U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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Ultrasonic Measurements (MIMIC-RUSL)

Advanced Sensors and Instrumentation Annual Webinar

October 30, 2019

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INL

Project Overview

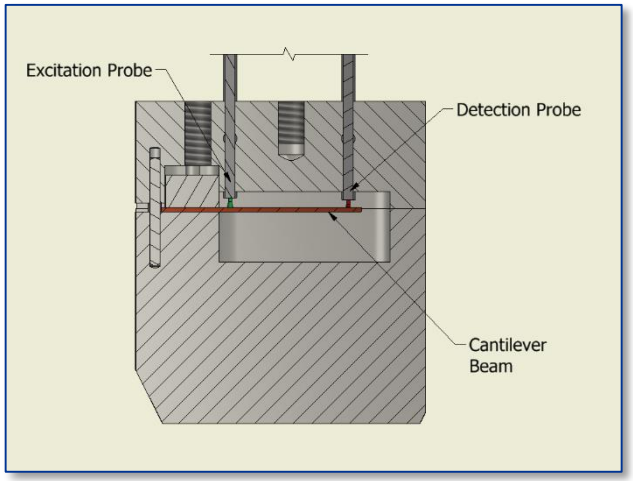
- The goal of this work (FY19) was to design, fabricate, and perform microstructural monitoring during in-pile irradiation using laser-based resonant ultrasound spectroscopy (RUSL).
- Elastic properties of materials are profoundly influenced by microstructure. Thus monitoring elastic properties can be used to indirectly extract microstructure information.
- Participants (2019)
  - WP Manager: Zilong Hua
  - Robert Schley (PI), David Hurley, Nic Woolstenhulme, Larry Agesen
- Schedule
  - Feb 2019 – Presented prototype measurement results at ANS-NPIC-HMIT conference.
  - Mar 2019 Completed fabrication of test capsule
  - Apr 2019 Delivered RUSL capsule to TREAT
  - May 2019 Performed measurements during TREAT irradiation
  - Sept 2019 Reported on data analysis and preliminary modelling results

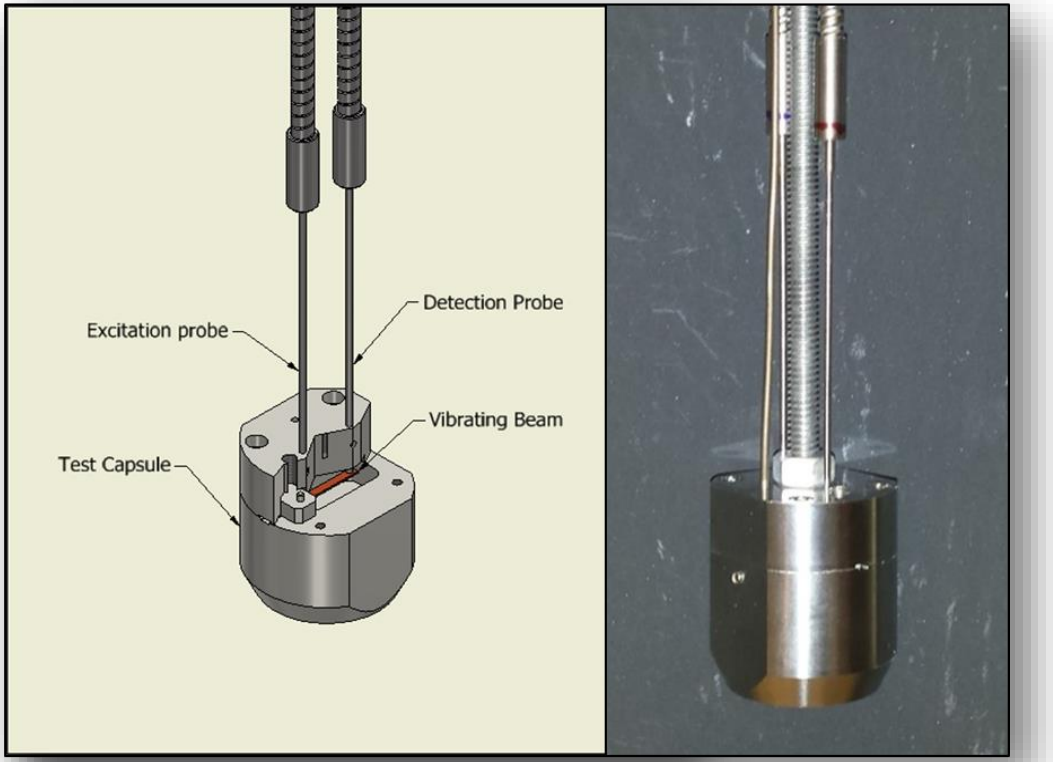
Accomplishments – Associated Milestones

- FY19 Milestones
  - M2CT-19IN0707073 – Design and Fabricate Installation-ready Test Capsule for the In-Situ Measurement of Elastic Properties using an Optical Fiber Based Measurement Technique – Completed March 2019
  - M2CT-19IN0707036 – Design and Fabricate an Irradiation Test Capsule for the in-situ Measurement of Elastic Properties using Laser-Based Resonant Spectroscopy – ready to insert (Deployment) – Completed April 2019
  - M2CT-19IN0707078 – Detailed Analysis of RUS Insertion Experiment and Scoping Studies for Performing Next Experiment using an Enriched Fuel Sample – Completed Sept 2019

