

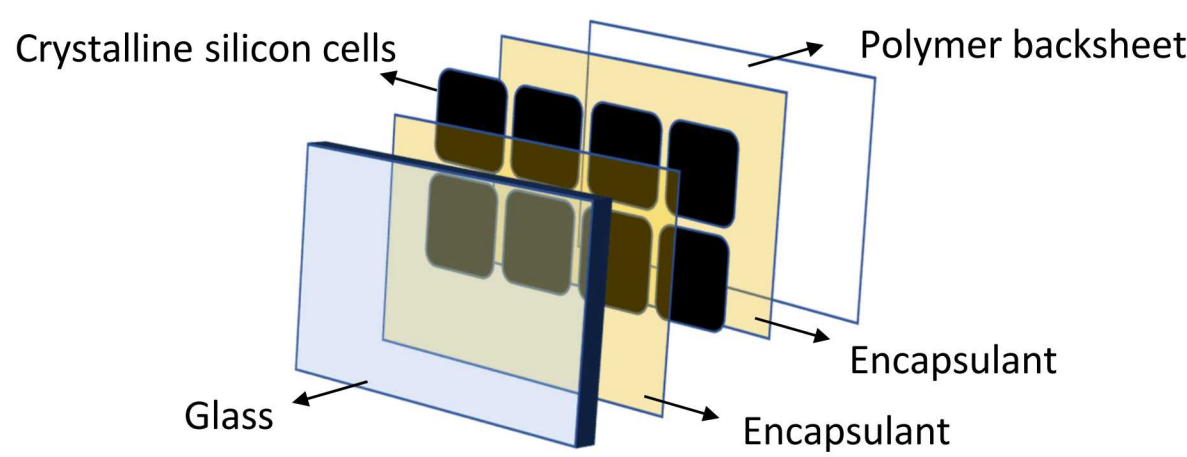
Thermal and Viscoelastic Behavior of Photovoltaic Module Encapsulants

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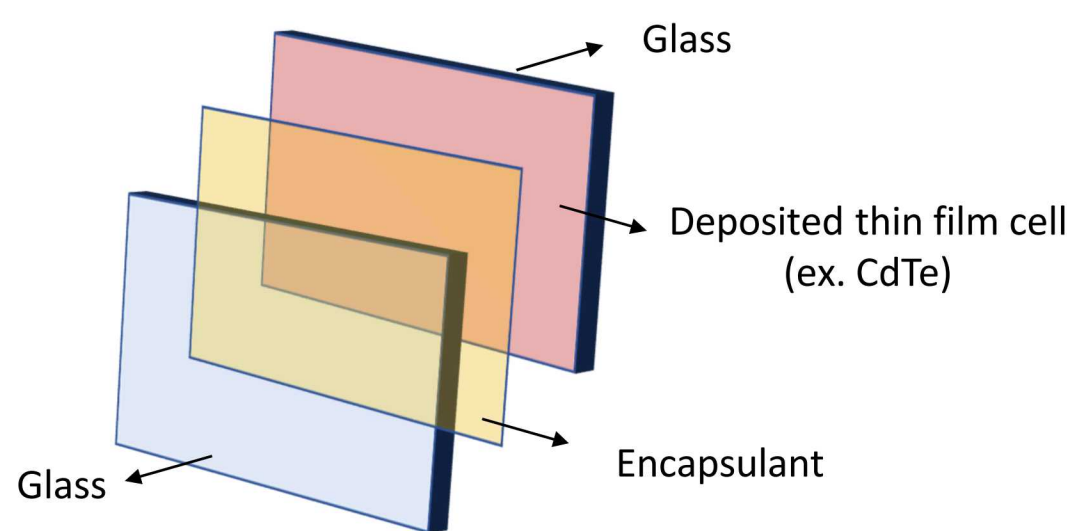
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Introduction and Motivation

