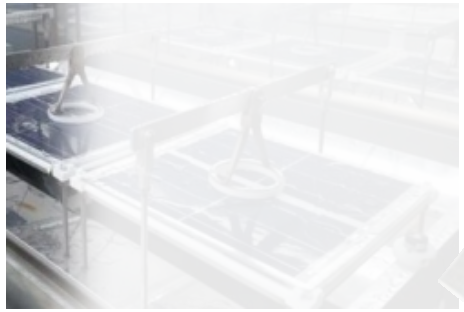
Utilize stress relaxation to validate linear viscoelastic Maxwell constitutive model utilized by FEM

EVA is a Maxwell solid at 25 °C with a modulus (and relaxation time?) that depends on water content.

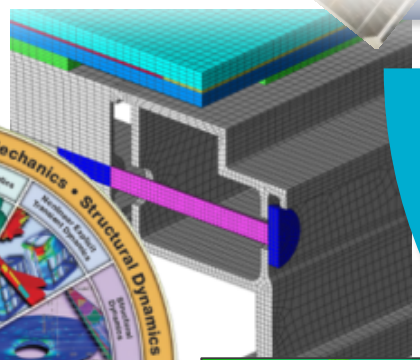
ACCELERATE DESIGN CYCLES THROUGH COMPUTATIONAL MODELING

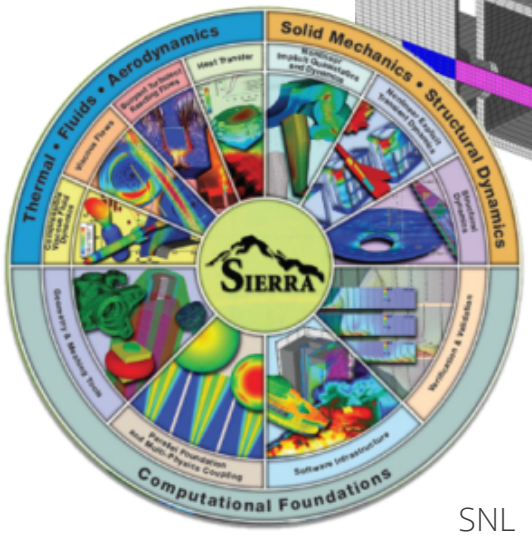


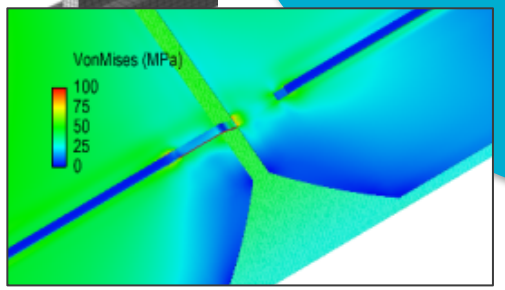
SNL



NREL







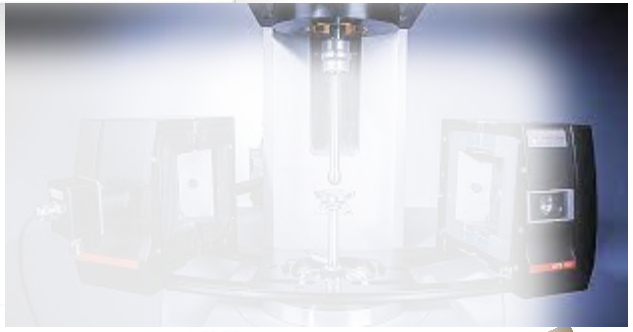
SNL

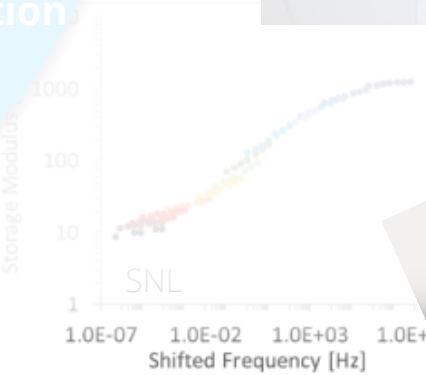
Validate

Design

Computational Model

Materials Characterization





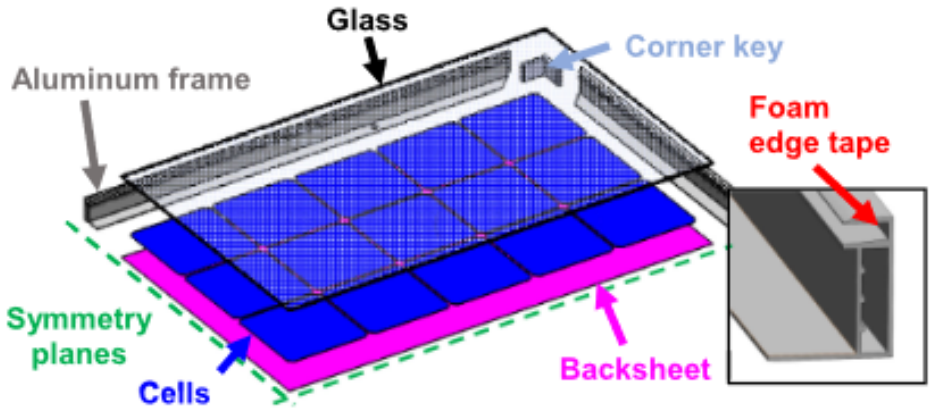
FINITE ELEMENT MODEL CONSTRUCTION

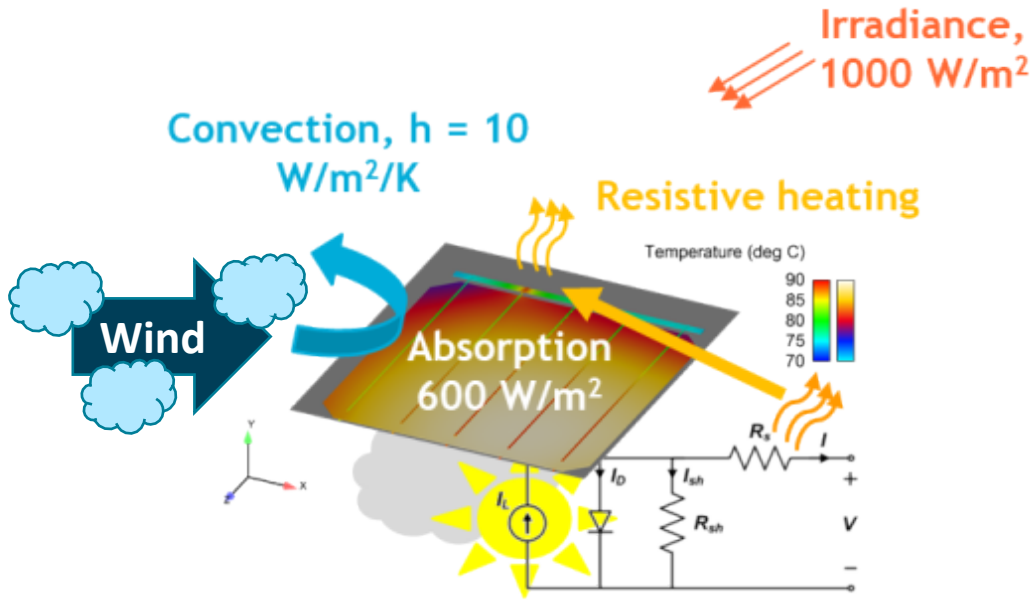
Collaborations with module manufacturers have identified key construction details