Accomplishments - 1

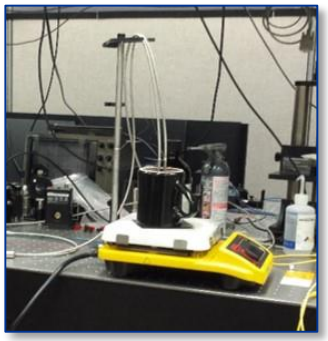
- Development of prototype capsule
- Presentation at ANS NPIC-NMIT Conference in Feb 2019.

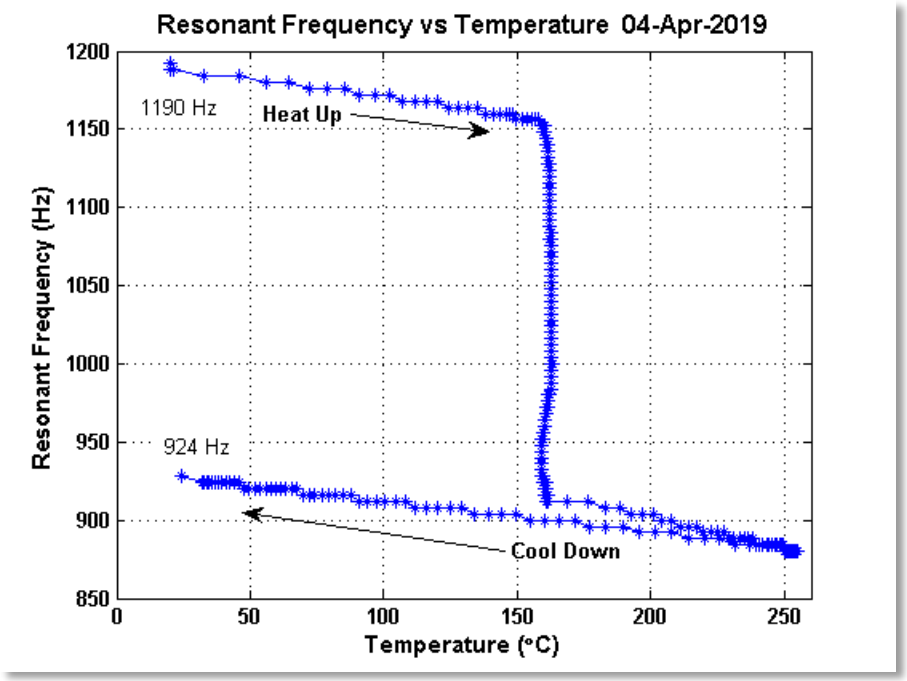


