INL/CON-22-69256-Revision-1

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October 2022

Changing the World's Energy Future

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**Prepared for the**
**U.S. Department of Energy**
**Under DOE Idaho Operations Office**
**Contract DE-AC07-05ID14517**

# Mechanical response and microstructure evolution from multiaxial stress relaxation in textured zircaloy nuclear cladding

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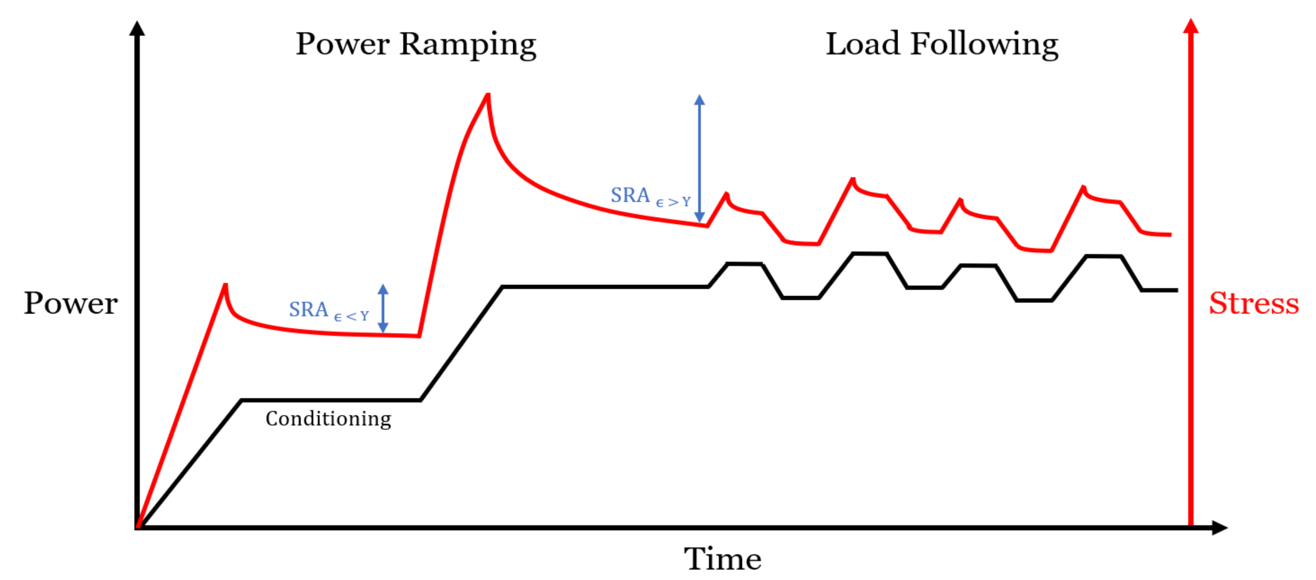
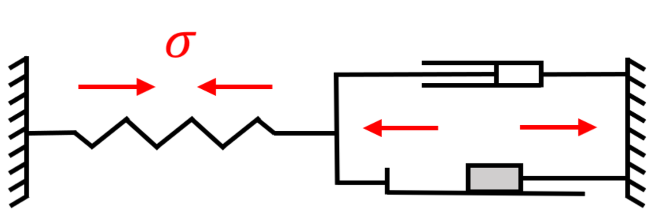
## Motivation


- Pellet cladding interactions can cause cladding degradation and failure
- Relaxation periods are used to reduce peak stress and improve ductility
- Modern energy markets require more load following from nuclear fleet
- Biaxial stress relaxation is important for safe and efficient cladding use




## Background

- Stress accumulates during strain because elastic strain stores energy in the material: elastic energy
- Elastic energy is dissipated during stress relaxation as elastic strain converts to inelastic strain
- Rheological models visualize elastic, plastic, and viscoplastic response of material upon loading