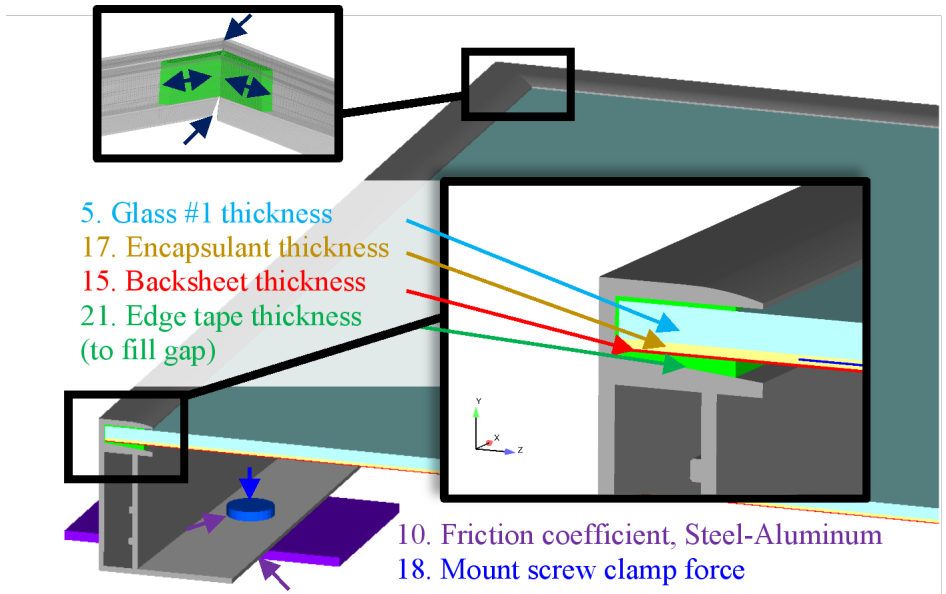
Glass-glass and conventional silicon modules

Quarter symmetry or mini-module approaches

Physics: Thermal stresses, mechanical loads,
thermal-electrical interactions
material and design tradeoffs



