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Anisotropic Effects of Loading on Zircaloy Cladding Performance

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Malachi Michael Nelson

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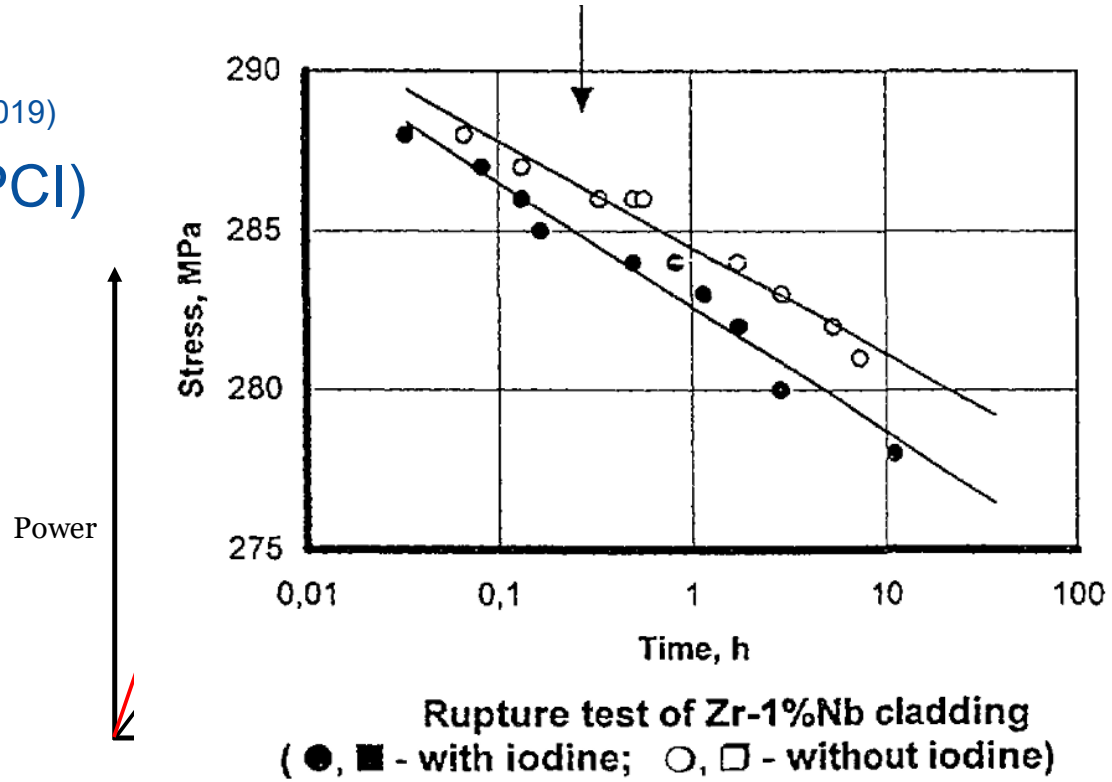
Overview

- Motivation
- Overview of testing methods
- Results of stress relaxation testing
- Comparison to current material models
- Implications

Stress Retention During Pellet Cladding Interactions

- Pellet-cladding contact ~20 GWd/MTU (IAEA, 2018), (Geelhood, 2019)
- Power increase → pellet-cladding interaction (PCI)
- Goal: understand stress accumulation and retention during PCI
- Investigate effects of anisotropy on stress

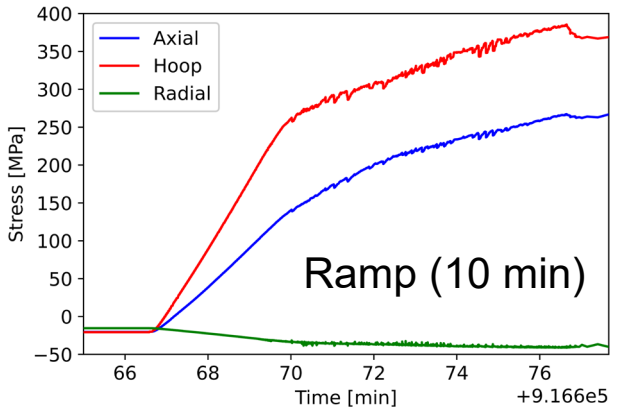


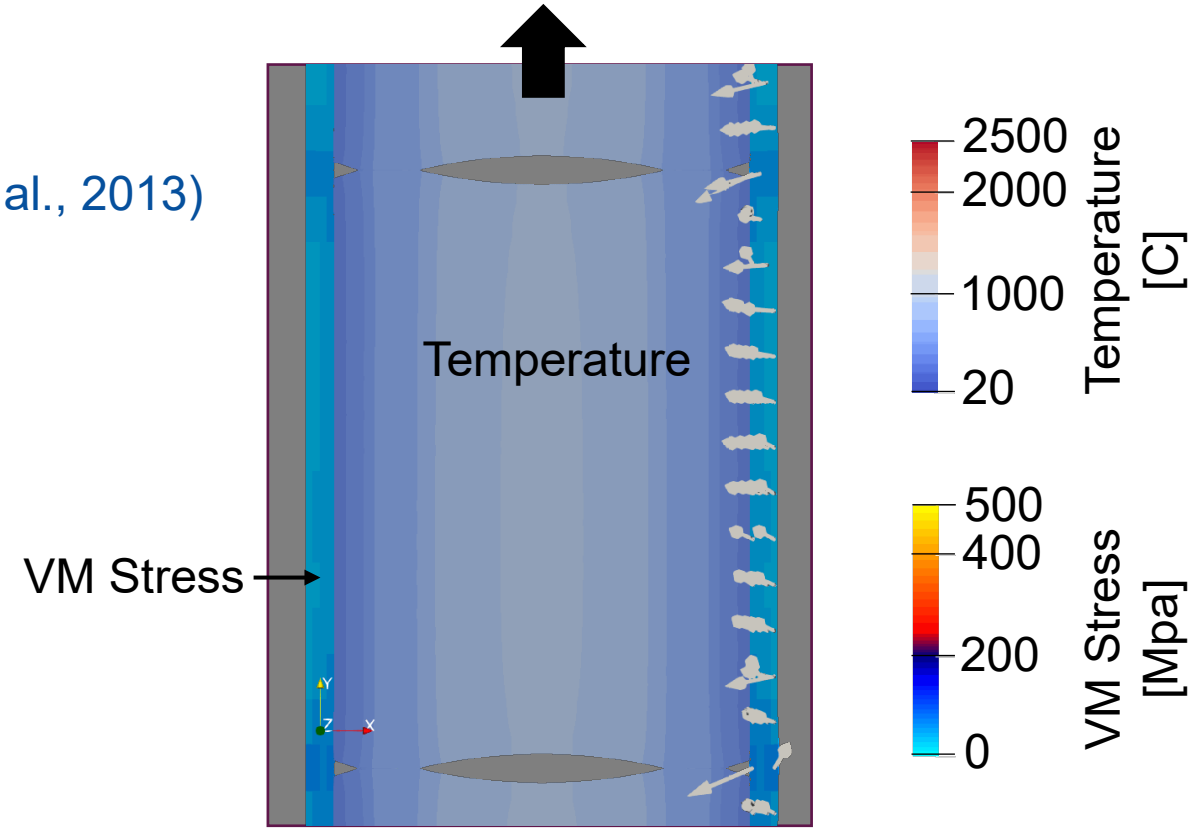
"[the] role of stress is very important: time to failure increases as the stress decreases"

(IAEA, 2021)