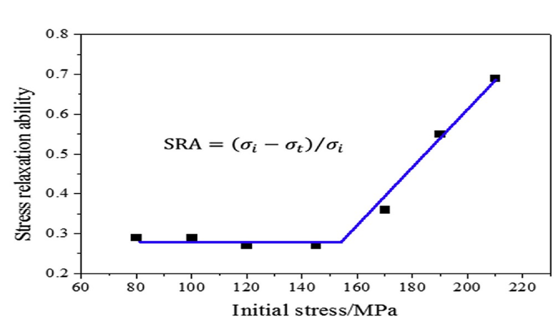

*Elastic*: $\sigma = \epsilon^e \cdot E$

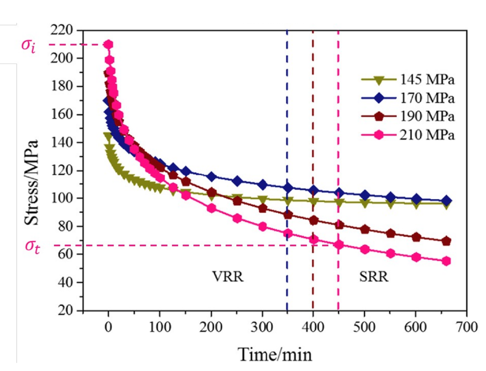
*Plastic*: $Y(\epsilon^p) \leq K \cdot (\epsilon^p)^n$

*Viscoplastic*: $g(\dot{\epsilon}^p) = \left(\dot{\epsilon}^p / \dot{\epsilon}_0^p\right)^m$

*Inelastic*: $\sigma = Y(\epsilon^p) \cdot g(\dot{\epsilon}^p)$

- Inelastic deformation results in lattice defects on interface between deformed/undeformed material
- These dislocations require significant energy to produce but much less to move



