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U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Advanced Sensors and Instrumentation Annual Review Meeting

Measurement Technologies for Prognostic Indicators for Advanced Reactor Passive Components

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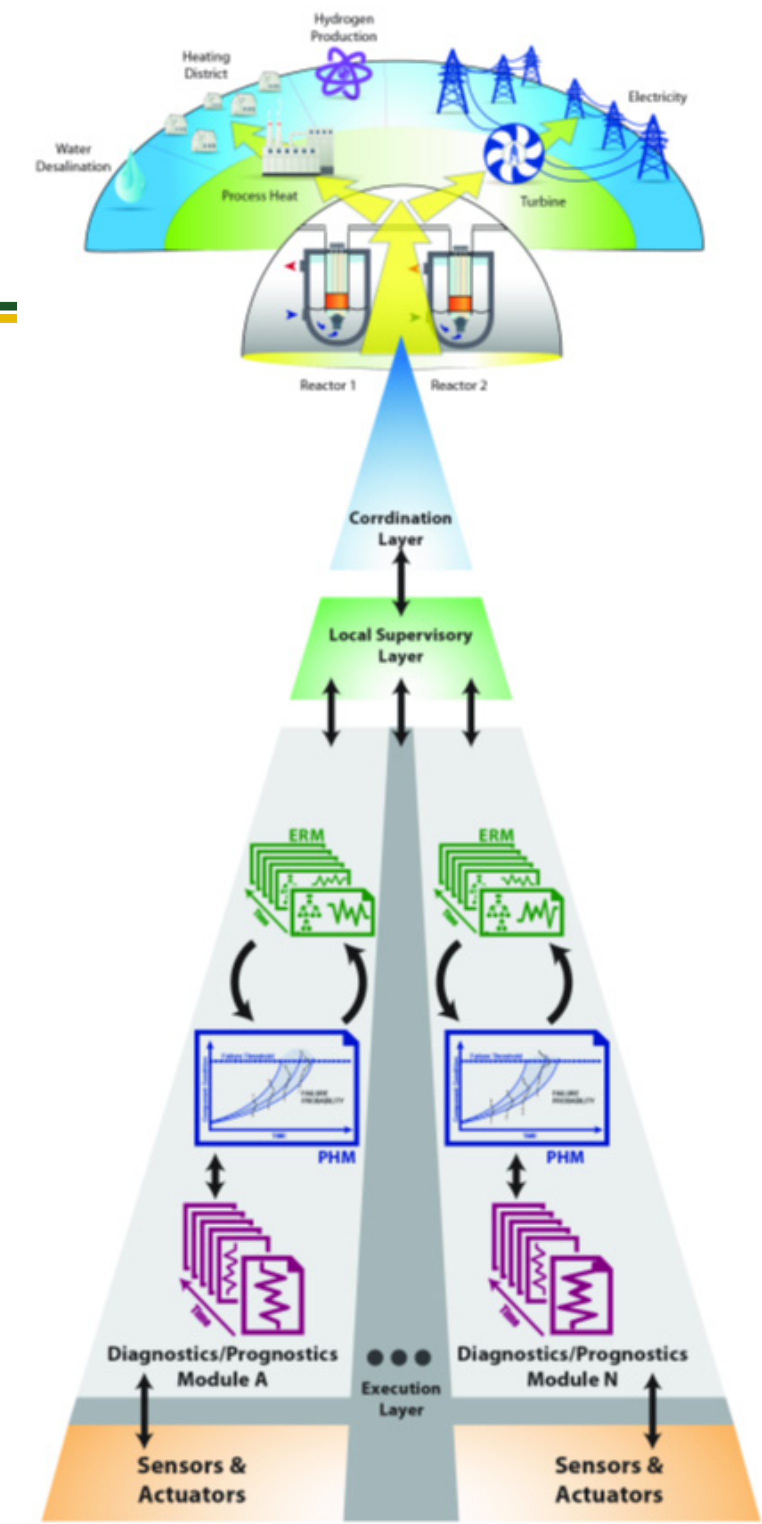
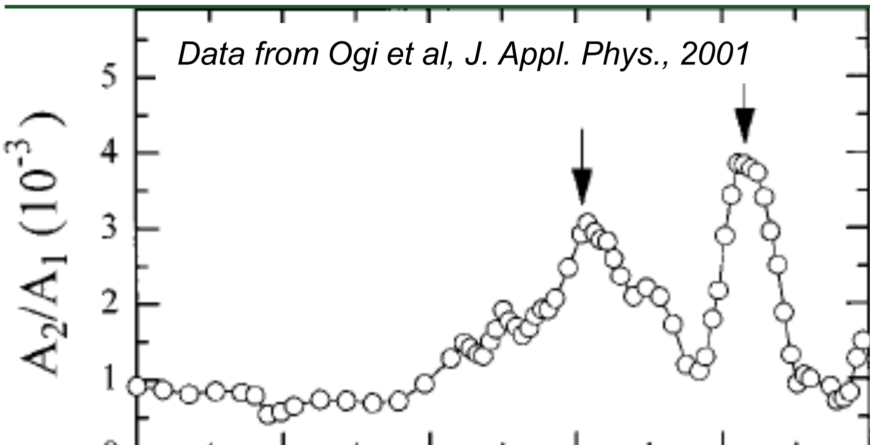
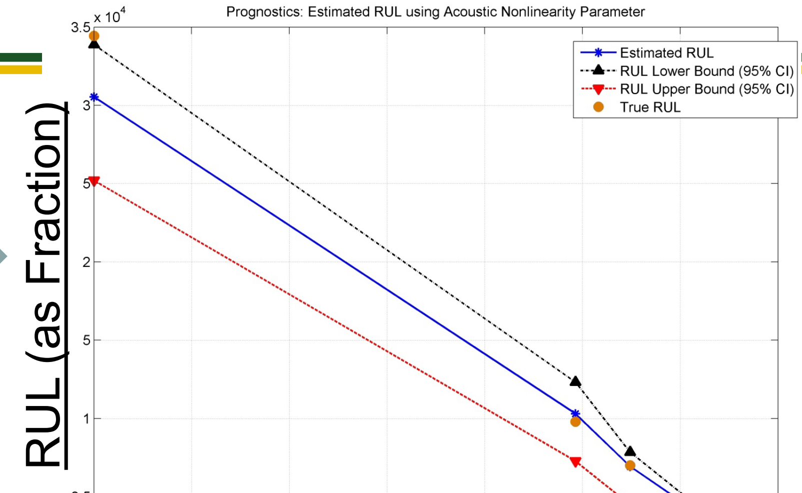
Overall Objective