Cladding Testing Methods

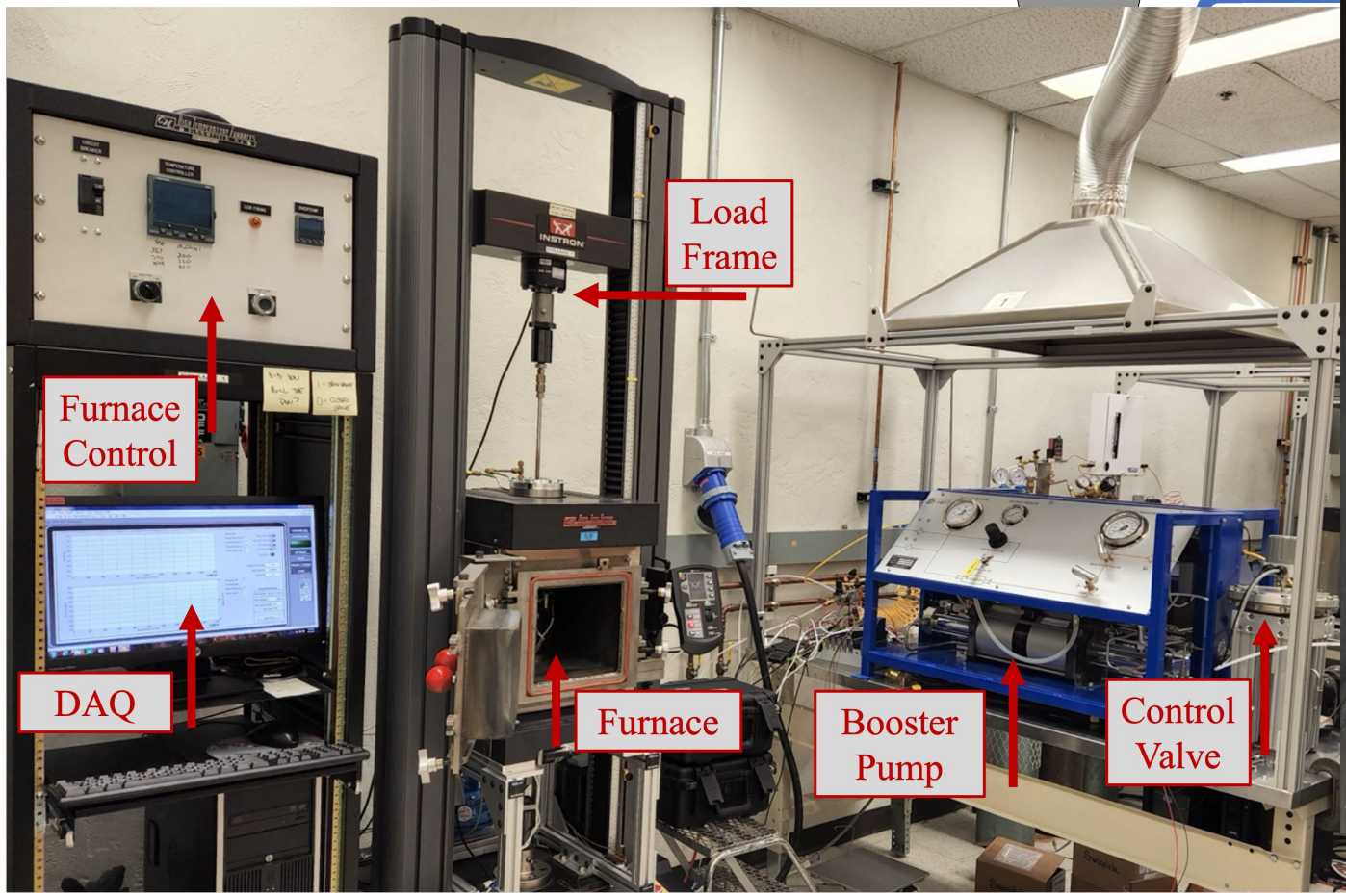
- Material: rolled plate or real cladding tubes?
- Loading: uniaxial or multiaxial?
- PCI achieve ~0.75 axial/hoop stress ratio
  - Experimental by (Suzuki et al., 2006), (Udagawa et al., 2013)
  - BISON modelling in present work
- Example methods
  - Uniaxial flat (rolled plate)
  - Uniaxial tube (Axial or hoop)
  - Internal pressure
  - Internal pressure + axial stress
  - Pellet compress-to-expand
  - Others?