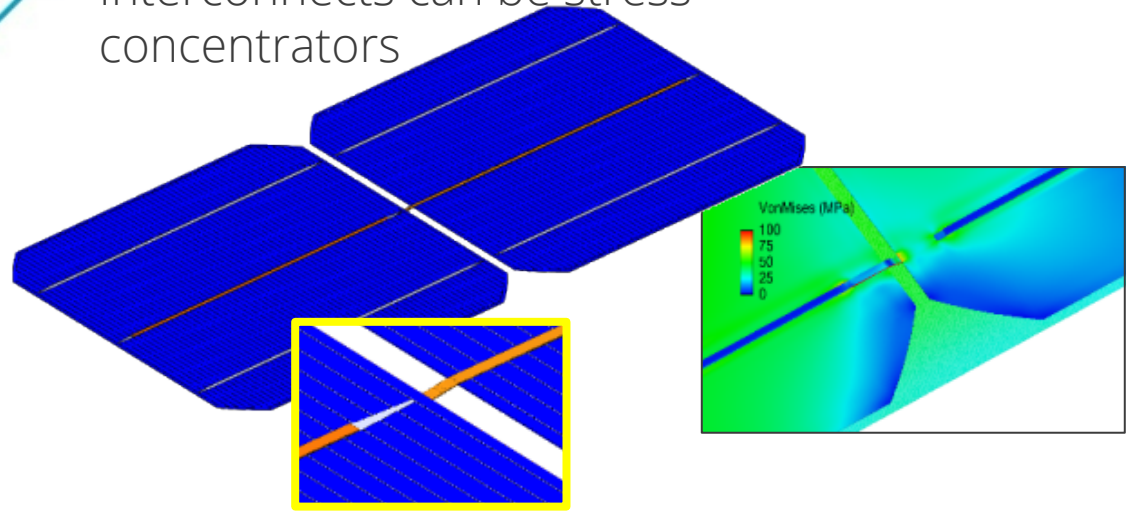


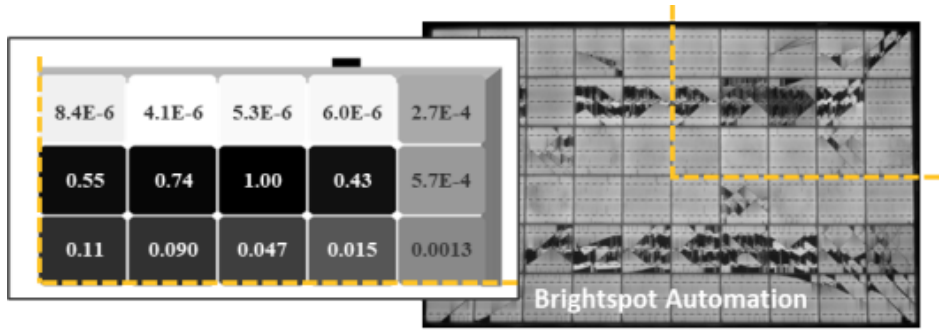


Hartley et al. *IEEE J. Photovoltaics* v10 no. 3 2020

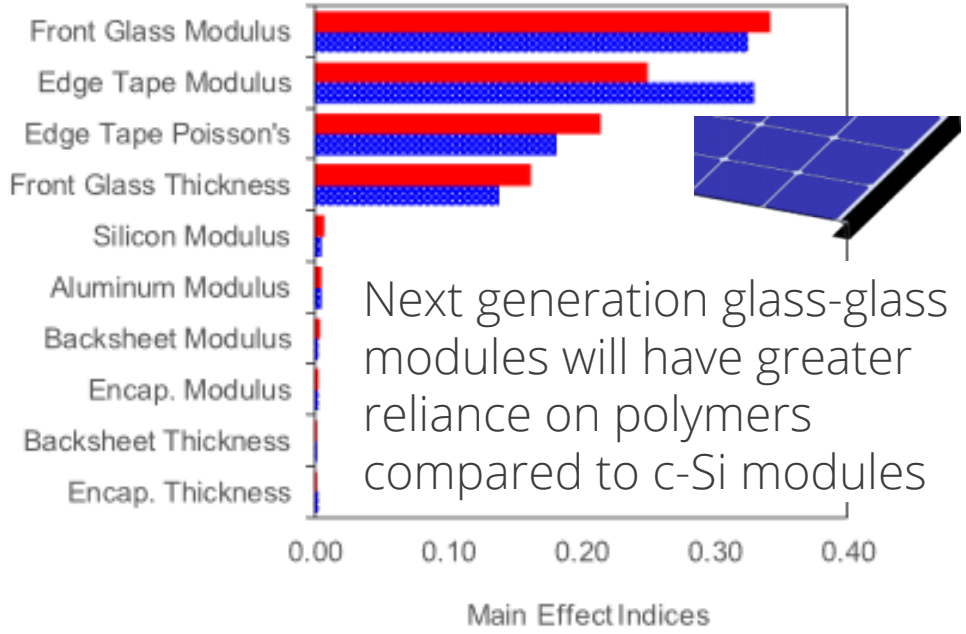
FINITE ELEMENT MODEL RESULTS

Interconnects can be stress concentrators

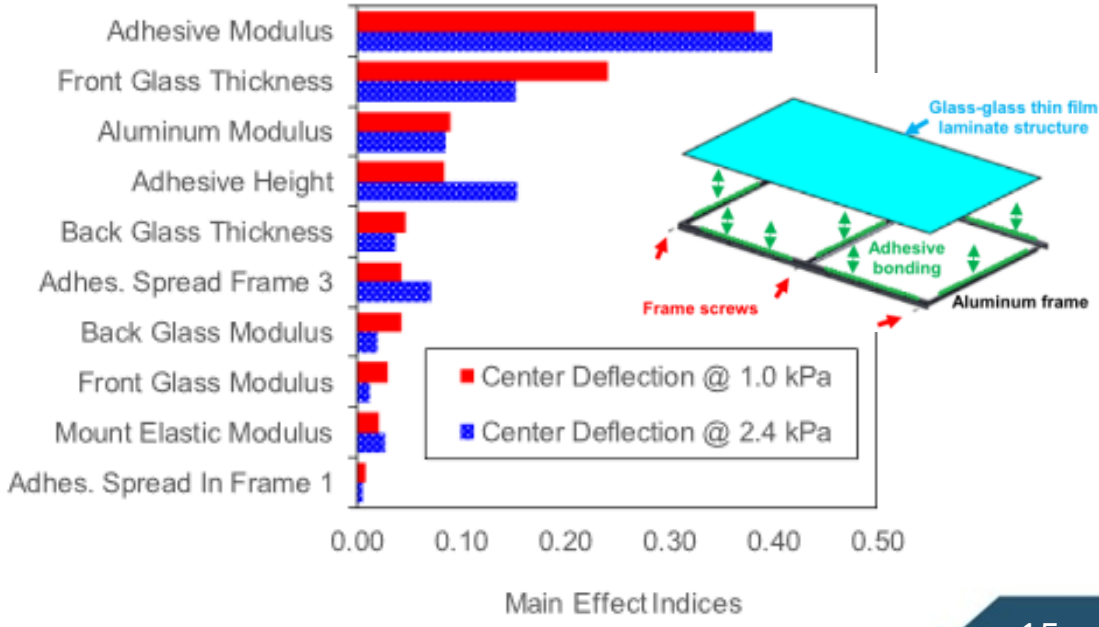




Probability of cell cracking can be predicted from applied load and polymer mechanical properties



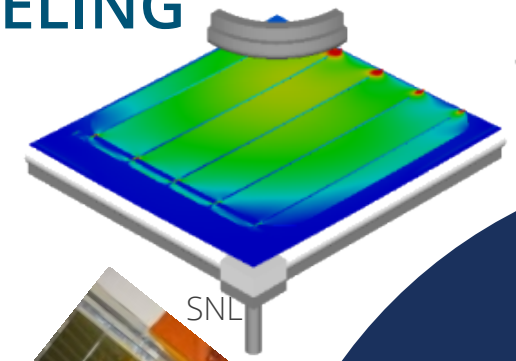
Next generation glass-glass modules will have greater reliance on polymers compared to c-Si modules