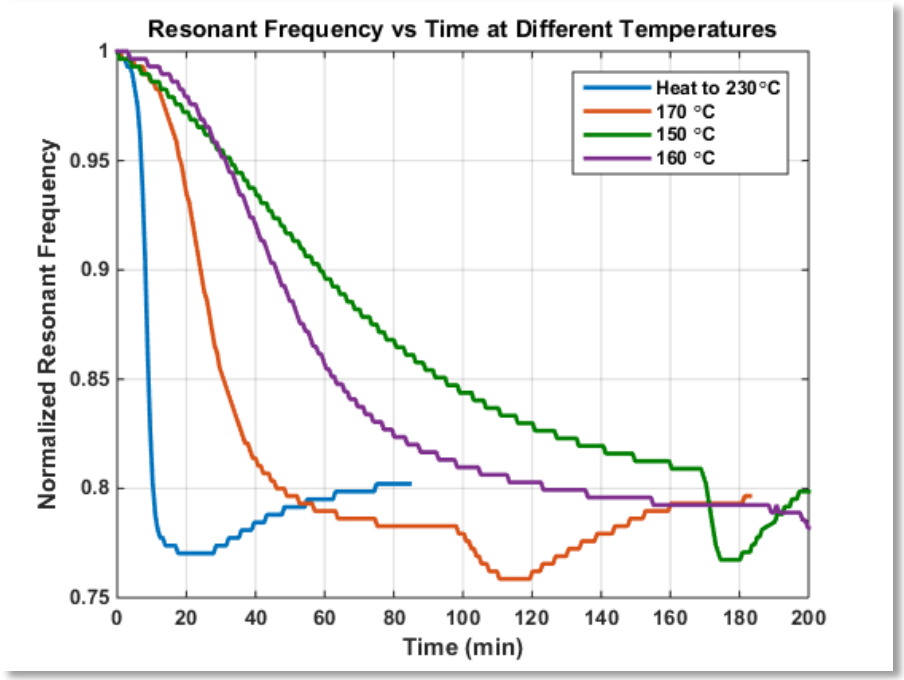


Accomplishments - 2

- Testing of temperature vs Recrystallization rate

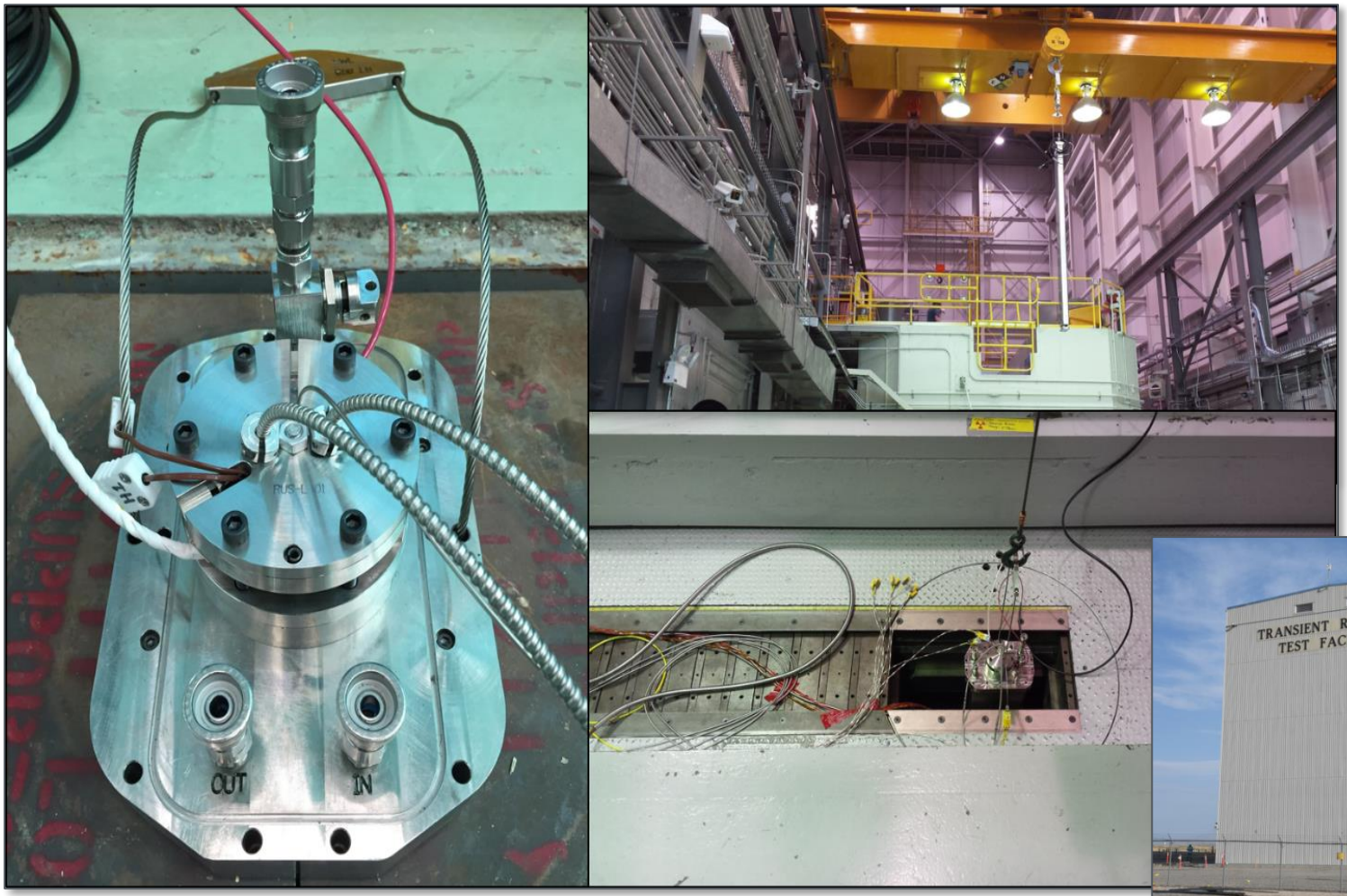