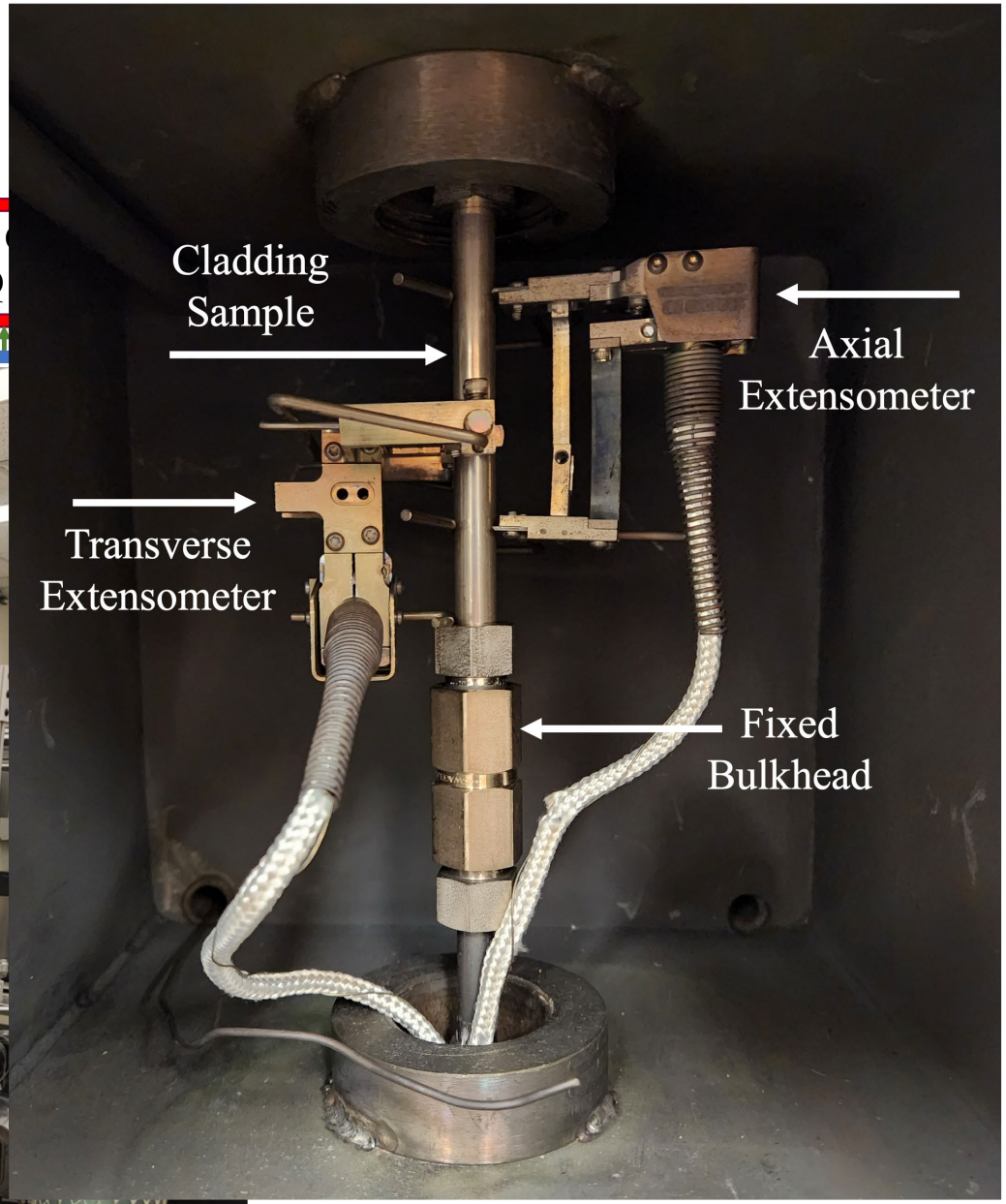




Mechanical Testing Methods

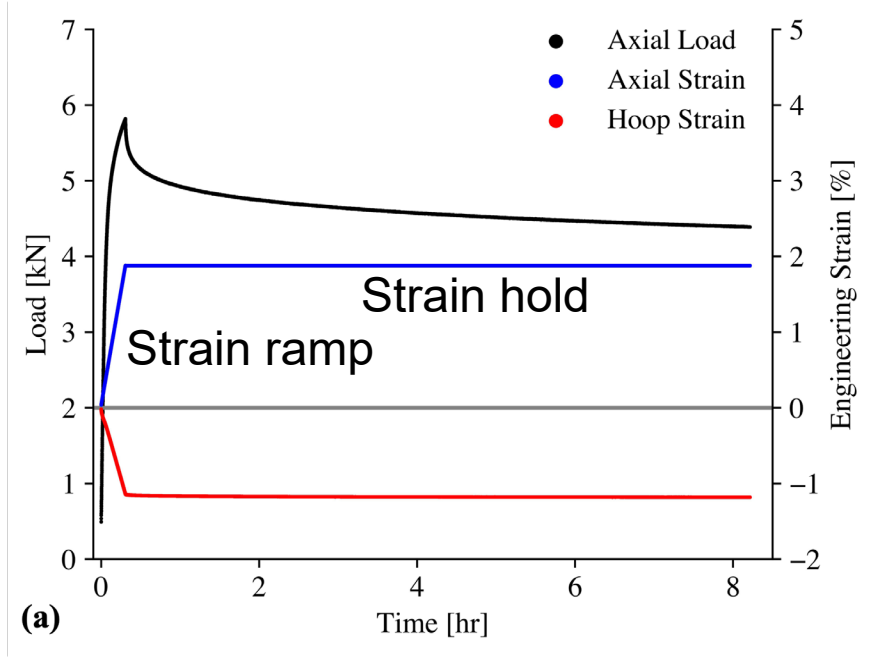
- Axial vs internal pressure



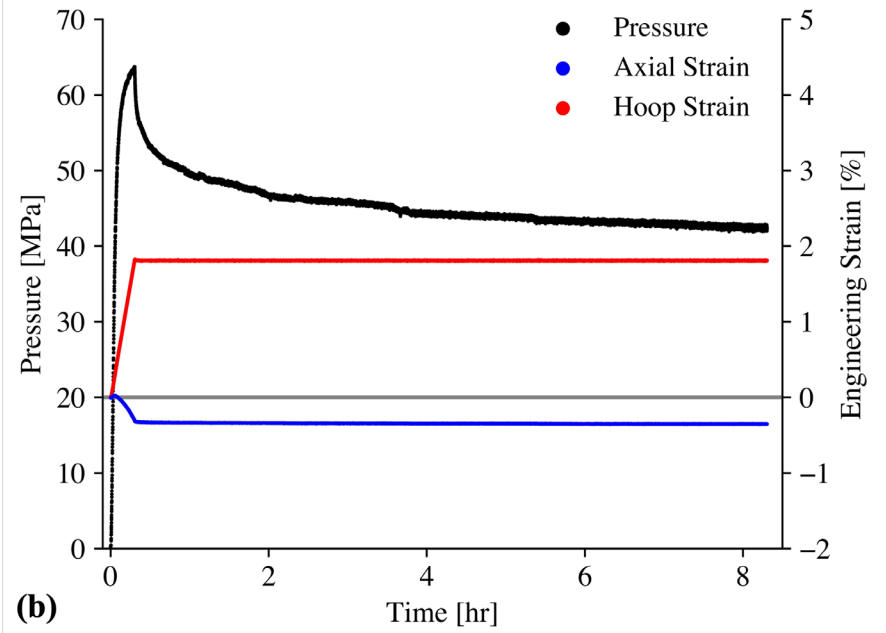


Stress Relaxation Testing Parameters

- Isothermal 300 °C in Ar
- Monotonic loading 0.1%/min (16.7 x 10^{-6})
- Hold strain for 8 hours
- Test multiple samples for repeatability
- Axial and internal pressure loading to 3 strains
  - 0.25% (below yield)
  - 1% (NRC limit for normal operation)
  - 2% (high strain



2% Axial (a)

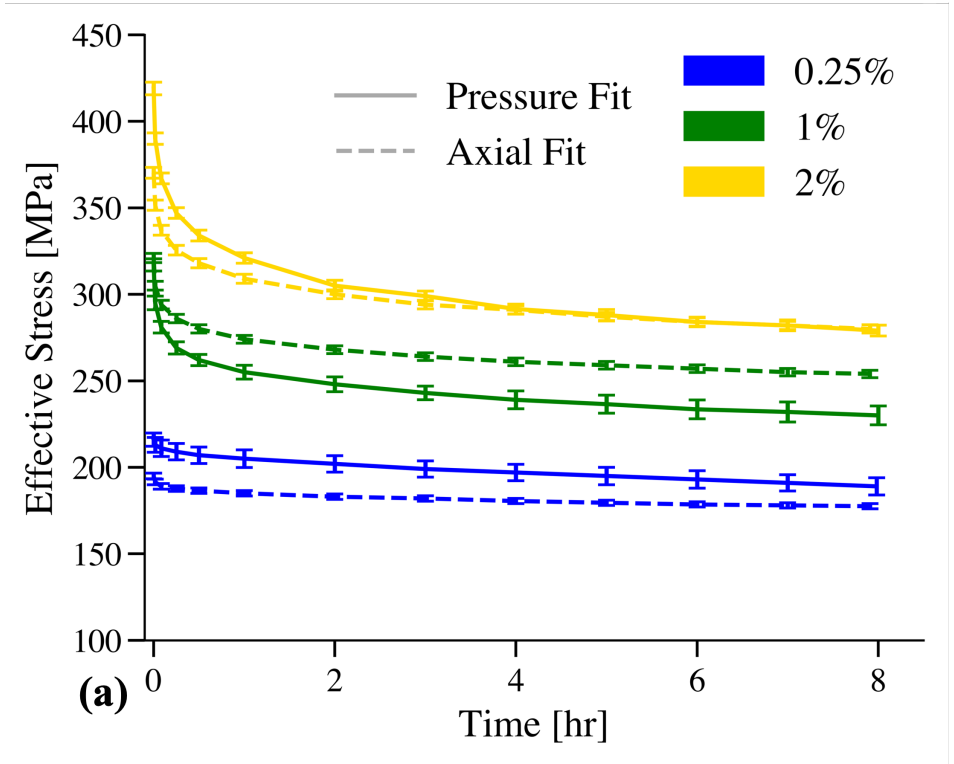


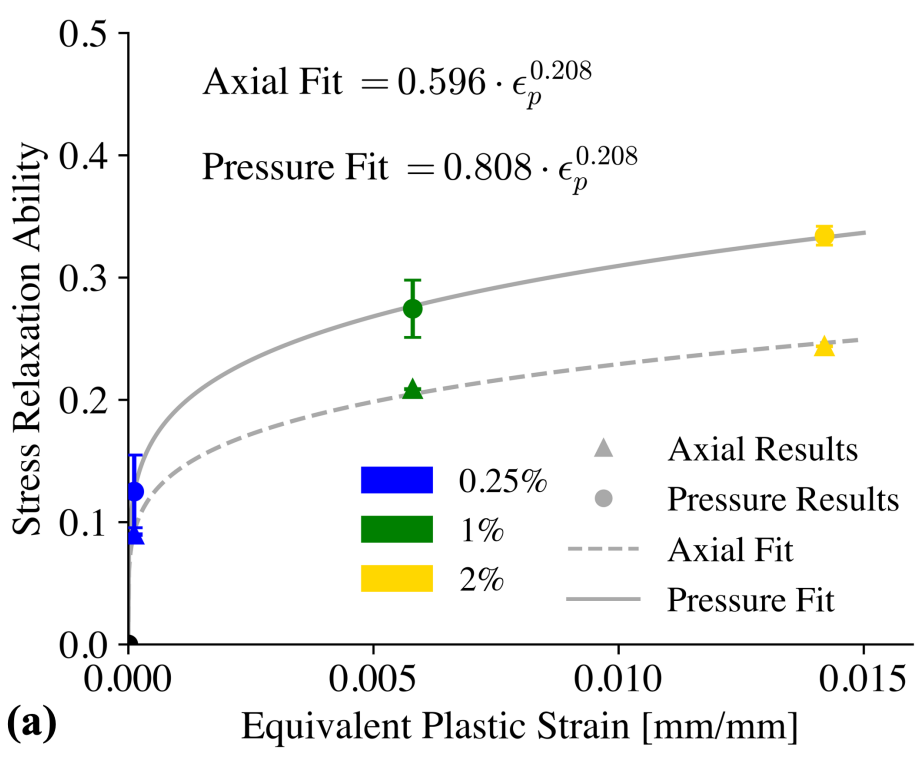
2% Pressure (b)

Stress Relaxation Testing Results

- Repeated testing demonstrates excellent repeatability
- Internal pressure samples display enhanced relaxation under all conditions

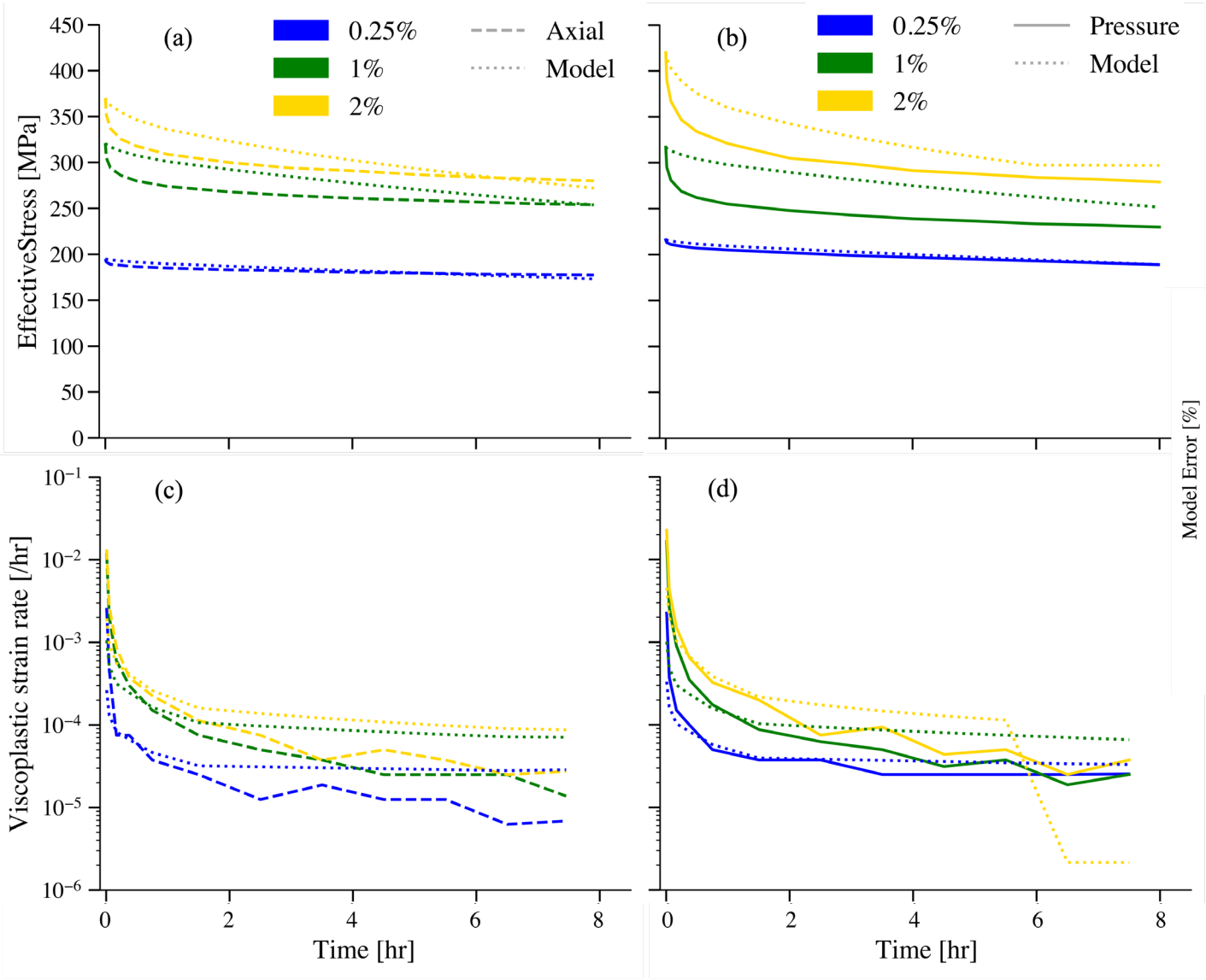
$$SRA = \frac{\sigma_{initial} - \sigma_{final}}{\sigma_{initial}}$$