Hartley et al. *IEEE J. Photovoltaics* v10 no. 3 2020

ACCELERATE DESIGN CYCLES THROUGH COMPUTATIONAL MODELING

NREL



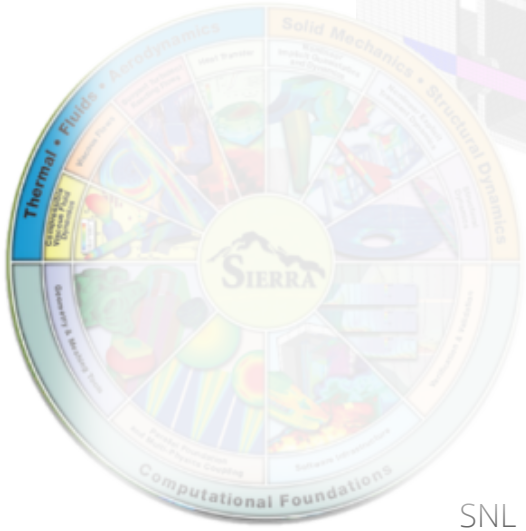
SNL

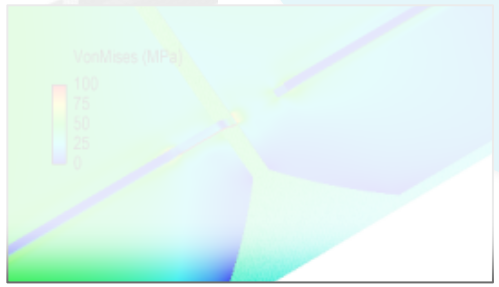
Validate

Design

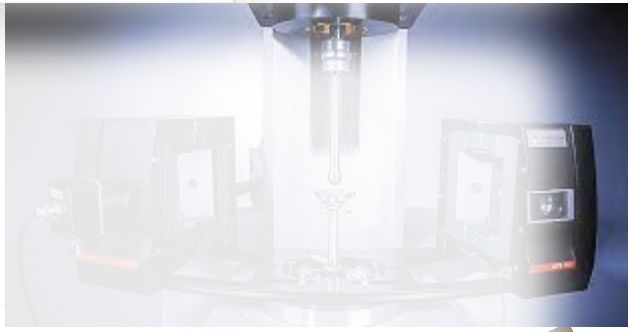
Materials Characterization

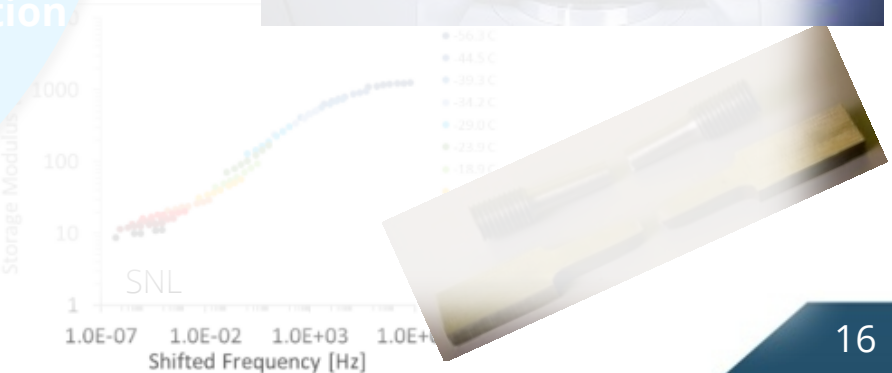
Computational Model





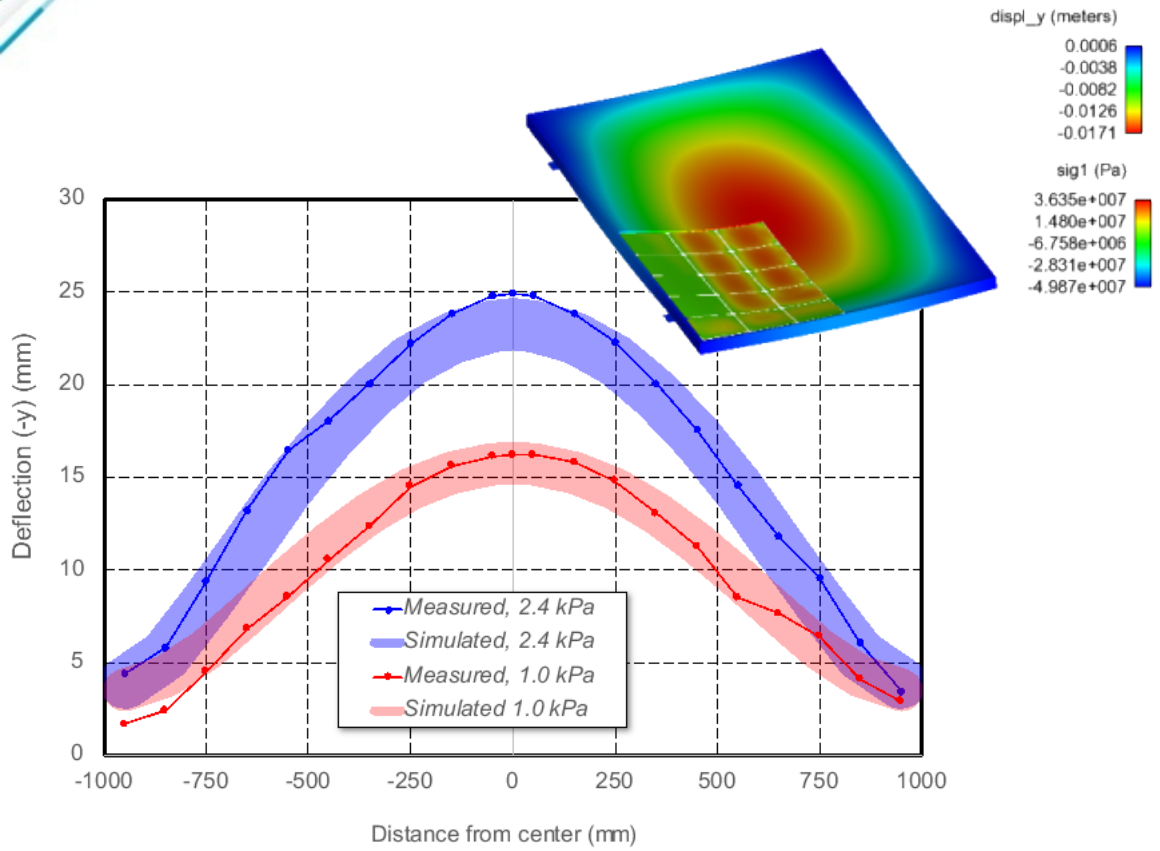
SNL





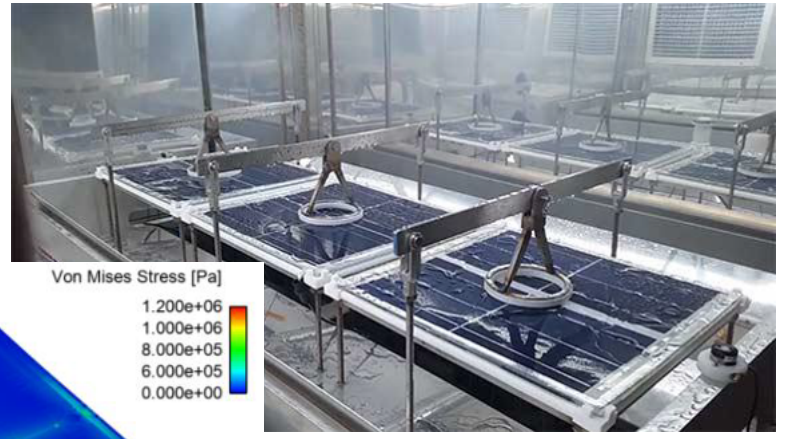
SNL

MODEL VALIDATION



Initial validation of FEM model

Compare predicted deflections against full-module flexure subjected to IEC61215 pressure loads