- This work is part of an ongoing **predictive modeling** effort developing multi-scale thermal-mechanical finite element models to better understand how module deployment environments induce the damaging stresses that lead to module degradation
- The viscoelastic nature of polymer encapsulant is potentially a key factor affecting component stress states
- This poster summarizes the **steps taken to populate a material model** for two encapsulant polymers: poly(ethylene vinyl acetate)(EVA) and a polyolefin elastomer (POE)
 - EVA is the most common encapsulant material used in PV modules
 - We characterized crosslinked samples of a fast-curing commercial EVA
 - Polyolefin films are a common alternative encapsulant with several improved characteristics that are especially valued in thin-film PV modules
 - We characterized commercial POE samples that were heated and pressed to mimic manufacturing lamination conditions



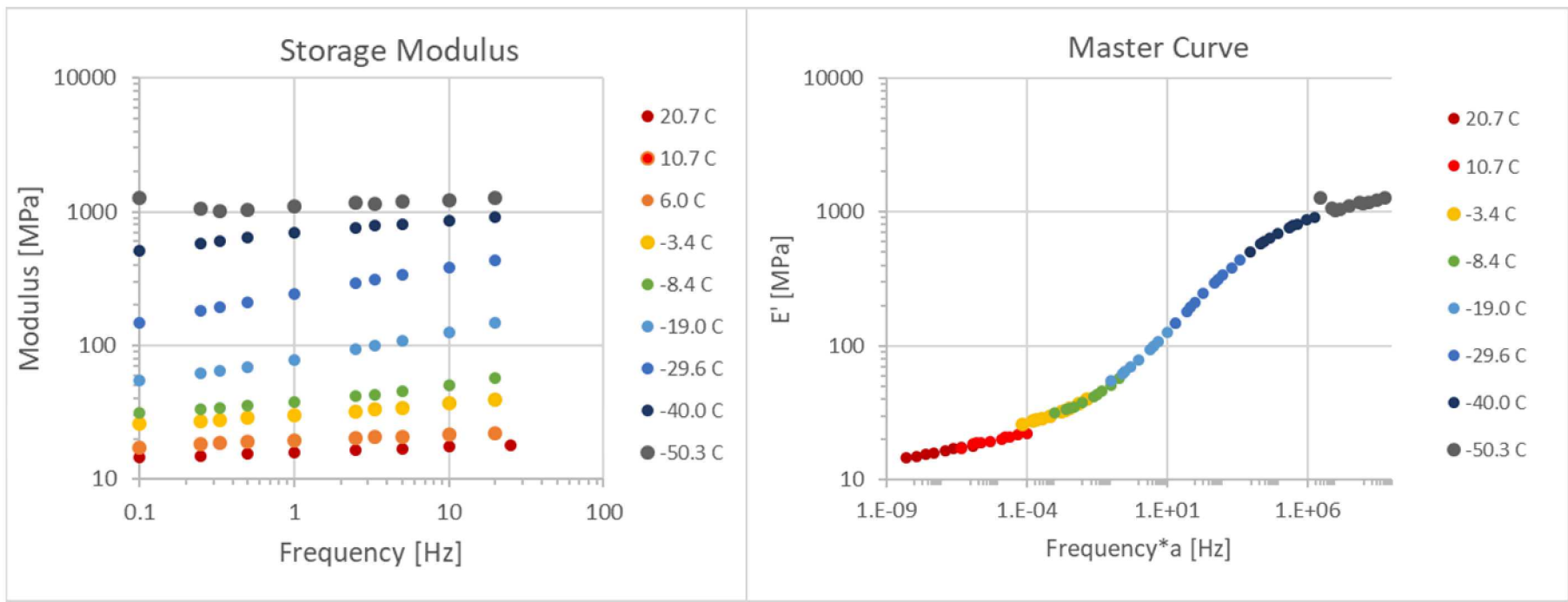
Layers in silicon PV modules



Layers in thin-film PV modules

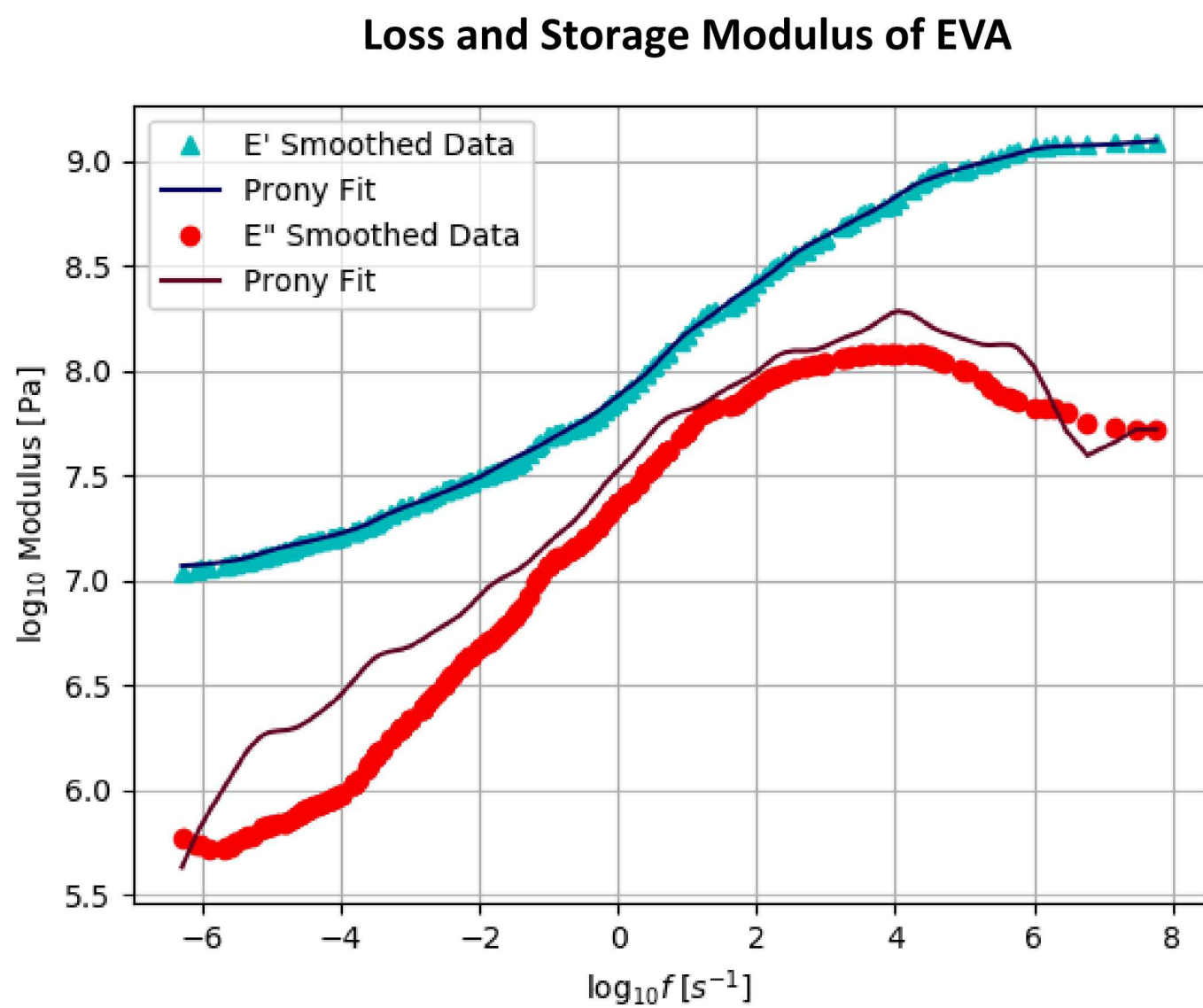
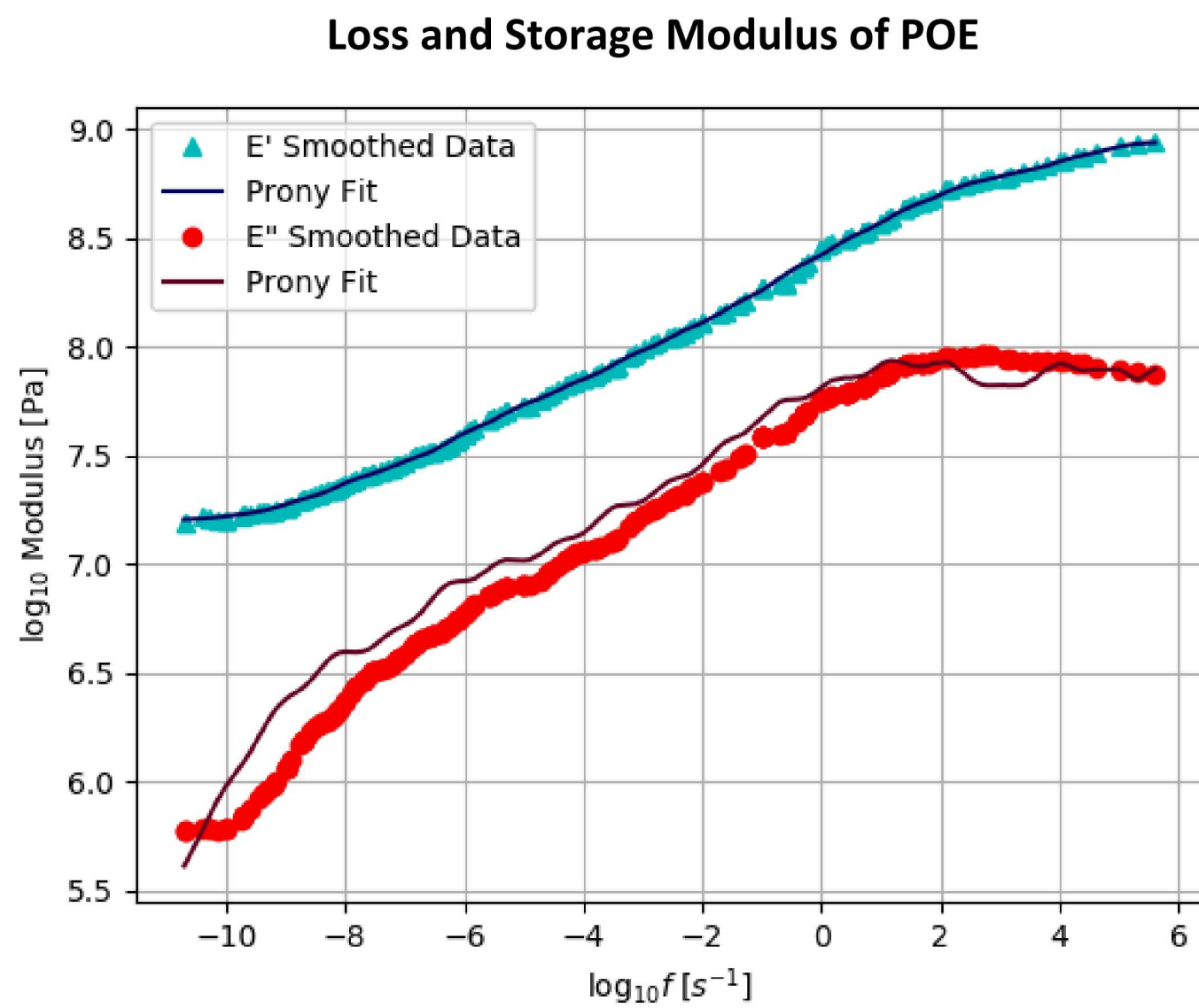
1: Time-Temperature Superposition