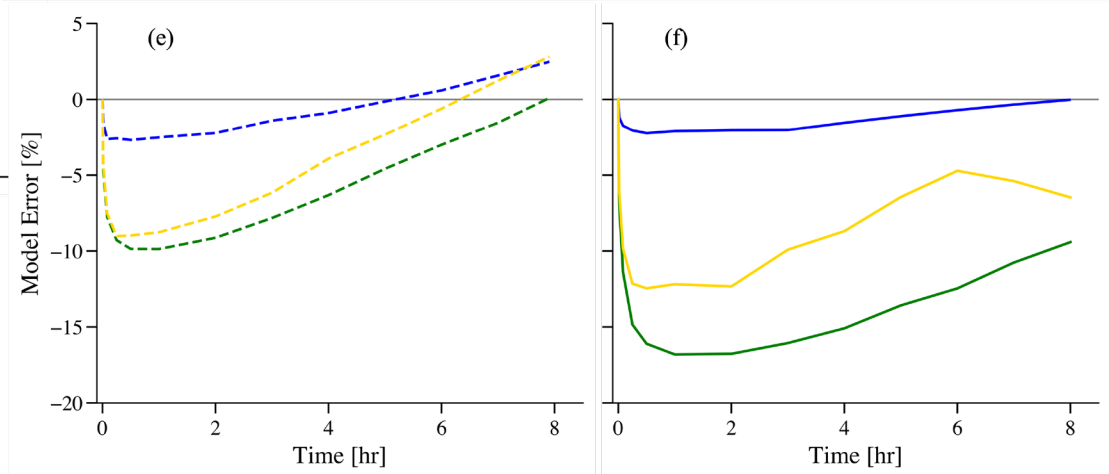


(Nelson & Kombaiah et al., 2024)

Comparison to Thermomechanical Material Models



Primary and secondary creep from (Matsuo, 1987) using Limback-Andersson model.

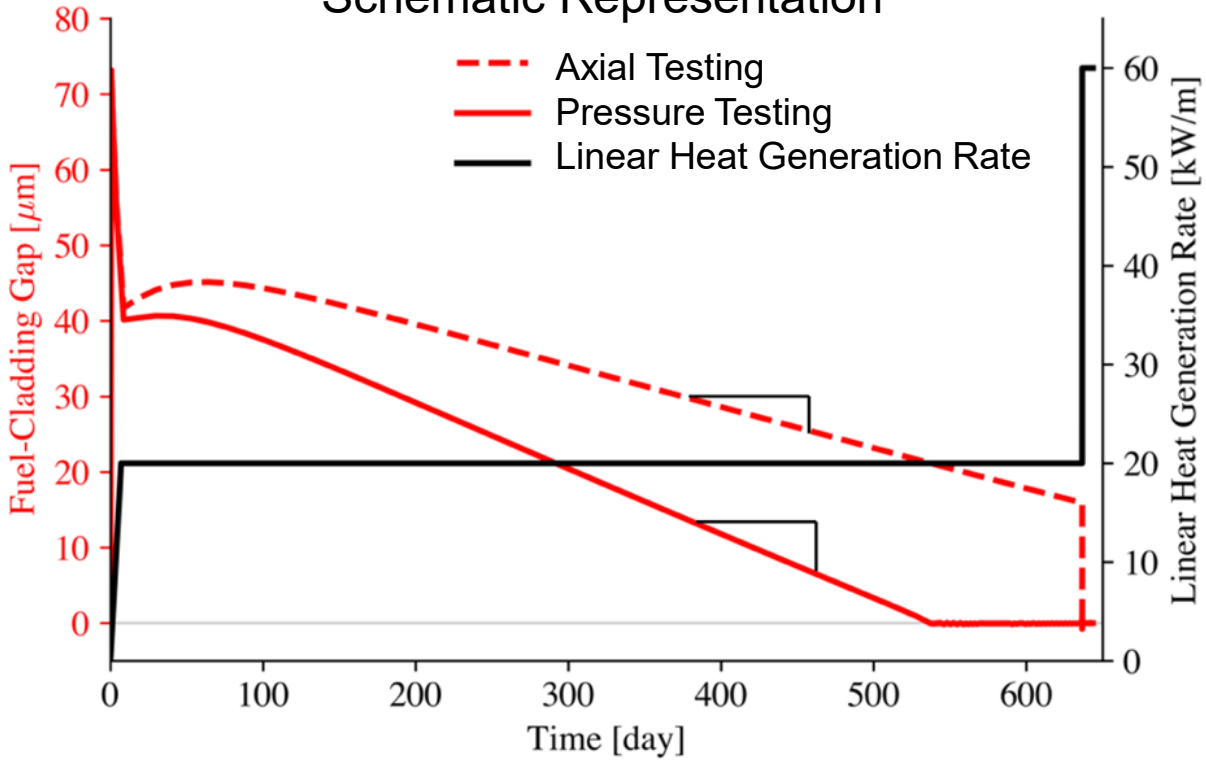


Implications for PCI

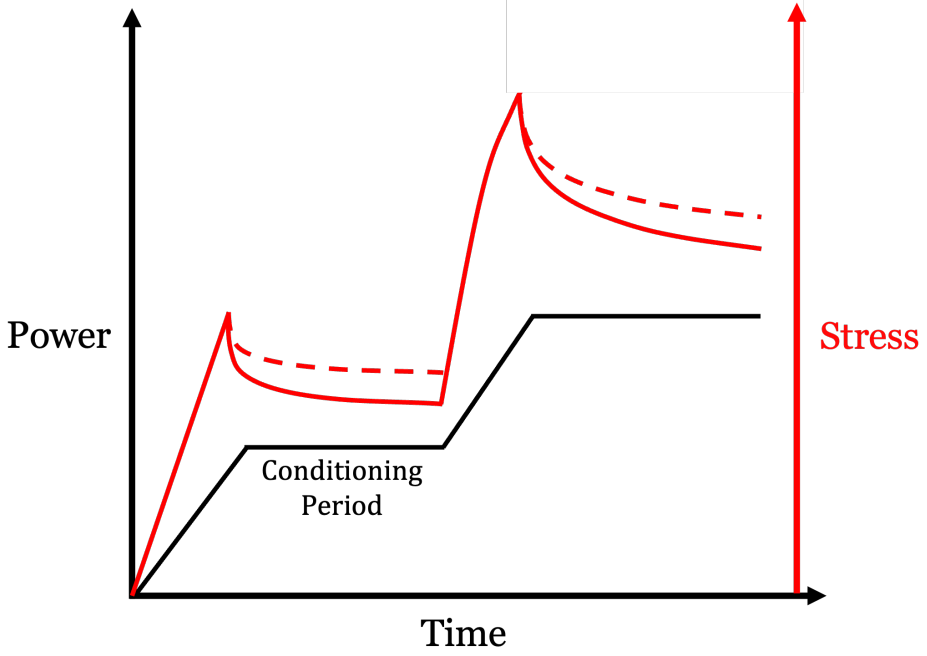
- Axial testing can underpredict stress accumulation *and* stress relaxation
- Examination of underlying mechanisms indicates this affects relaxation and creep