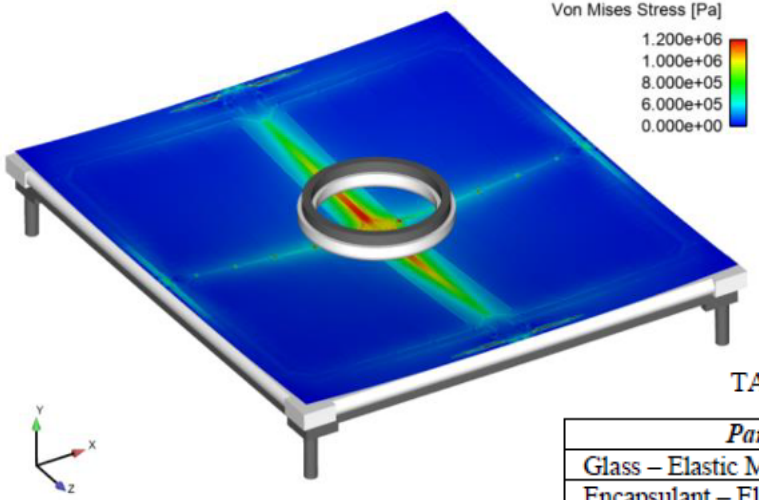
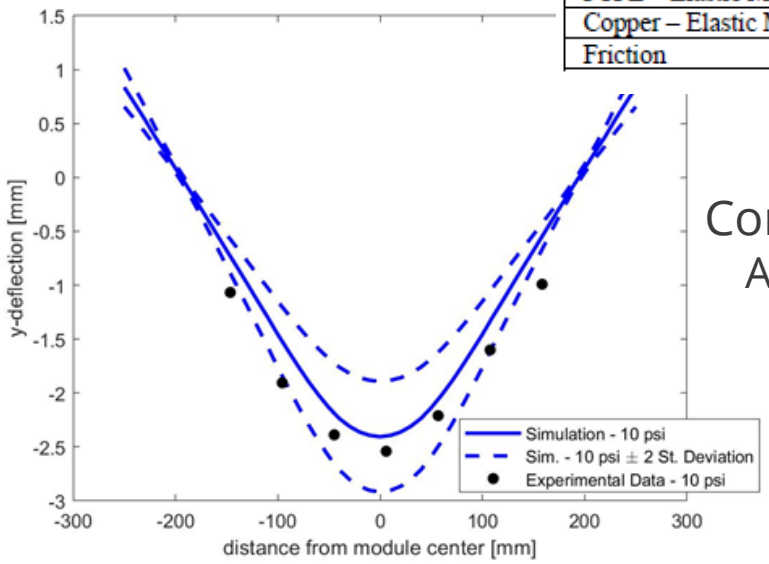


TABLE II. KEY SENSITIVITIES

Parameter	*Correlation Coefficient*
Glass – Elastic Modulus	0.6604
Encapsulant – Elastic Modulus	0.3082
PTFE – Elastic Modulus	0.2004
Copper – Elastic Modulus	0.1914
Friction	0.1595