- Isothermal frequency sweeps (0.1 Hz to 10 Hz) were collected with a dynamic mechanical analyzer (DMA) at and above the materials' glass transition regions (EVA: -40°C, POE: -60°C)
- Williams-Landel-Ferry (WLF) equation was used to find shift factors (a_T), with parameters C_1 and C_2 optimized to storage modulus (E') data

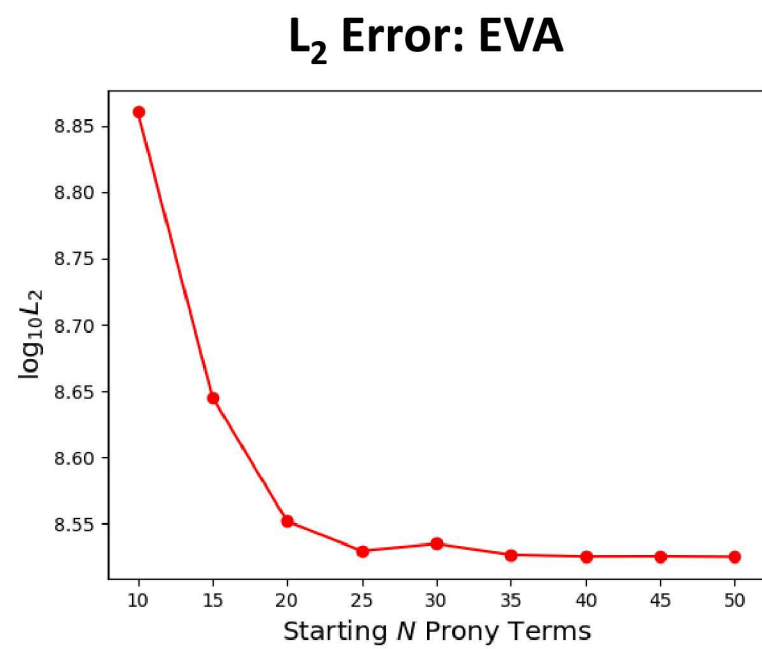
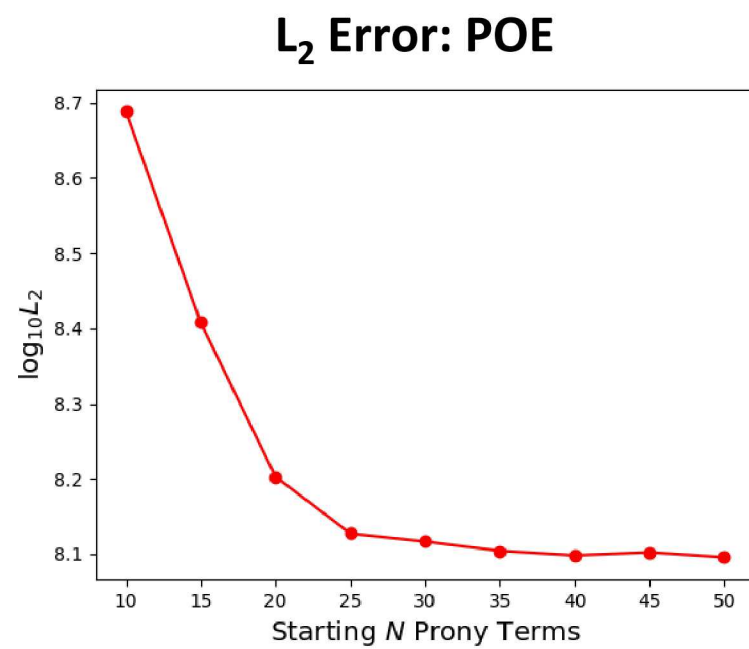