Cladding Creepdown

Schematic Representation

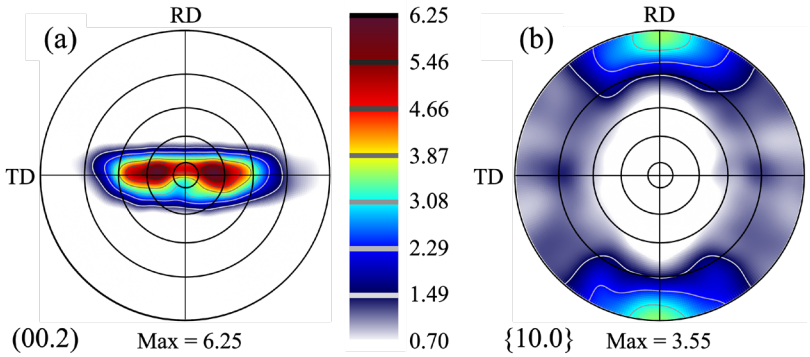


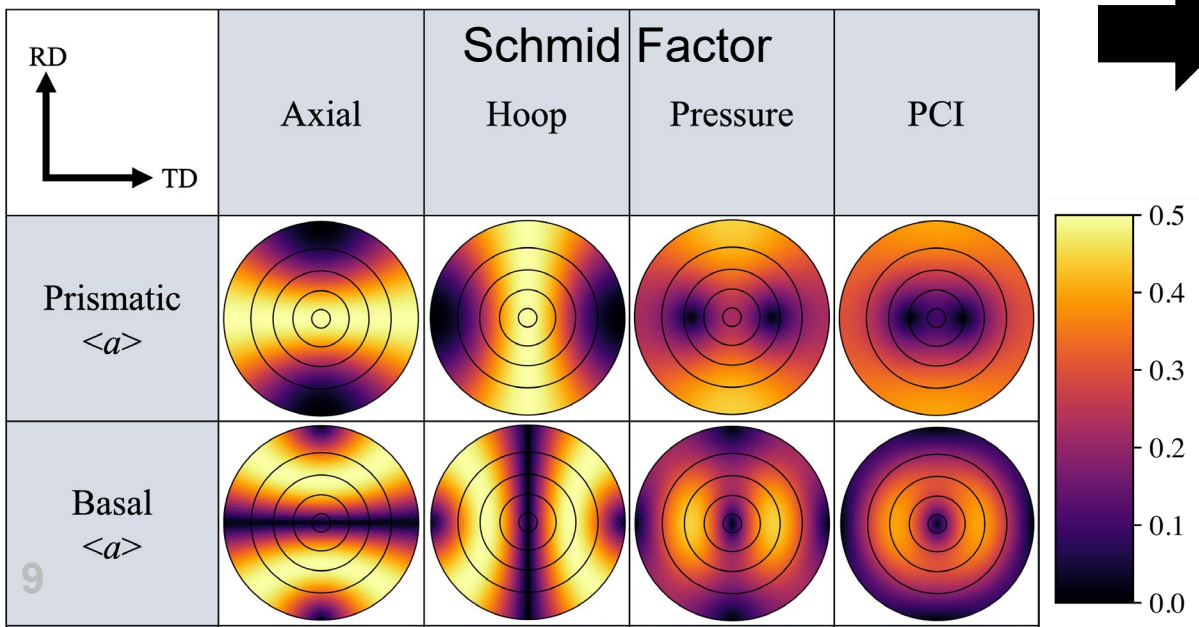
PCI Stress Relaxation

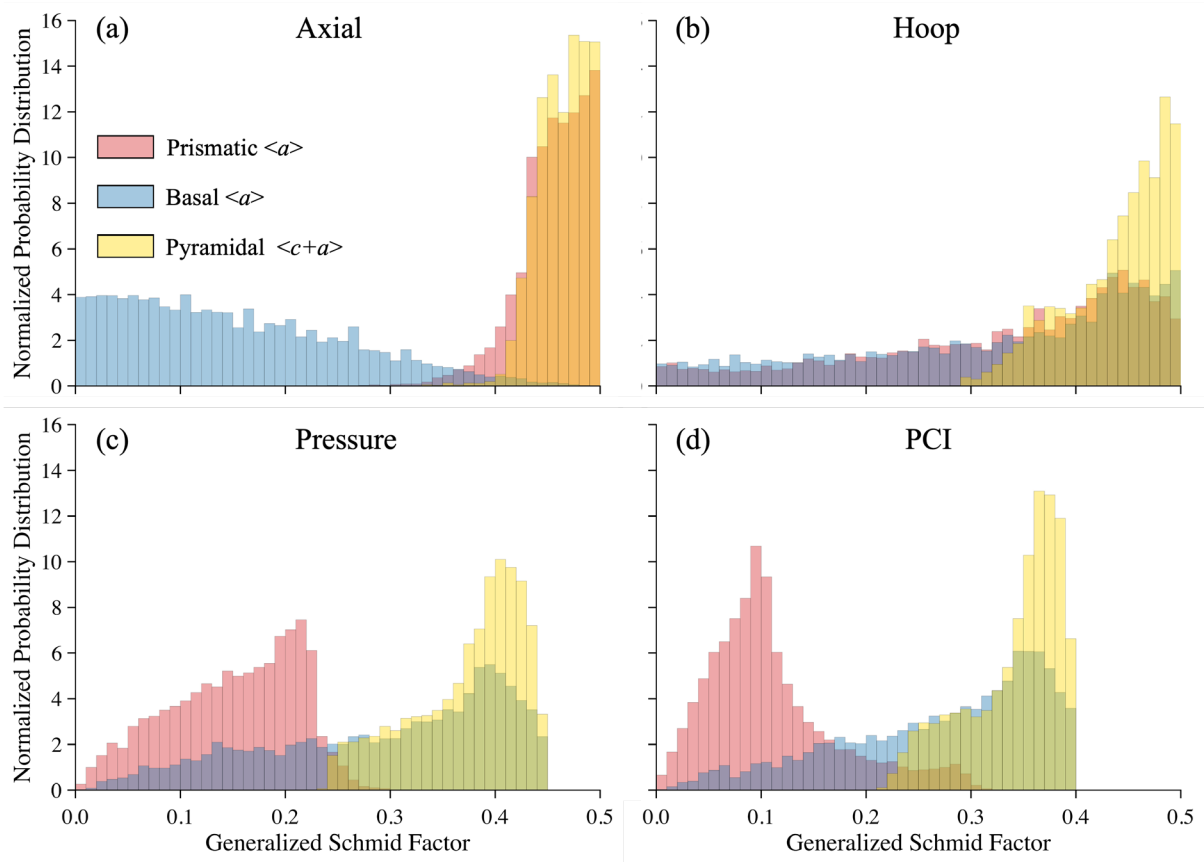


Extension to Hoop Ring Tension

- Analysis indicates that uniaxial hoop tension is much closer to PCI than axial







(Nelson & Kamerman et al., 2024)