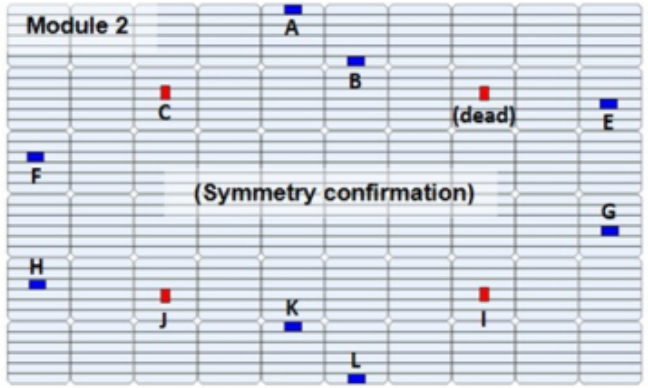


Comparison against C-AST

Accelerated stress testing performed at NREL

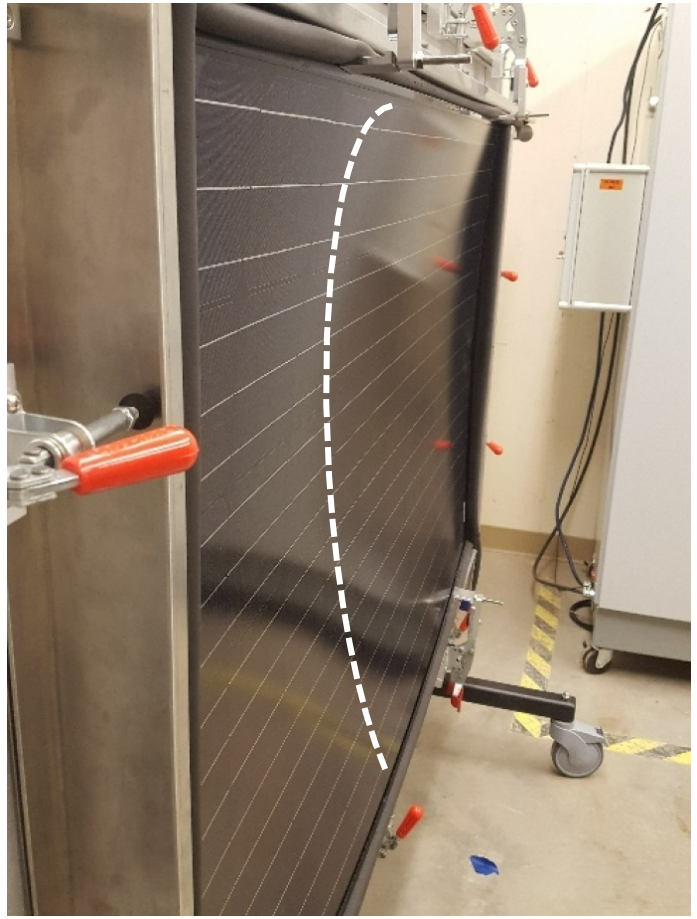
Meert et al. 2020 47th *IEEE PVSC*

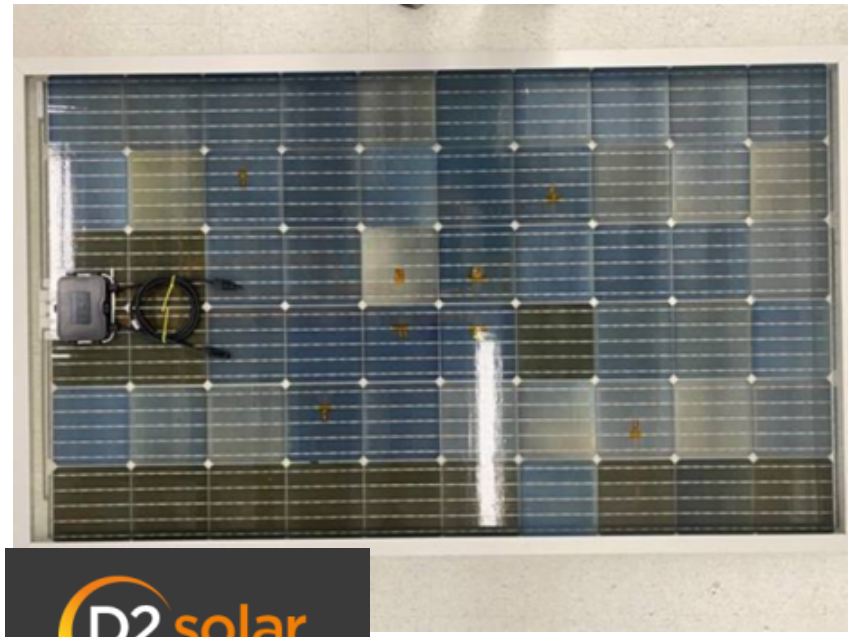
VALIDATION: INSTRUMENTED MODULE

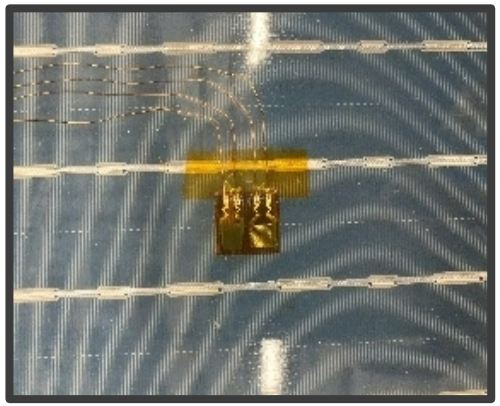


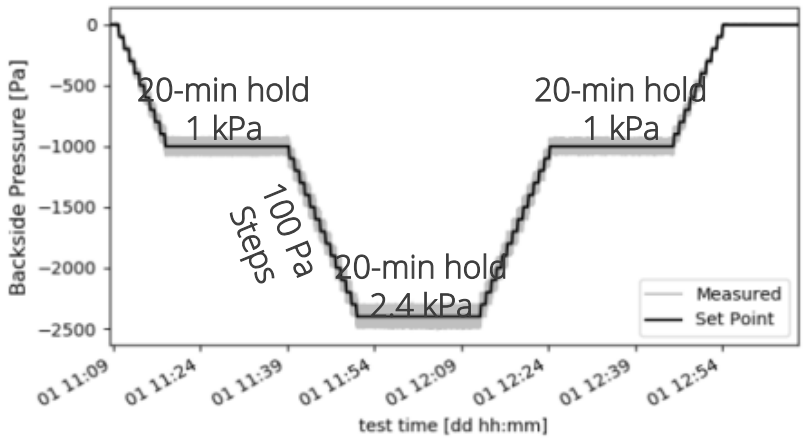
4 instrumented modules constructed with strain gauges to give more granularity to model comparisons.