Example of shifted isothermal frequency sweep data - EVA

2: Model of Linear Viscoelastic Behavior

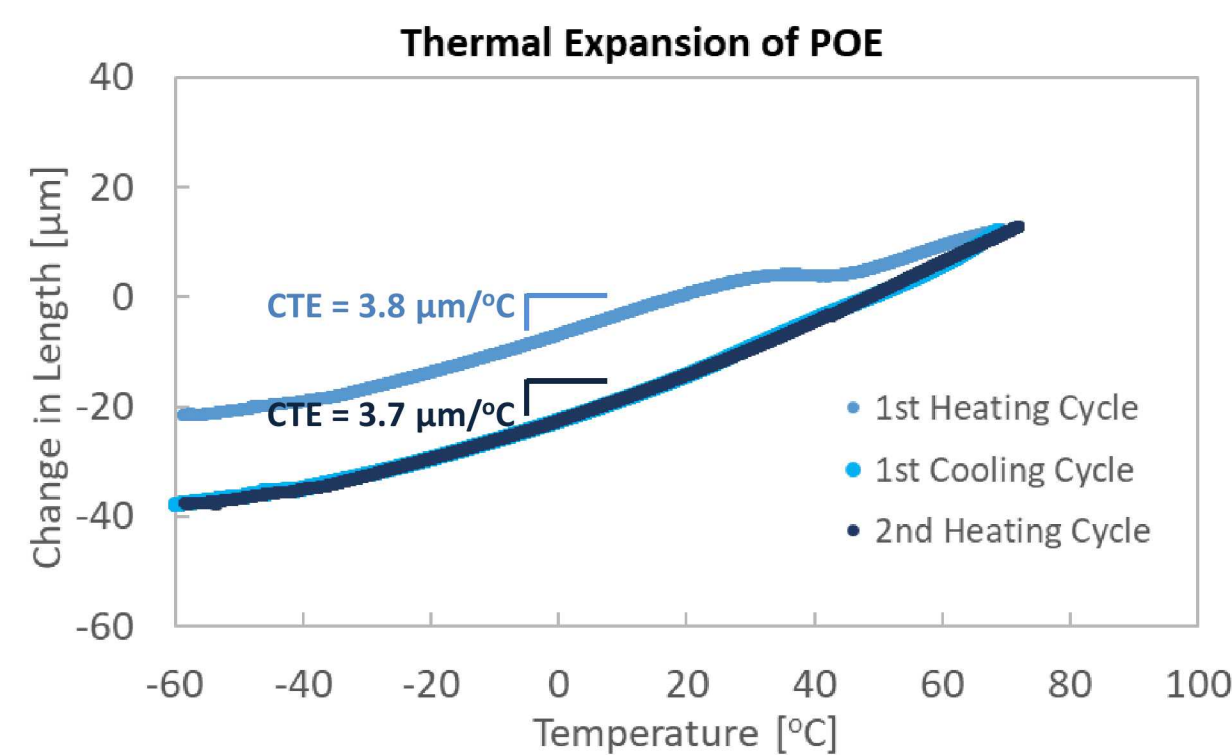
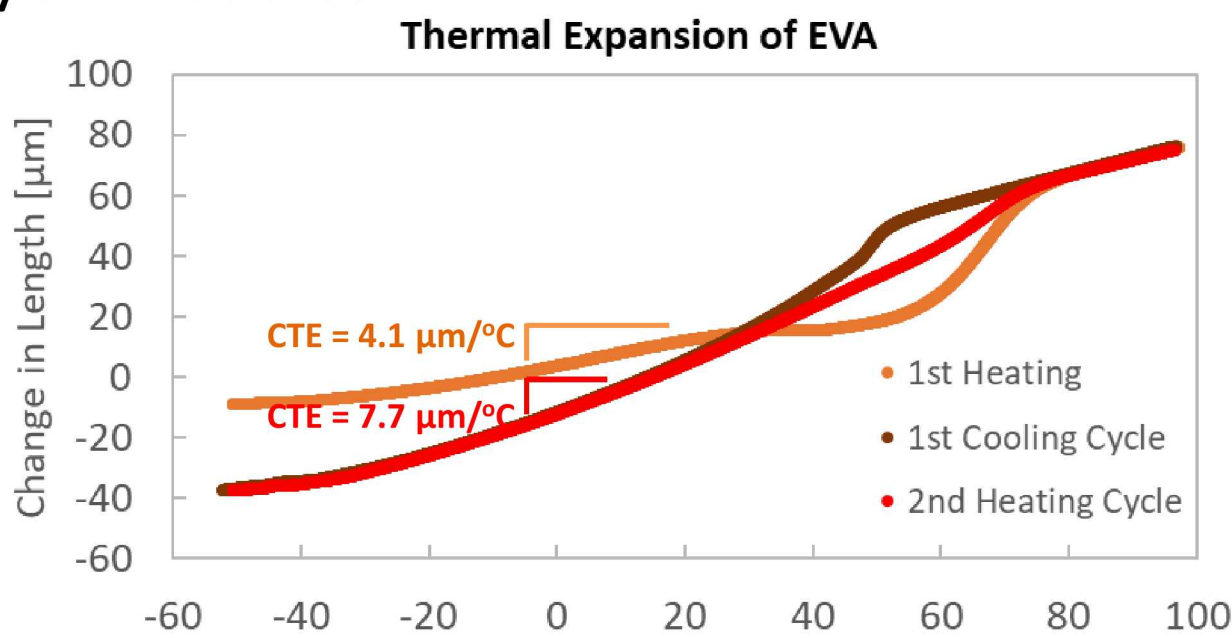