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- (Nelson & Kombaiah et al., 2024) Nelson, M., Samuha, S., Kombaiah, B., Kamerman, D., Hosemann, P. “Enhanced Stress Relaxation Behavior *via* Basal <*a*> Dislocation Activity in Zircaloy-4 Cladding” under review, Journal of Nuclear Materials http://dx.doi.org/10.2139/ssrn.4838638
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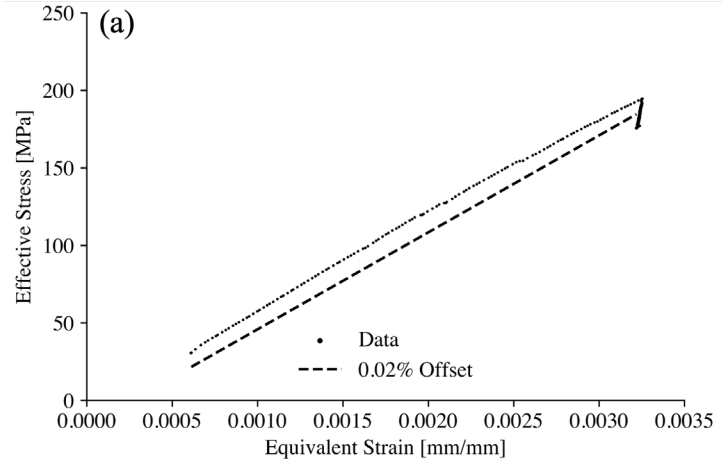
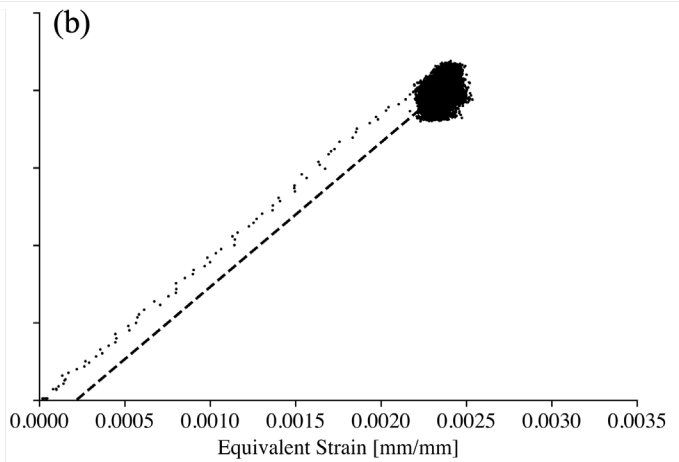
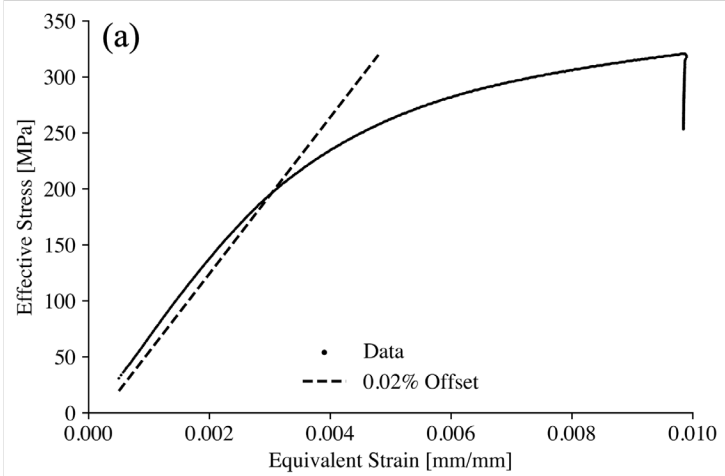
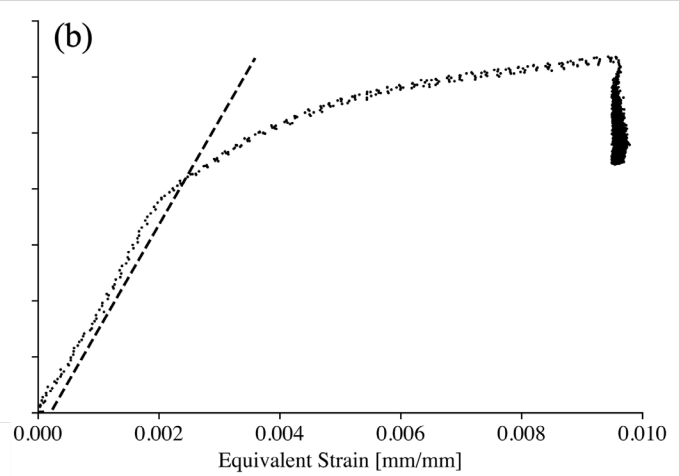
- (Nelson & Kamerman et al., 2024) M. Nelson, S. Samuha, D. Kamerman, and P. Hosemann, “Temperature-Dependent Mechanical Anisotropy in Textured Zircaloy Cladding,” *J. Nucl. Mater.*, vol. 595, p. 155045, Jul. 2024, doi: 10.1016/j.jnucmat.2024.155045.