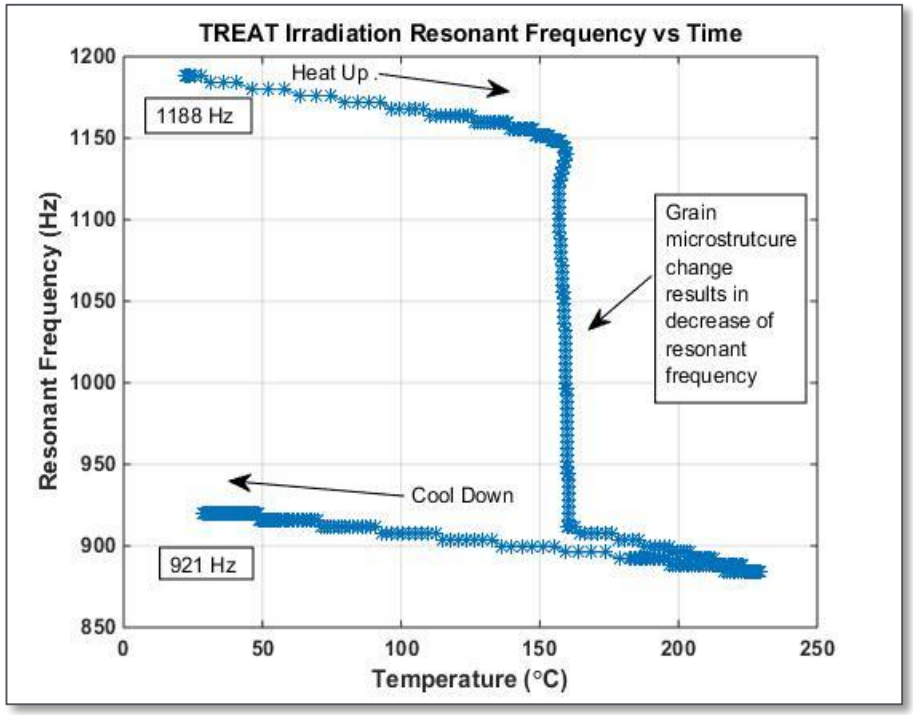
Accomplishments - 3

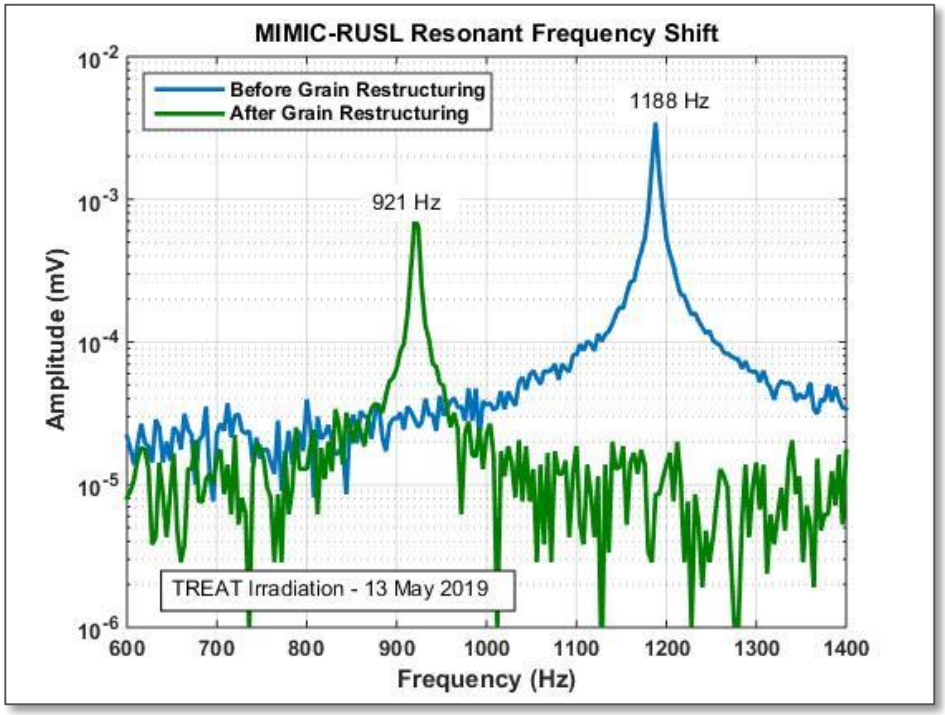
- Irradiation test in TREAT reactor (MIMIC-RUSL) performed May 13, 2019