Load Spot provides deflection
Simultaneous electroluminescence imaging



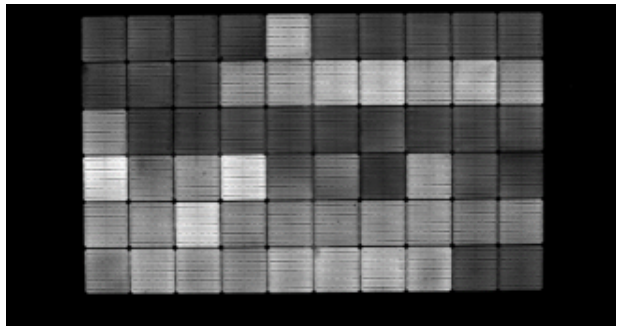




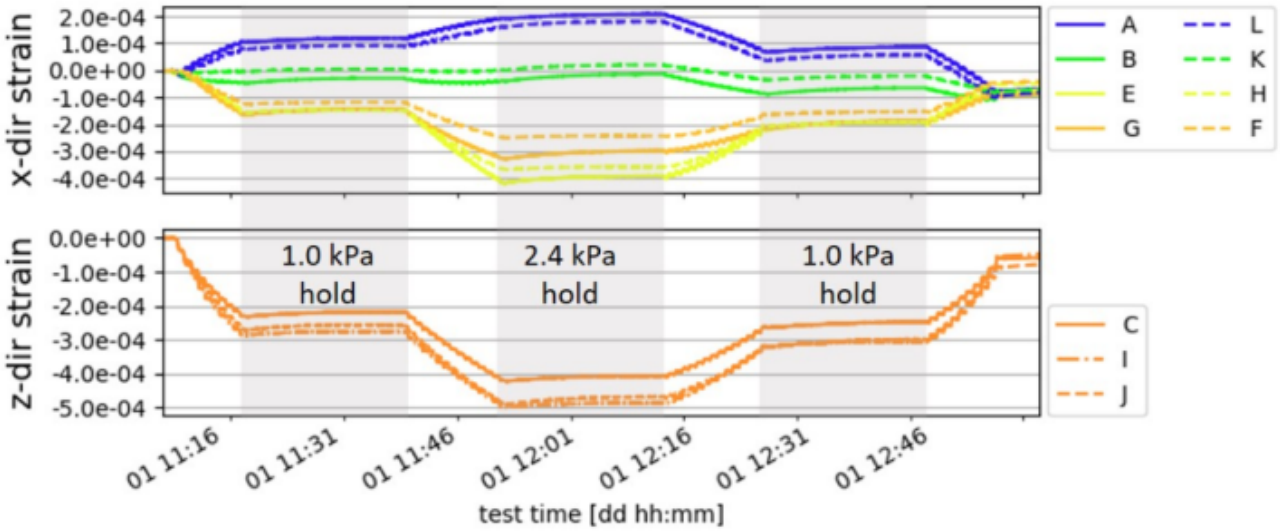


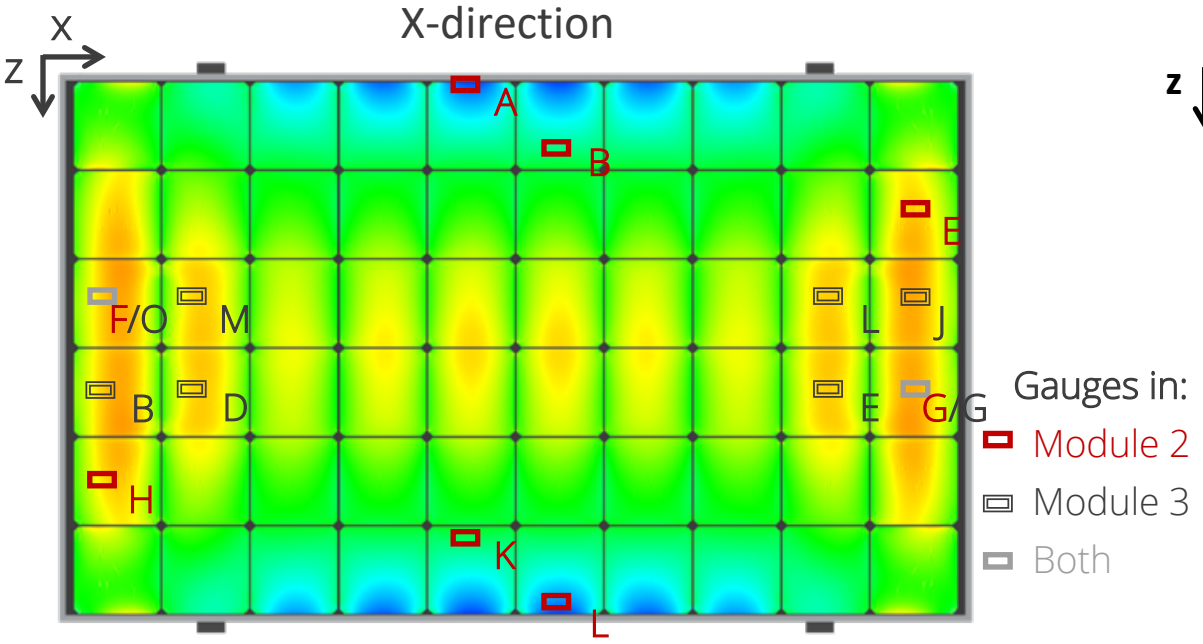
D2 solar

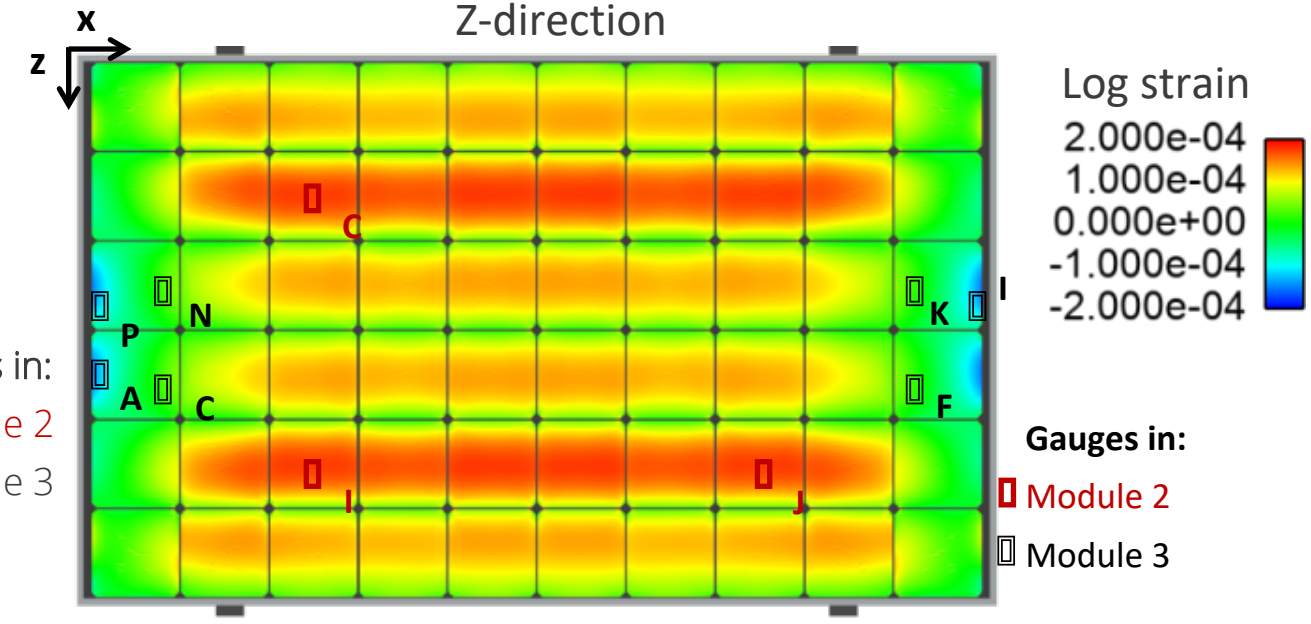
VALIDATION RESULTS



EL imaging shows modules are functional, but not optimized for electrical performance