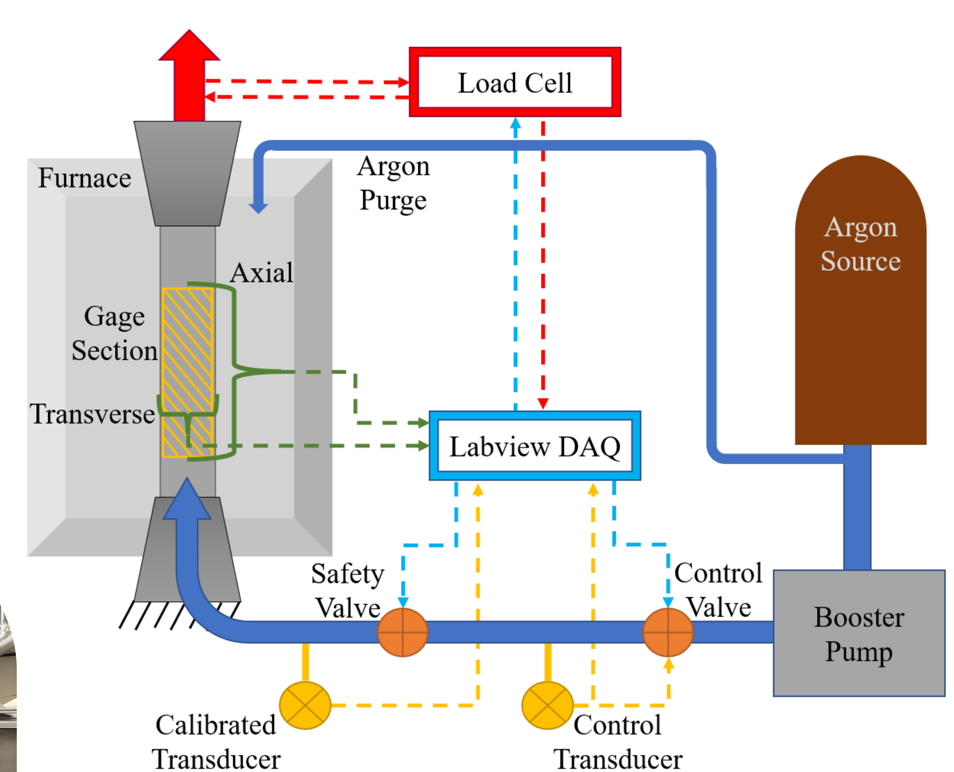



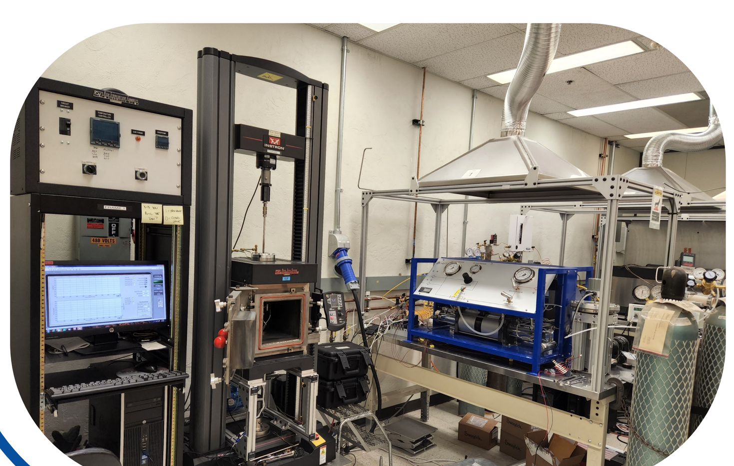

Material: Al-Cu alloy
Test temp: 165C
Yield stress: 145 MPa
(Yang, 2020)

- Initial dislocations allow elastic energy dissipation and defect annihilation without defect production
- Stress relaxation behaves differently when loaded above/below yield stress: stress relaxation ability
- Dislocation production during plasticity strongly affects stress relaxation behavior

## Experimental Capabilities

- Commercial cladding testing
- Programable stress- or strain-controlled loading
- Internal pressure up to 135 MPa
- Supplementary independent axial loading
- High temperature capability: 20-650 °C
- Argon purge to prevent oxidation
- Simultaneous material property measurement
- Rated for cladding burst testing
- *Hydriding capabilities also available