Accomplishments - 4

- Irradiation test Results

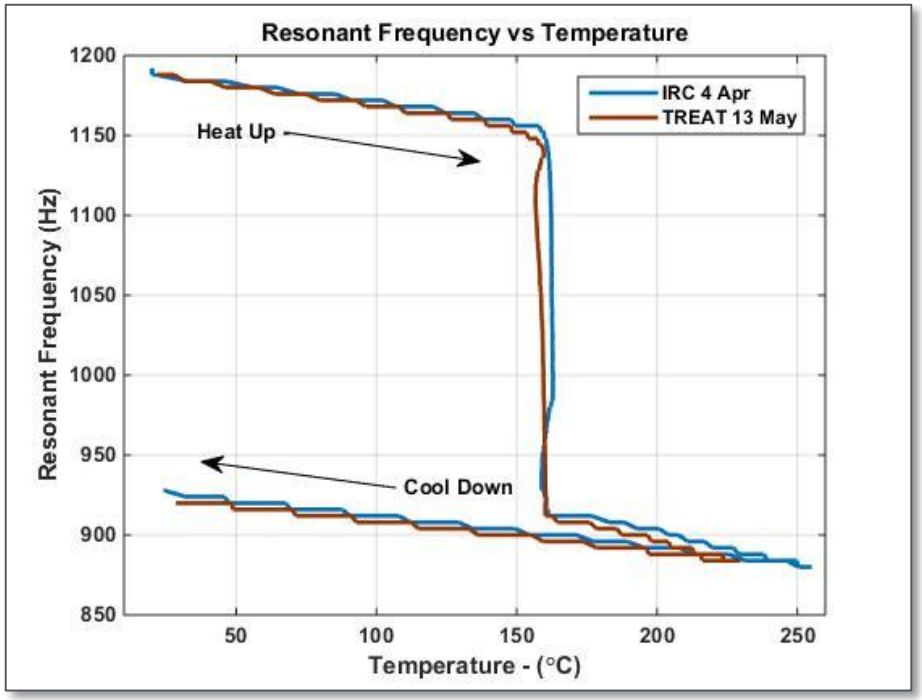


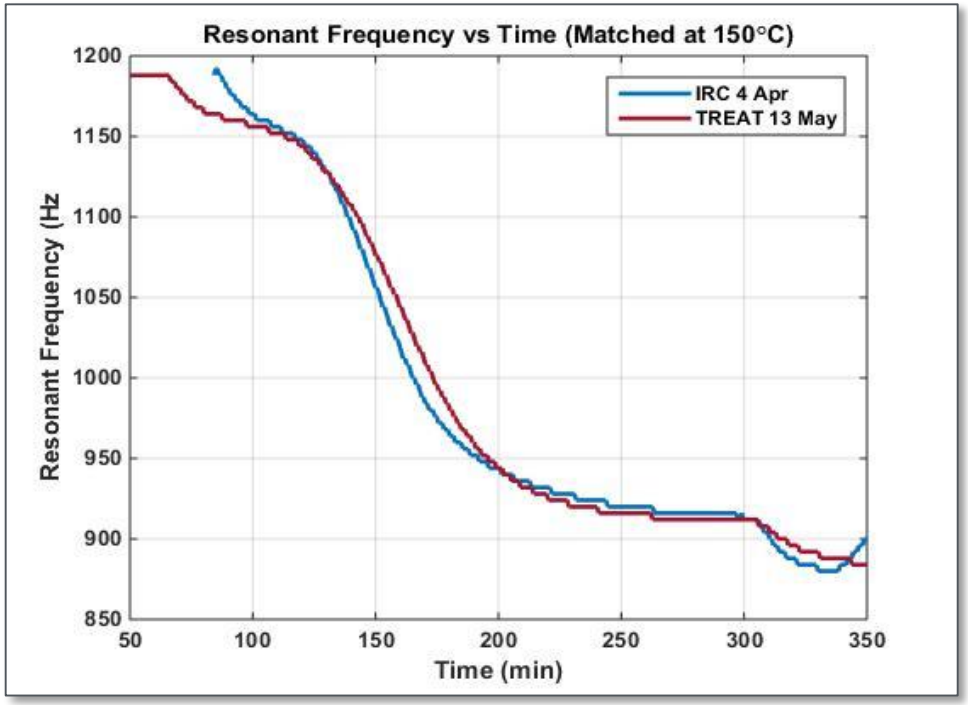


Grain restructuring causes in a change in the elastic properties of the material resulting in a decrease in the resonant vibrational frequency of the beam.