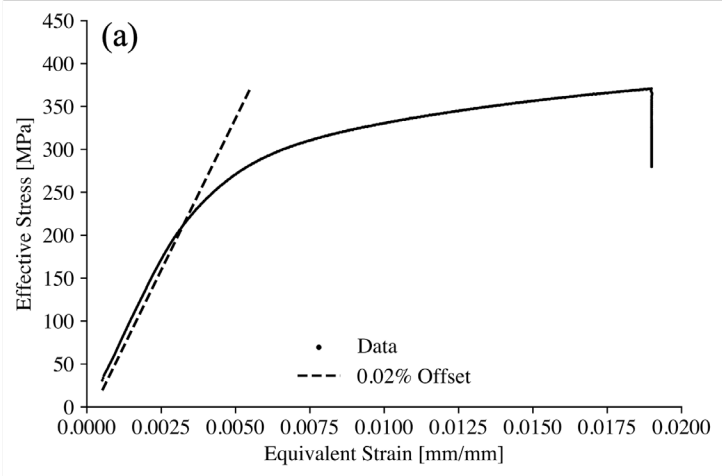
Yield Offset

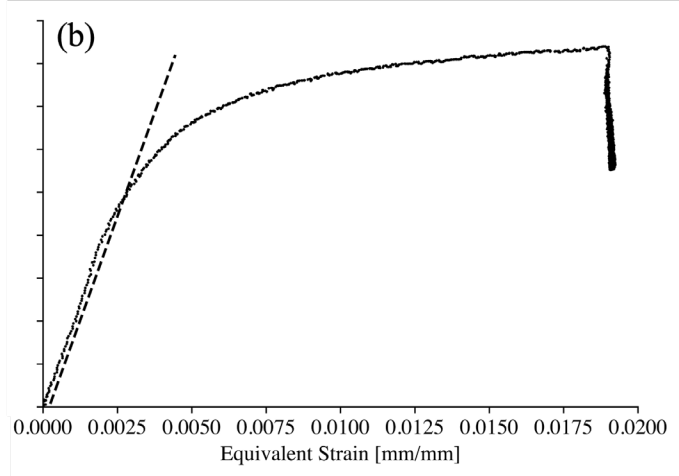






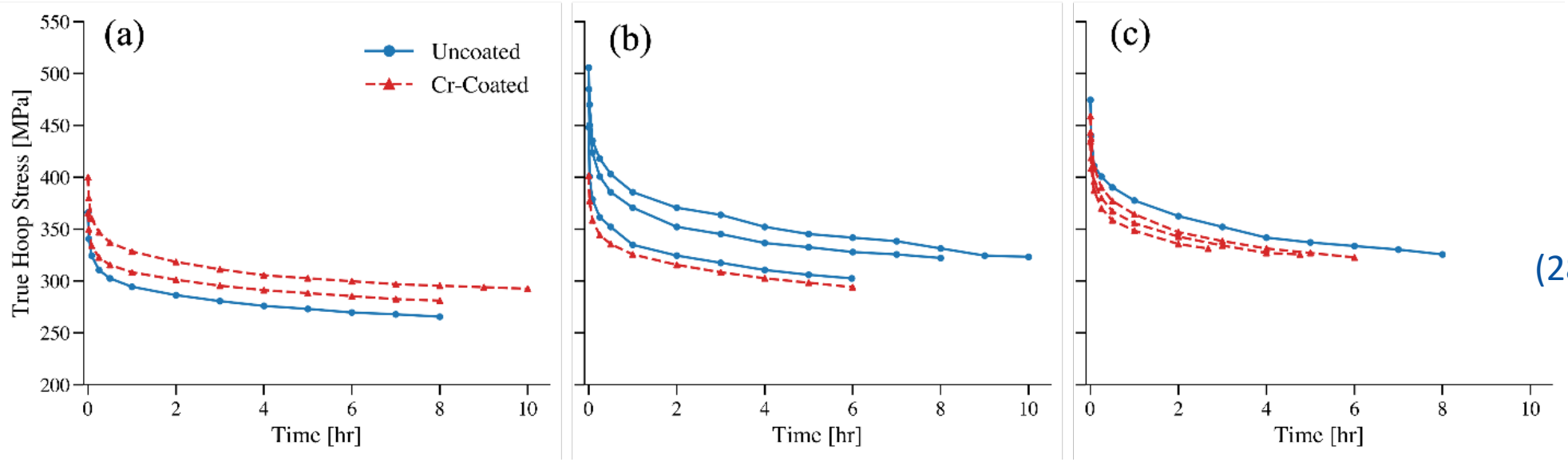




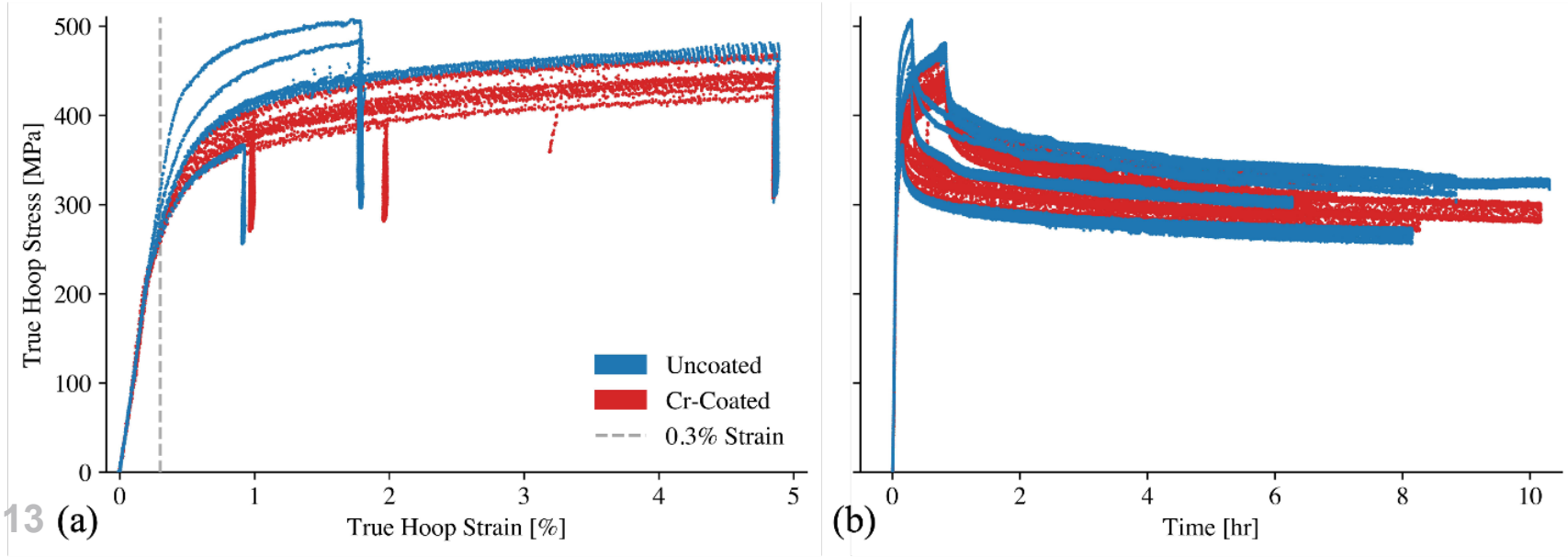


BORATORY

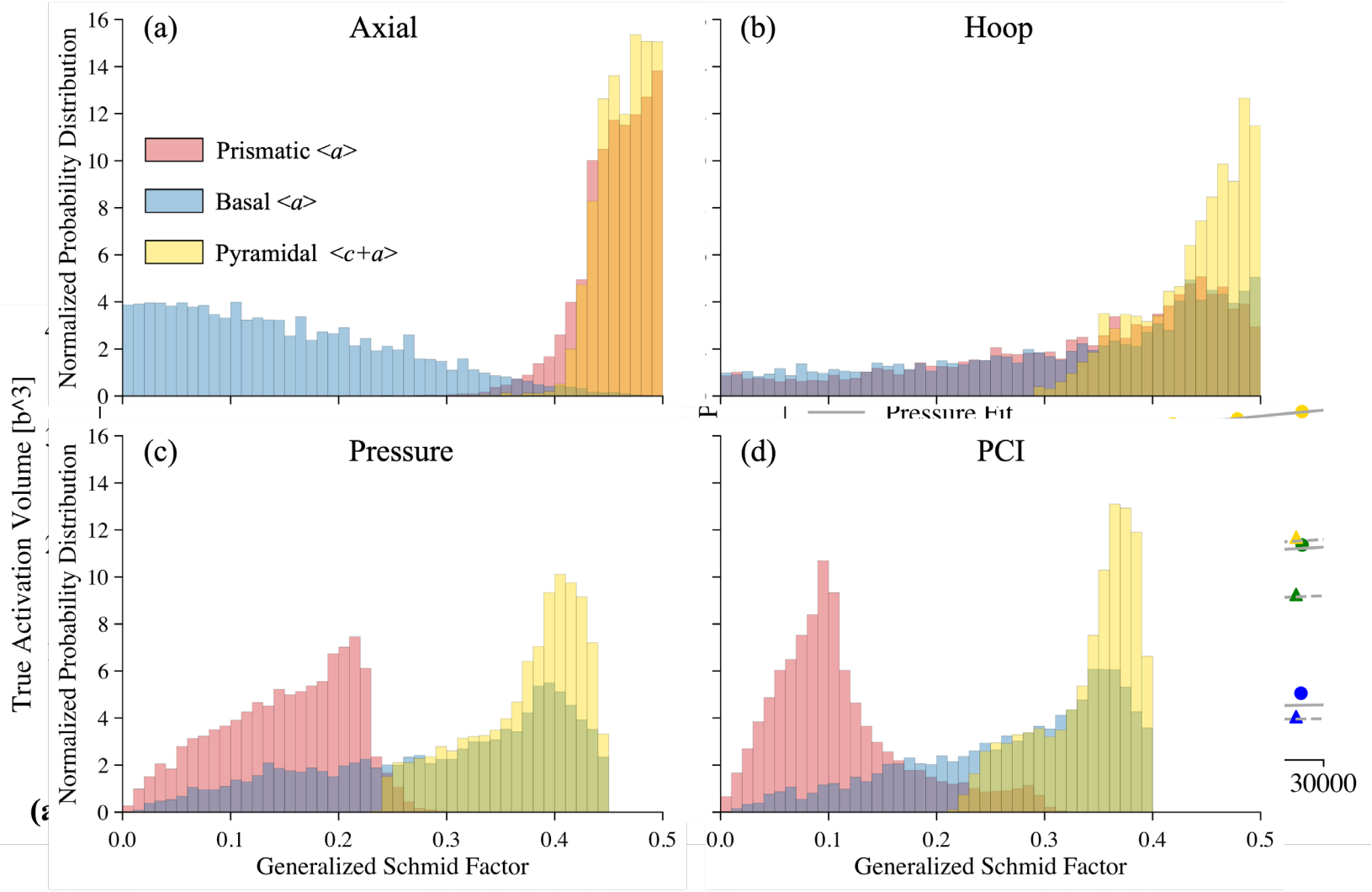
Extra material on Cr-coated comparison

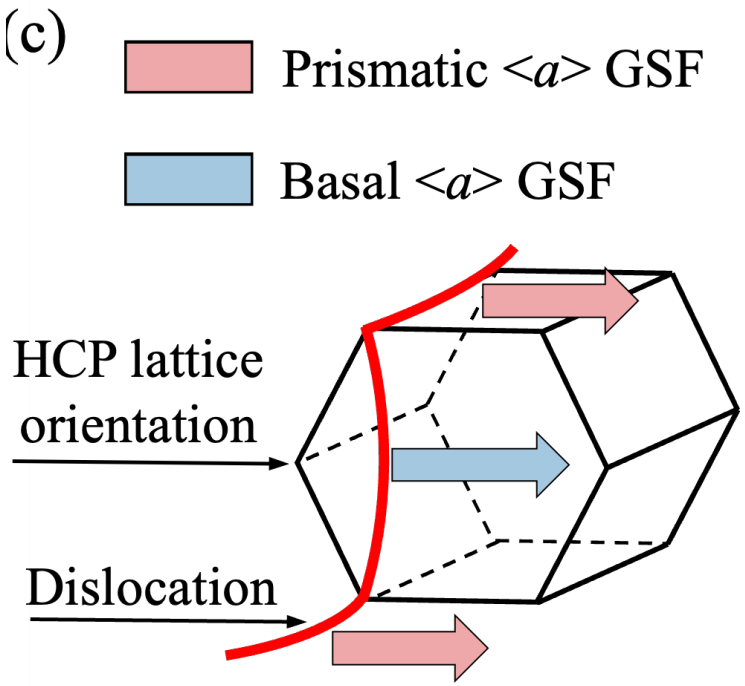


Hoop Stress at Yield [MPa]	
Uncoated (280 ± 50 MPa)	246
	251
	278
	368
	242
Cr-coated (245 ± 7 MPa)	247
	255
	242
	236
	248
	241