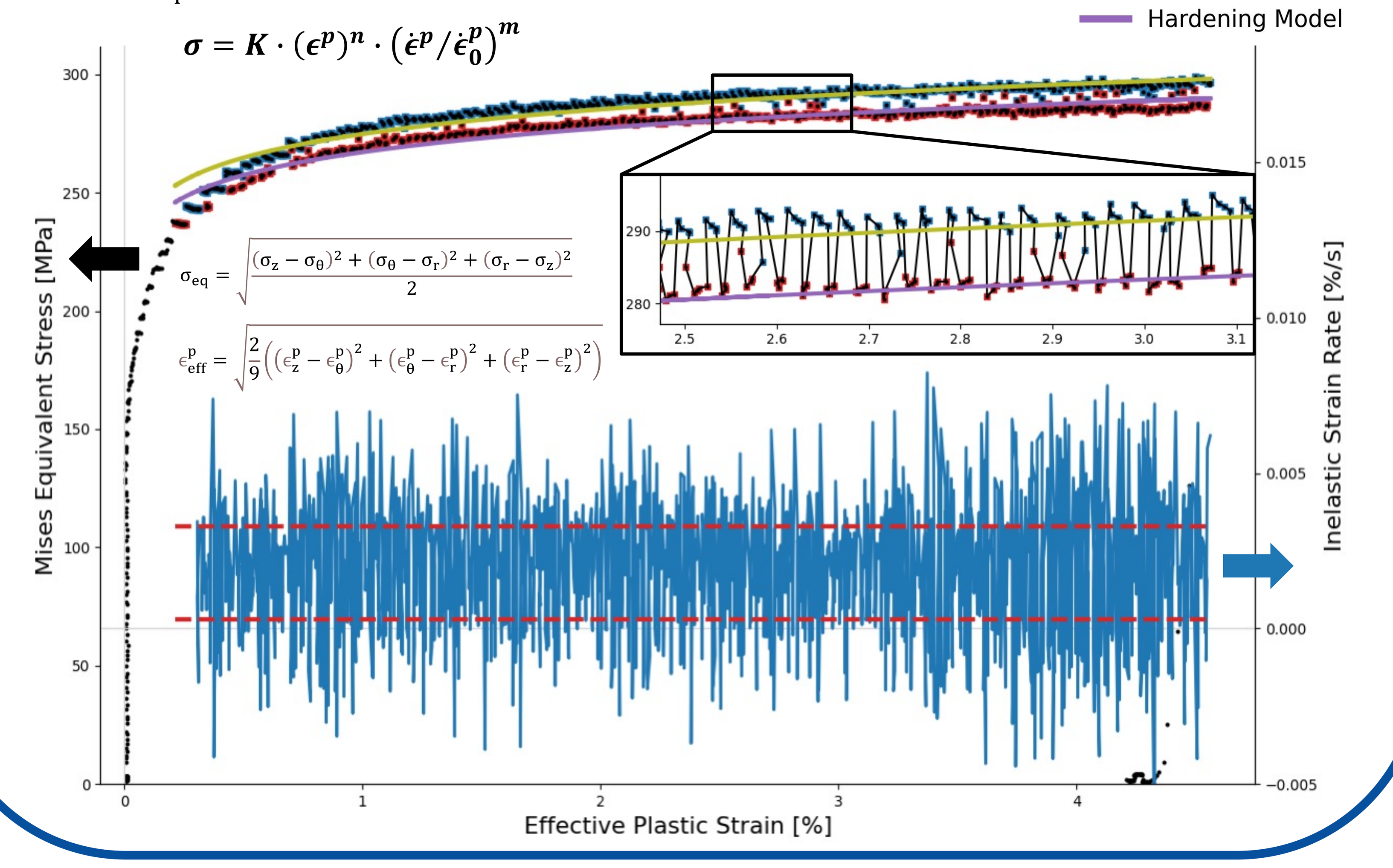


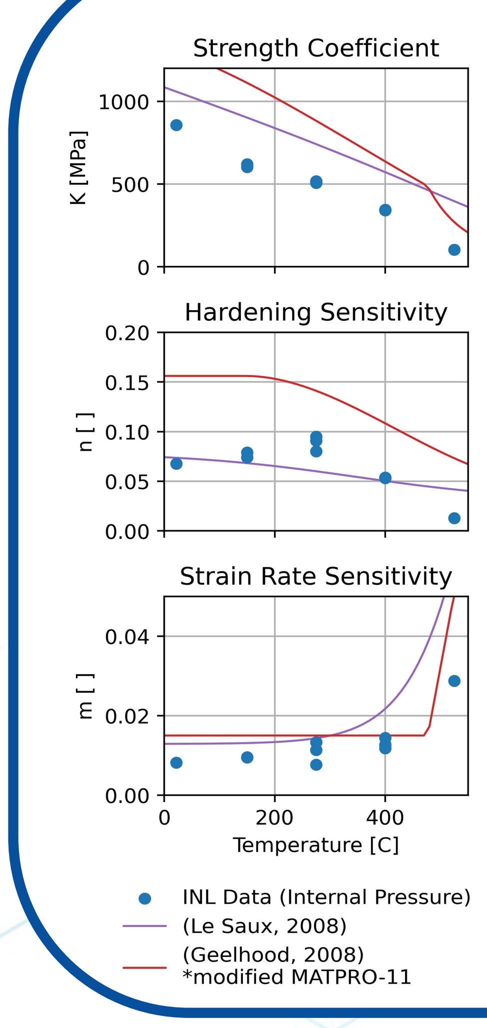
## Data Analysis

Nonlinear regression used to calculate power law hardening model coefficients from reference data set. Then the strain rate sensitivity exponent was calculated using high strain rate data set fitted to compound model:

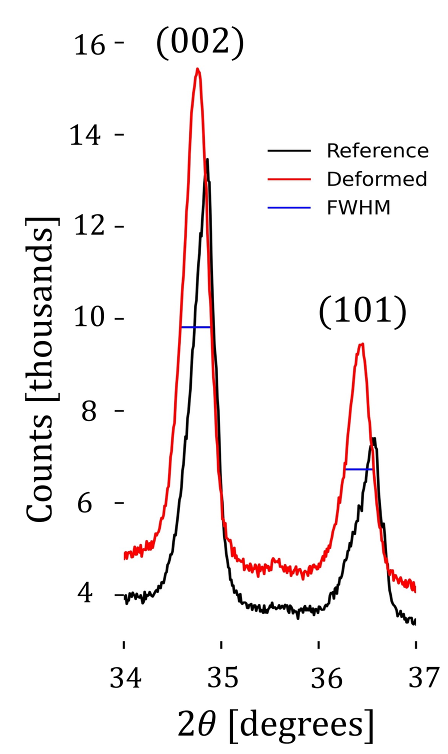
$$\sigma = K \cdot (\epsilon^p)^n \cdot \left(\dot{\epsilon}^p / \dot{\epsilon}_0^p\right)^m$$