Accomplishments - 5

- Comparison of in reactor vs lab test Results

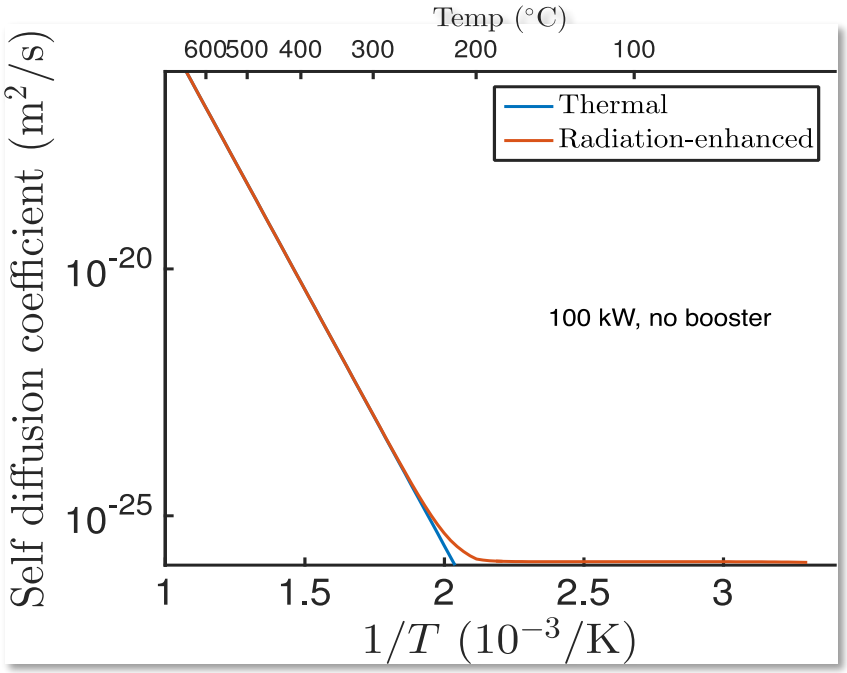


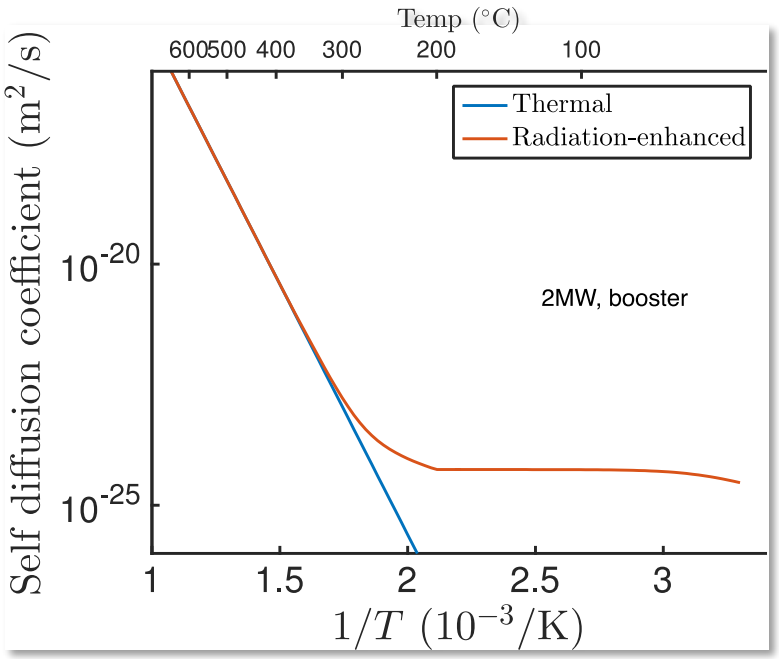


Differences are likely due to slight differences in the heating profile.

Accomplishments - 6

- Radiation Effects Scoping Study





Radiation-enhanced self diffusion of copper alloy in TREAT at 100 kW with and without uranium booster.

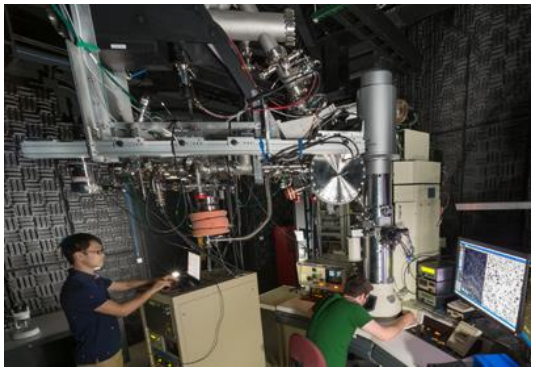
No difference unless T<260 C. For this alloy at this dpa radiation not expected to make a difference due to the long duration of the process.

FY20 Work

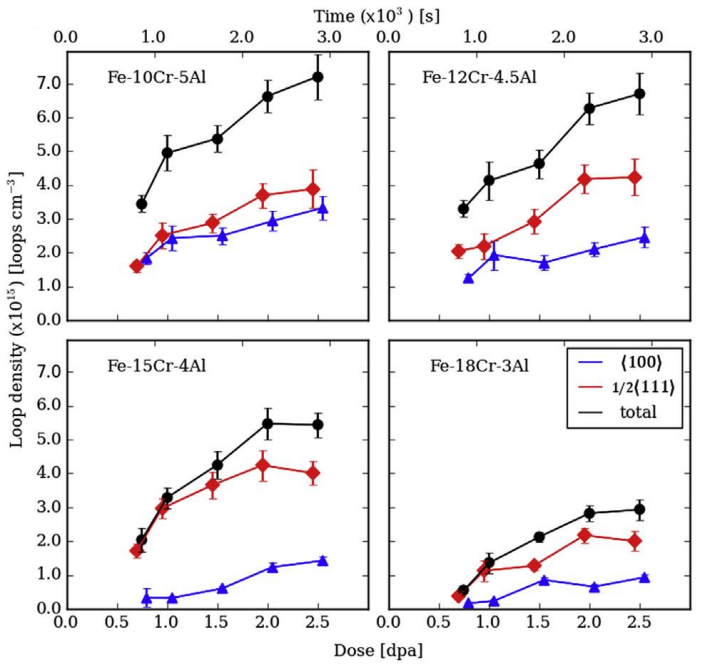
- Modify RUSL design to accommodate free standing samples which will eliminate uncertainties in the cantilever boundary condition.
- Complete scoping studies to determine the change in the phase transition temperature of metallic fuels
- Define specifications for RUSL Validation & Verification test for fuel microstructure characterization in coordination with NEAMS.