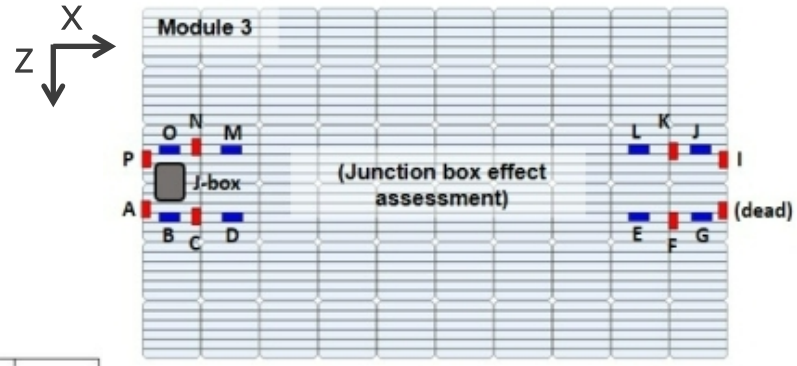


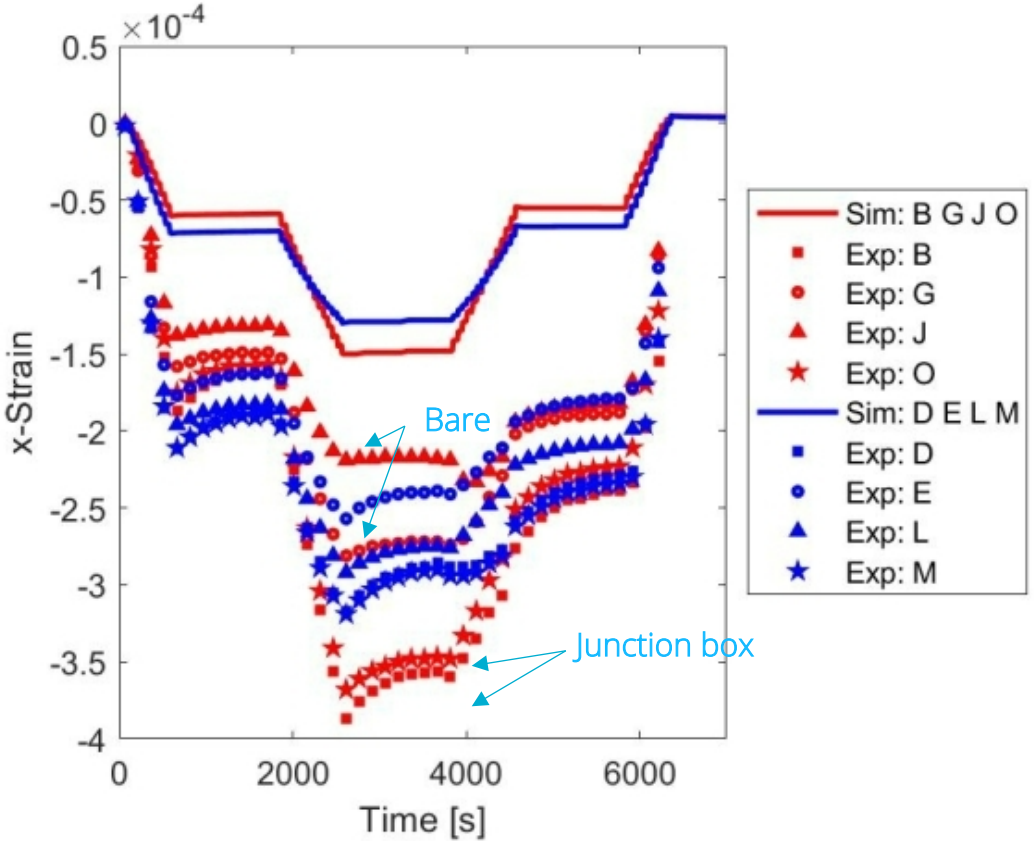


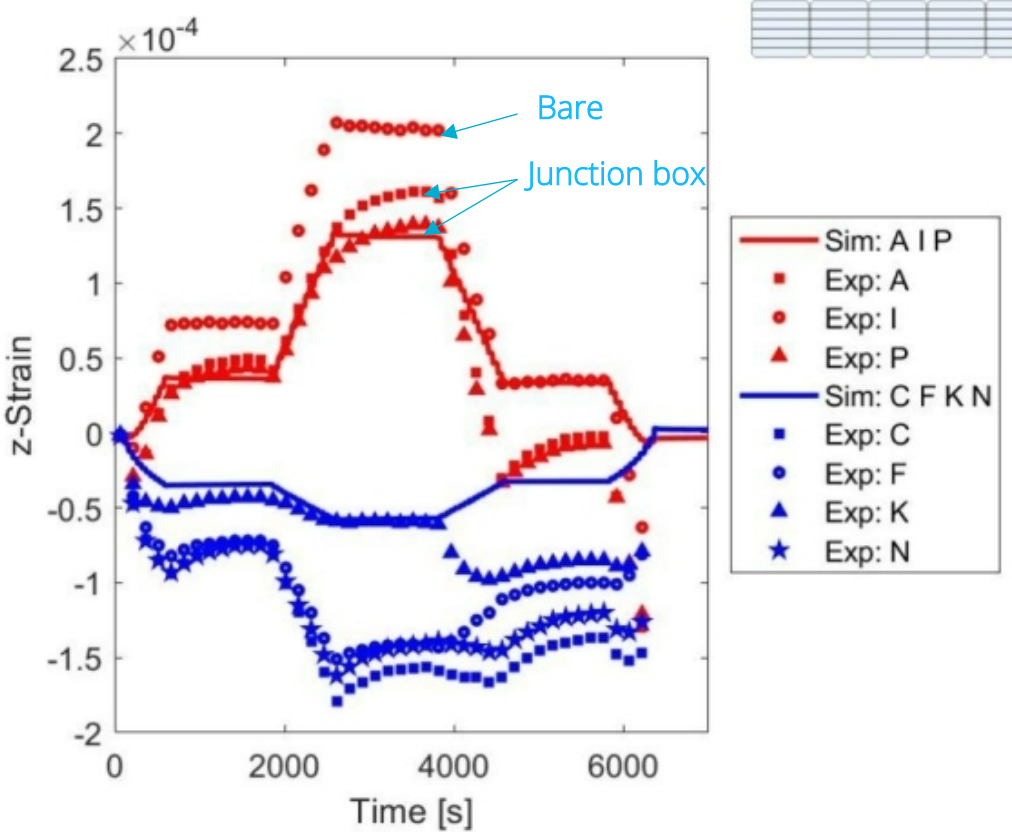


Predicted strains (color) qualitatively match experimentally observed deformation for all strain gauge locations.

EFFECT OF JUNCTION BOX



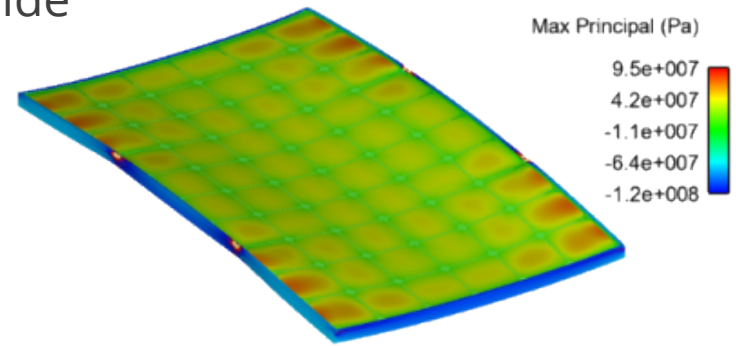




Junction box damps Z-strain and increases X-strain
Model under-estimates stresses: Reassess FEM complexity, strain gauge placement
Model under-represents creep: Re-evaluate mechanisms or encapsulant material model

CONCLUSIONS

- Viscoelastic polymers provide photovoltaic module durability
  - Aging, stress relaxation, temperature all concerning to 30 year warranties
  - Aspirations for “50-year modules”
- Computational model developed through DuraMAT consortium can provide accelerated design cycles
- Plenty more to consider:
  - Modules creep over time, and manufacturing stresses relax
  - Next-generation module designs will rely more on polymer performance
  - Crystallization, crosslinking, polymer composition all could be important
  - Ruthless $/W standards mean every design feature must perform



Funding provided as part of the Durable Module Materials Consortium (DuraMAT), an Energy Materials Network Consortium funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office.

Christine Roberts: ccrober@sandia.gov
James Hartley: jkyuan@sandia.gov