- Master curves of each material consist of shifted DMA data collected on multiple samples and smoothed
- Prony series fits (*lines in plots above*) capture both the elastic and viscous material responses of polymers
 - The number of Prony terms was varied from 10 to 50, with 25 terms selected to minimize L_2 (*right*)



3: Thermal Expansion and Relaxation

- Coefficient of thermal expansion (CTE) was measured using a thermal mechanical analyzer (TMA).
- Significant variation between cycles due to thermal history of the films. Which is the relevant state for deployed modules?



4: Universal Polymer Model

- Parameters from the data fitting described above will be used to populate Sandia's Universal Polymer Model [DB Adolf, RD Chambers, J. Rheology 2007], including:
 - WLF parameters and reference temperature
 - Linear viscoelastic model Prony terms
 - CTE fit

Material Time Dependencies:

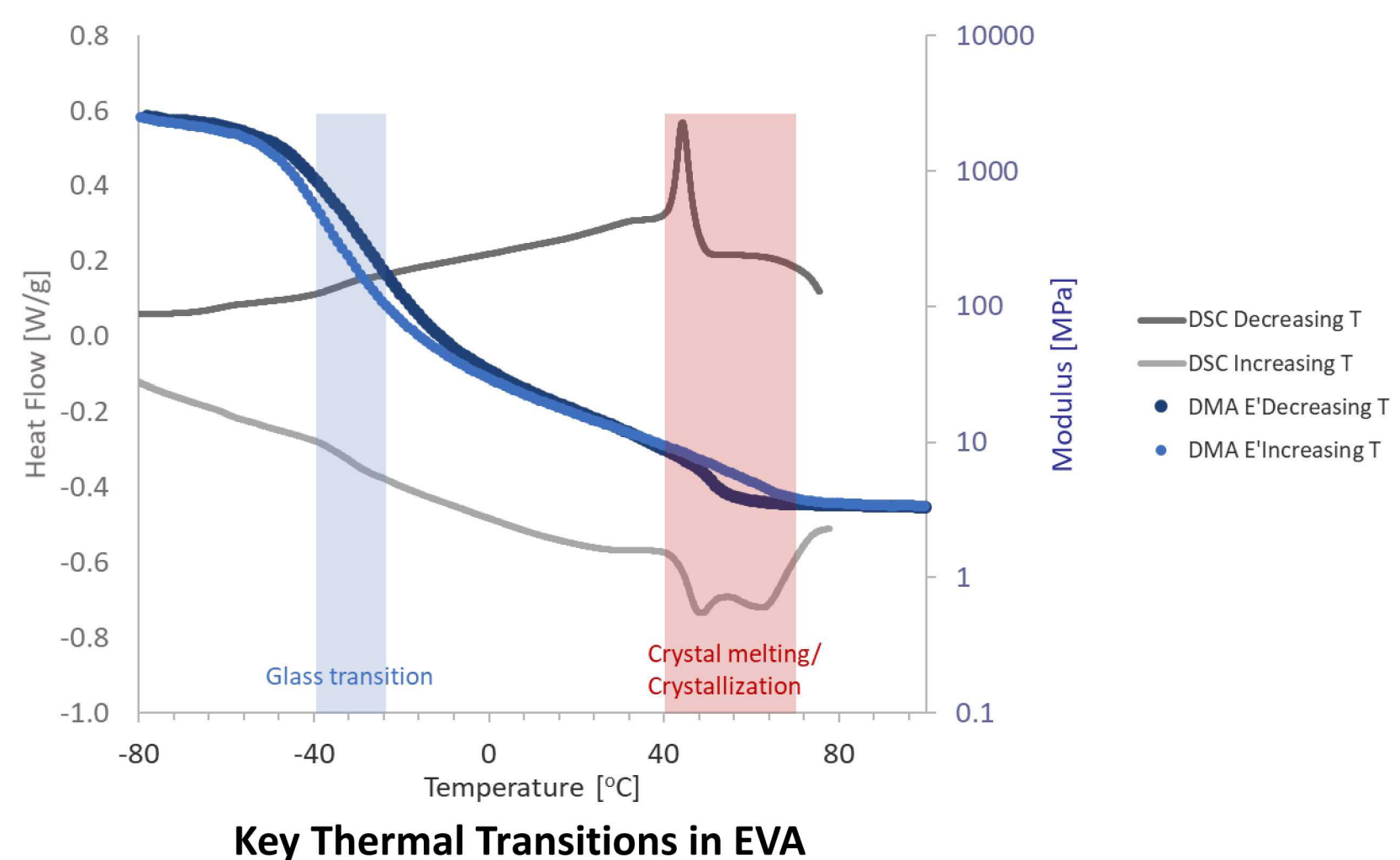
$$N = \left\{ T(t) - T_{ref} - \int_0^t ds f_1(t^* - s^*) \frac{dT}{ds}(s) + C_2 \left\{ T(t)_{ref} - \int_0^t ds f_1(t^* - s^*) \frac{dT}{ds}(s) \right\} \right\}$$
$$+ C_4 \left\{ \int_0^t ds du f(t^* - s^*, t^* - u^*) \frac{d\epsilon_{shear}(s)}{ds} \cdot \frac{d\epsilon_{shear}(u)}{du} + C_3(x(t)) \left\{ [x(t) - x_{ref}] - \int_0^t ds f_1(t^* - s^*) \frac{dx}{ds}(s) \right\} \right\}$$