Indirect microstructure characterization - mechanical spectroscopy

- Material performance and reliability relies on understanding how microstructure and material properties evolve during component operational lifetime
- Normal post-irradiation examination (PIE) methods for microstructure are not scalable to in-pile
- Must turn to indirect techniques – like RUSL – to recover microstructure in the conditions of interest



IVEM (ANL)
ne.anl.gov/ivem/

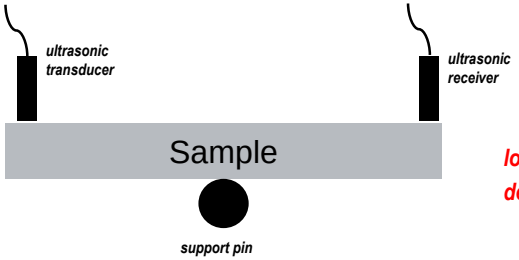


Haley, et al. Acta Mater. **136** (2017)

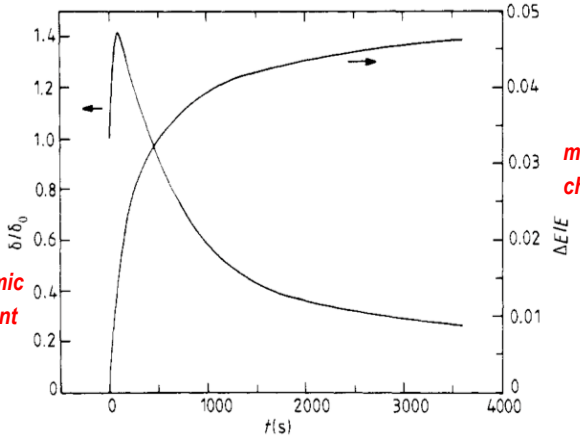
Elastic effects

Method

Internal Friction



Measured Quantity



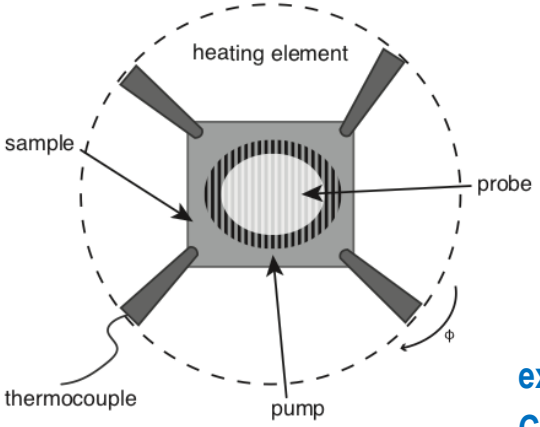
Parkin, et al. J. Phys. F: Met. Phys **17** (1987)

Microstructure Feature(s)

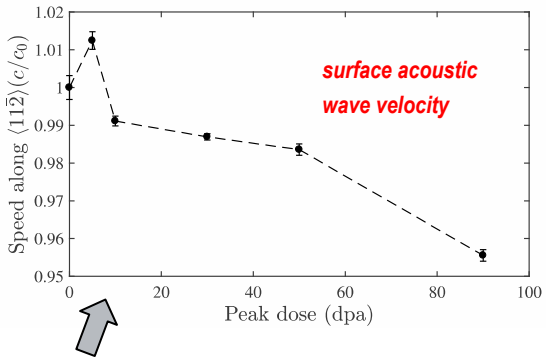
- dislocation density
- dislocation segment length
- point defect concentrations

ex. pure Cu under continuous e⁻ radiation

Laser Transient Gratings



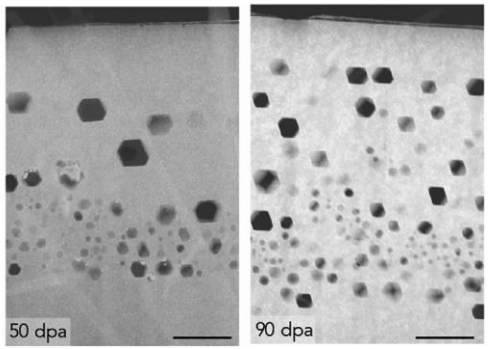
Dennett, et al. JOM (2019) *accepted*



ex. pure Cu under Cu self-ion irradiation

Dennett, et al. Acta Mater. **145** (2018)