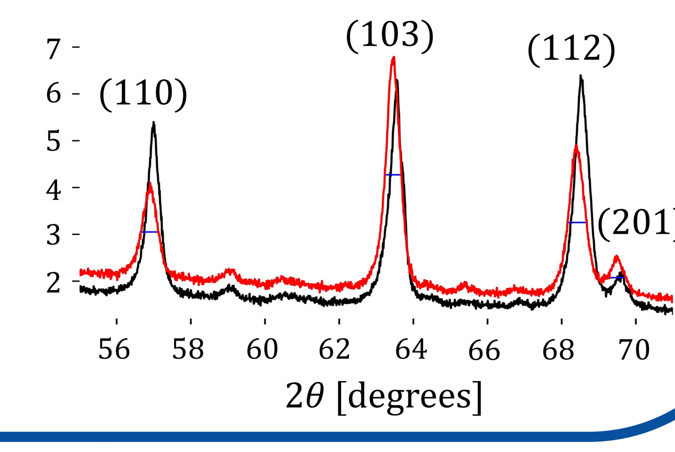

## Results




### Selected XRD Spectra



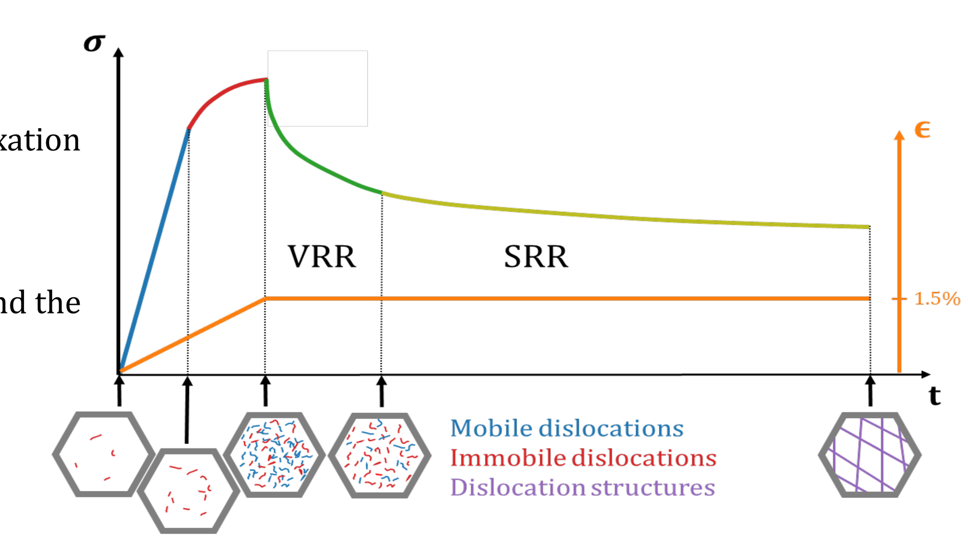

| System | Intensity [%] | ΔFWHM [degrees] | d [ Å] | ε [%] |
|---|---|---|---|---|
| (002) | 100. | 0.0409 | 2.5791 | 0.2852 |
| (101) | 48.6 | -0.0307 | 2.4628 | 0.3251 |
| (110) | 18.7 | 0.1023 | 1.6168 | 0.1481 |
| (103) | 44.9 | 0.0102 | 1.4643 | 0.1010 |
| (112) | 29.4 | 0.0613 | 1.3706 | 0.1575 |
| (201) | 8.45 | -0.0919 | 1.3517 | 0.1801 |




## Further Work

Investigate:
- Anisotropic stress relaxation behavior
- Microstructure evolution during stress relaxation
- Effects of varying loading configurations
- Textured material effects

The goal of this research is to better understand the relationship between microstructure and mechanical properties in the context of stress relaxation.




## Acknowledgements

This work was supported through the U.S. Department of Energy Advanced Fuels Campaign under DOE Idaho Operations Office. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

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