Thermal, Pressure, Shear Deformation, Matrix Cure

- This model has already been demonstrated with curing kinetics in structural foams [K. Long et al., SAND2018-9096]

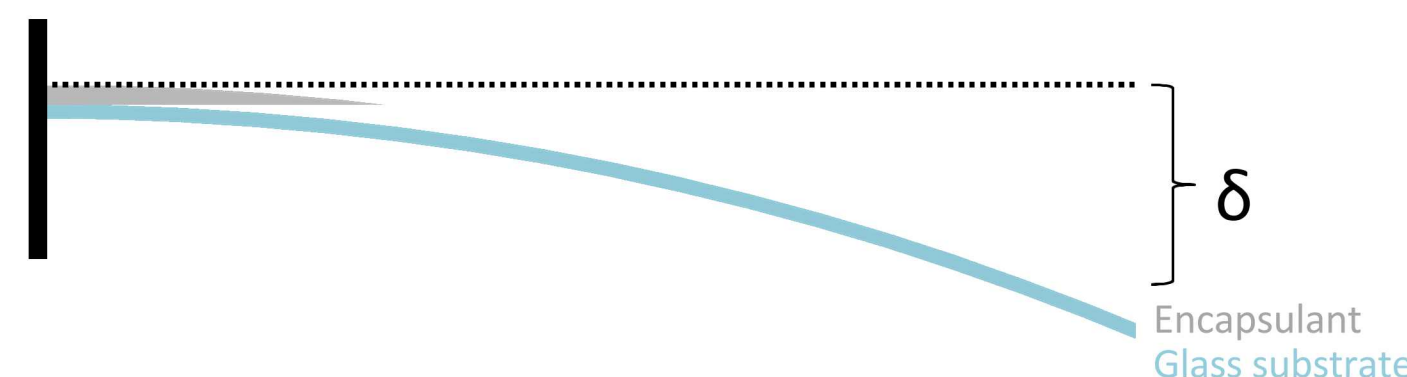
5: Polyethylene Crystallization

- A key thermal transition not yet captured in the EVA Universal Polymer model is polyethylene crystallization/melting, observed in differential scanning calorimetry (DSC), DMA and TMA
- This transition affects the thermal expansion as well as the viscoelastic behavior of the material and occurs within the operating temperature range of PV modules



6: Model Validation Efforts and Future Work

- Conduct stress-relaxation experiments to increase confidence in viscoelastic model in the low frequency regime
- Validate the constitutive material model using a cantilever deflection technique on encapsulant laminates:



- Additional work will investigate the possibility of adding curing kinetics and crystallization to the material models
- Similar experimental methodologies will be used to characterize samples collected from the fielded module library capability in development at Sandia