- volumetric void swelling
- precipitation/segregation



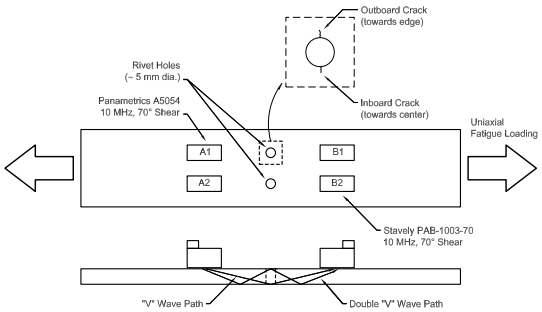
Attenuation effects

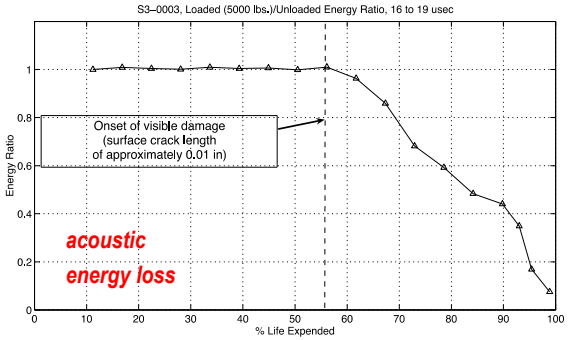
Method

Measured Quantity

Microstructure Feature(s)

Ultrasonic Fatigue Detection



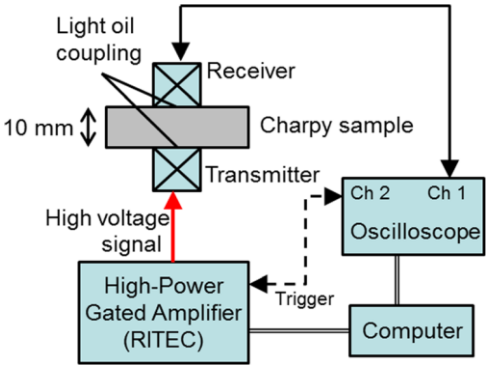


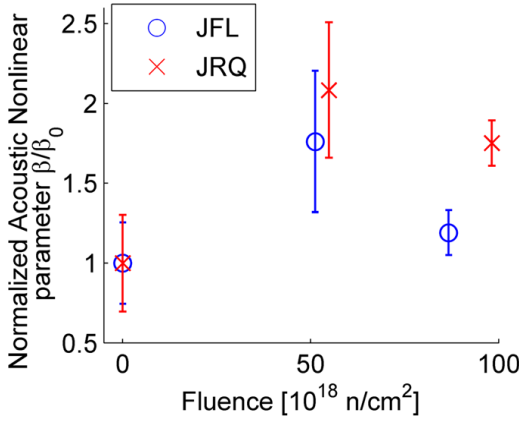
Michaels, et al. AIP Conf. Proc. **760** (2005)

- flaw detection
  - cracks
  - pits
  - holes

ex. fatigue in aluminum

Nonlinear Ultrasonics





Matlack, et al. J. Appl. Phys **111** (2014)

- voids
- precipitation
- dislocation pinning
- dislocation loops

ex. reactor pressure vessel steel under neutron irradiation

Mechanical spectroscopy - takeaway

- RUSL is just one example of a rich class of techniques which could be utilized for indirect in-pile microstructure characterization
- Models exist for many of these techniques to directly correlate measured acoustic/elastic responses with microstructures of interest

Technology Impact

In-pile Ultrasonic Measurements:

- *Provide a new capability for measuring microstructure evolution during irradiation.*
- *Provides the computational materials science community direct access to a time-dependent, in reactor environment.*
- *Enable monitoring in-pile material behavior that cannot be captured in a post-irradiation environment.*
- *Supports the ultimate goal of improved nuclear fuels and materials by providing a better understanding of how microstructure changes under irradiation.*
- *Design efforts have been funded for aLEU-RUSL which will implement this technique for the study of LEU U-Mo and other candidate alloys.*

Conclusion

An instrument for monitoring microstructure evolution under irradiation has been presented. A prototype instrument has been designed and tested. An irradiation test was performed in the TREAT reactor in which a highly textured copper sample underwent recrystallization and the results were compared with laboratory tests. Scoping studies on expected radiation effects were conducted.

This work has demonstrated the ability to monitor grain restructuring or recrystallization which occurs in both metal and ceramic nuclear fuels.

FY20 work seeks to extend the capabilities to free-free beams and identify verification and validation testing.

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