Extra material on underlying mechanisms

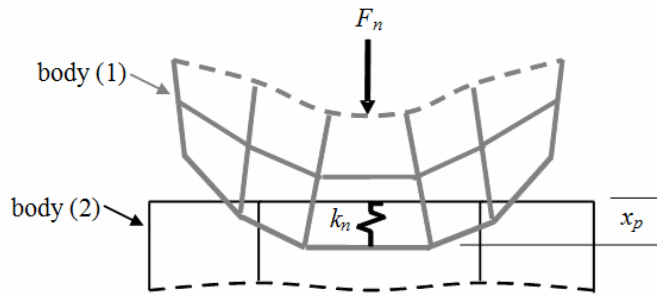


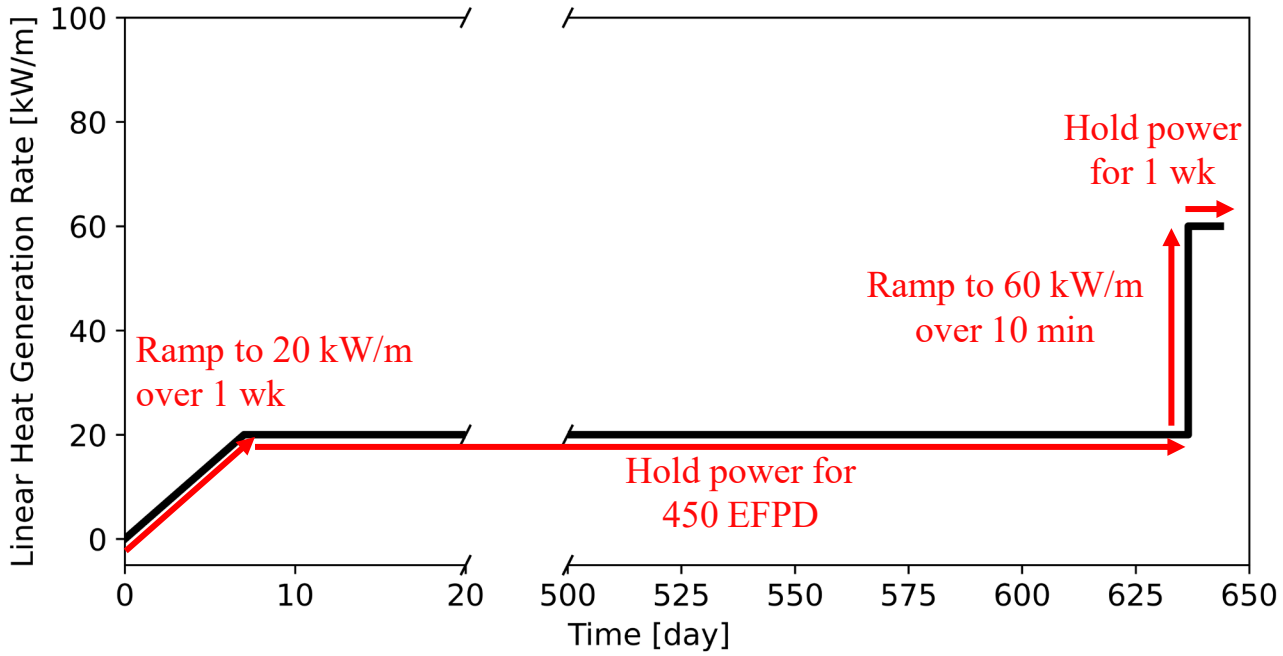


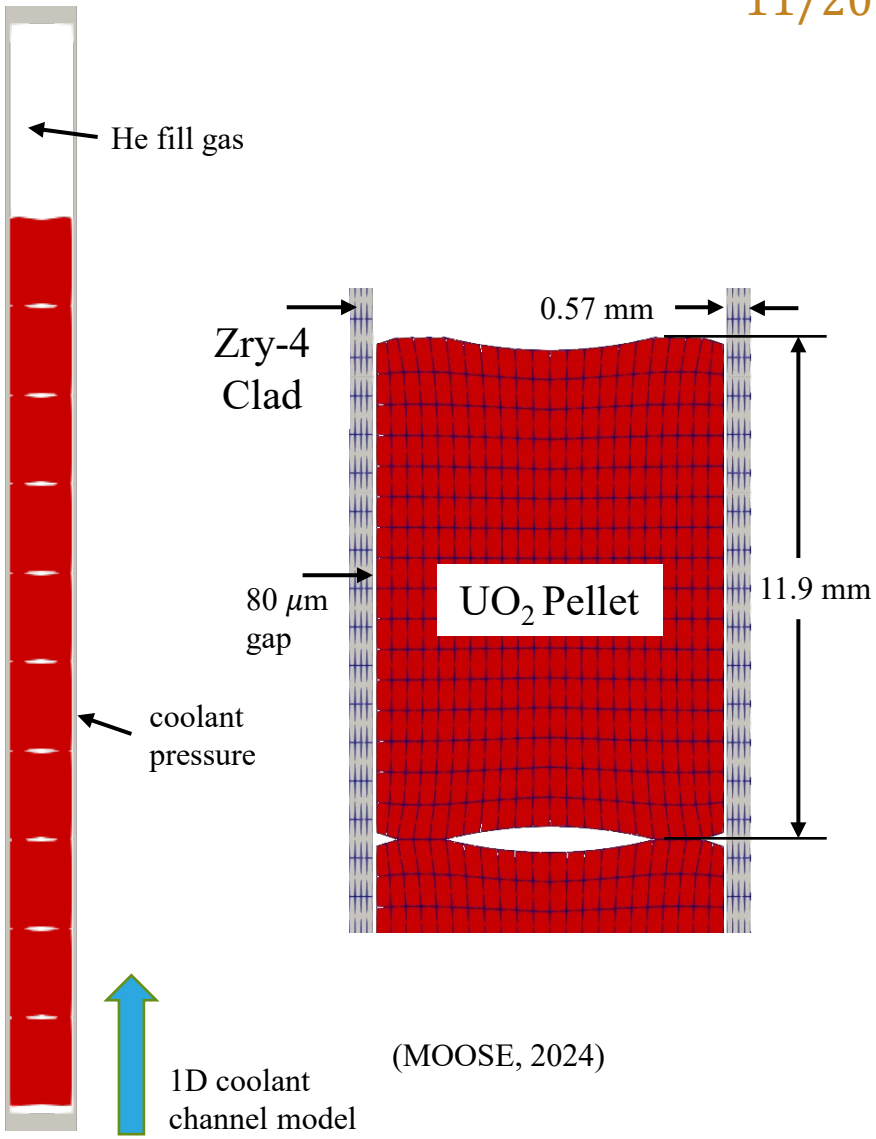
BISON Simulation of PCMI

Mechanical contact model

- Coulomb friction: $F_f = \mu \cdot F_N$
- Augmented Lagrange convergence
  - Iterative penetration penalty

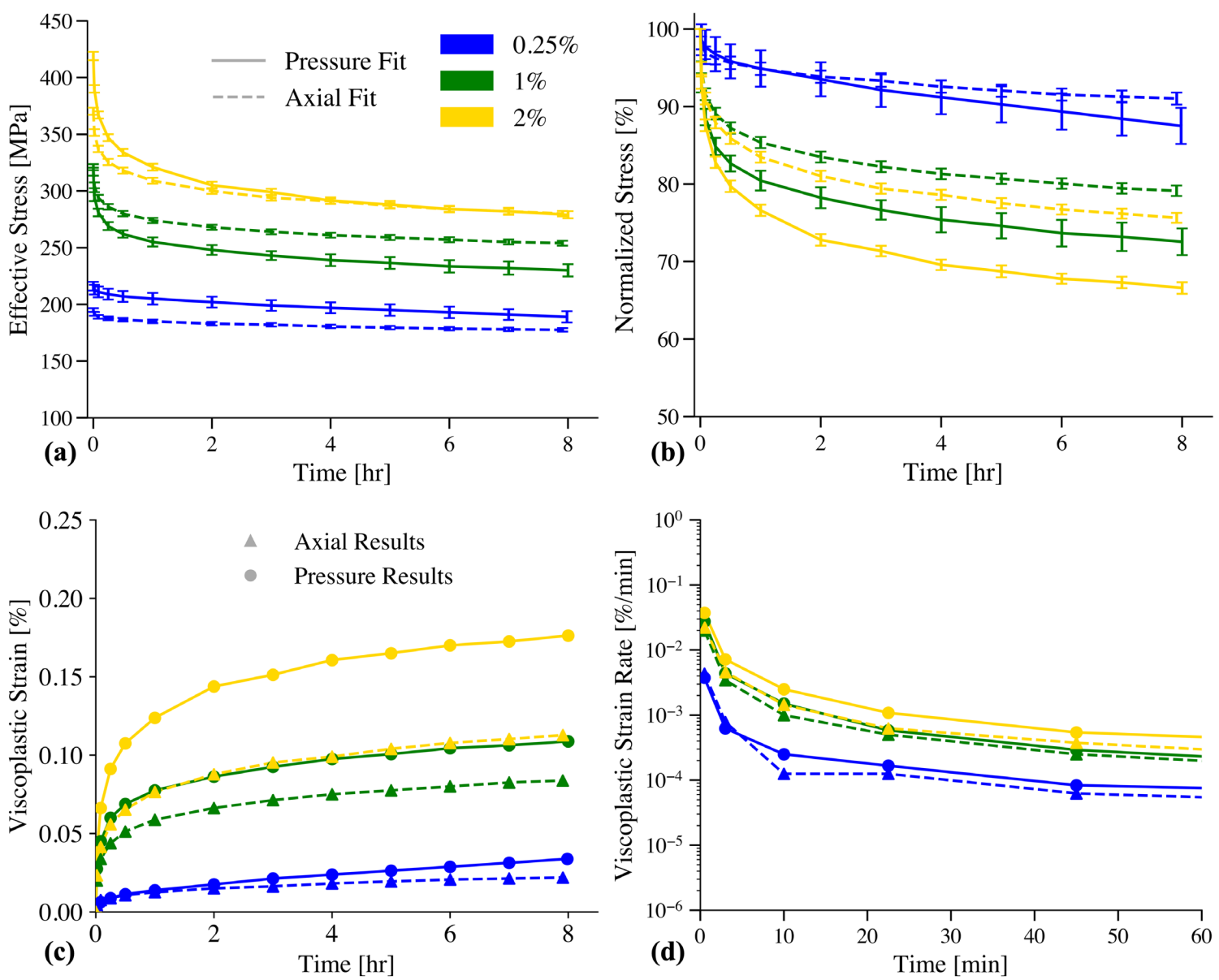






(MOOSE, 2024)

Additional Stress Relaxation Results



Mechanical Testing at Various Temperatures (Plastic)