- **Technologies for increased situational awareness of advanced reactor component condition and margins to failure, enabling proactive operations and maintenance**
  - Sensors and measurement technologies for in-situ monitoring of hard-to-replace advanced reactor passive components
  - Diagnostic technologies for assessing material and component condition
  - Prognostic health management (PHM) for predictive estimates of probabilities of failure

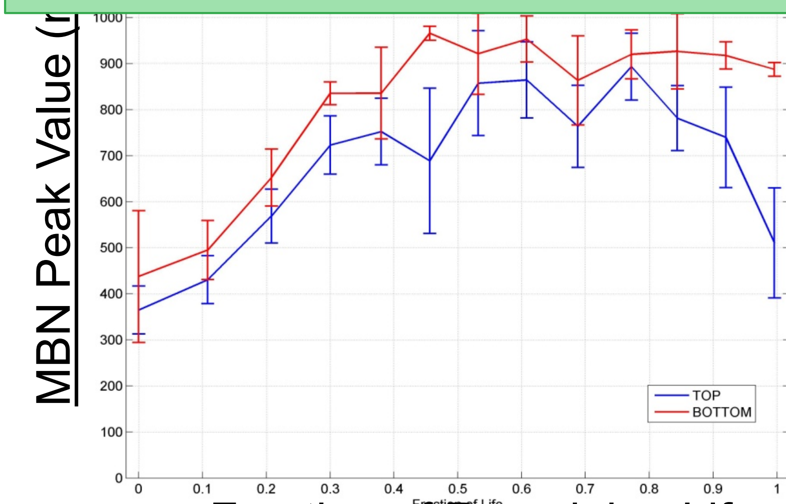


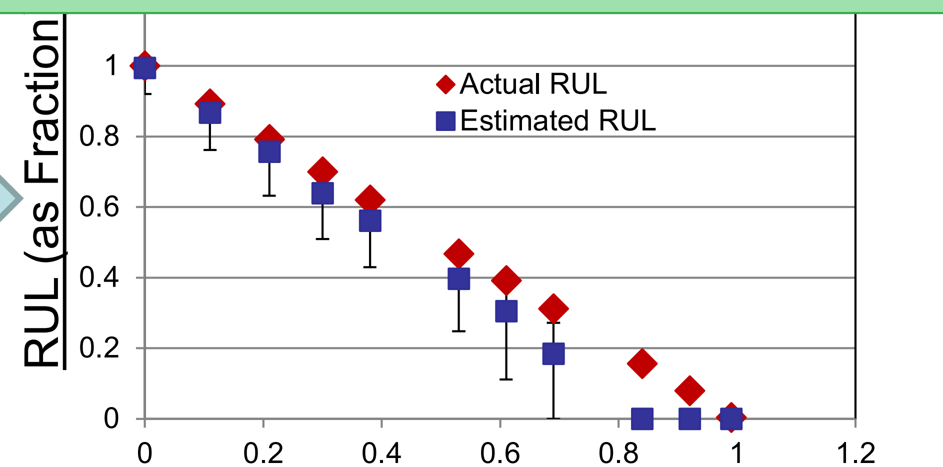
Previous Research Addressed Statistical Tools for Damage Prognostics





Assessment of remaining life for passive components requires nondestructive measurement of prognostic indicators (signatures that are sensitive to material damage condition) and the ability to monitor components over time.





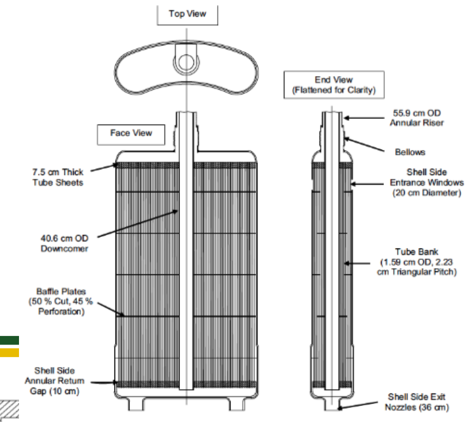
Measurement Technologies for Prognostic Indicators... Objectives

- Identify in-situ measurement technologies that support early detection of degradation modes of interest to advanced reactors, especially in inaccessible and hard-to-replace components
- Complete design and fabrication of necessary sensors for in-situ nondestructive evaluation (NDE) of components
- Evaluate sensitivity of selected in-situ NDE measurement technologies to selected advanced reactor (AR) passive component degradation modes
- Assess diagnostic and prognostic ability from NDE measurements for selected advanced reactor passive component degradation modes

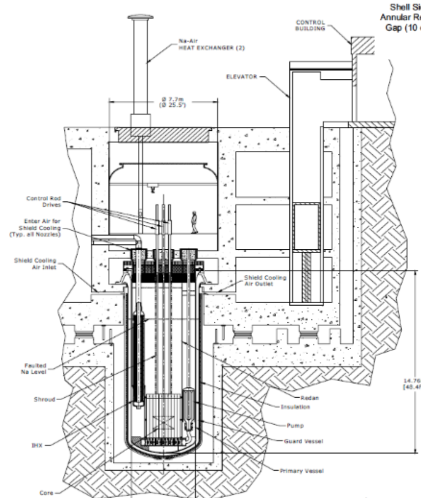
Technology Impact

- **Enhanced asset condition awareness and early warning of loss of integrity by measuring key indicators of degradation**
  - Early warning of potential degradation in inaccessible passive components leading to failure in advanced reactor environments
- **Greater understanding of precise plant component conditions, leading to improved estimates of margins to failure**
  - Offset limited knowledge of physics of failure mechanisms for materials in advanced reactor environments
- **Reduce labor demands arising from current requirements for periodic equipment surveillance and inspection**
  - Enhance affordability and safe operation of Advanced Reactors over their lifetime
- **Enable condition-based maintenance activities, which support lifetime degradation management and a science-based justification for extended plant lifetime**

Technical Approach



- **Focus: In-situ sensing to detect and characterize *cracking* in hard-to-access and hard-to-replace SFR passive components (mostly primary system components), complementing and in some cases replacing periodic in-service inspections**
- **Simulation modeling: Initial assessment of measurement capability and deployment options**
- **Sensor and instrumentation design and evaluation**
  - Leverage existing work where applicable
- **Sensitivity and reliability estimates based on laboratory measurements**
  - Limited simulation studies to augment laboratory studies
  - Qualitative and quantitative assessment of diagnostic and prognostic capability



Primary Vessel Assembly

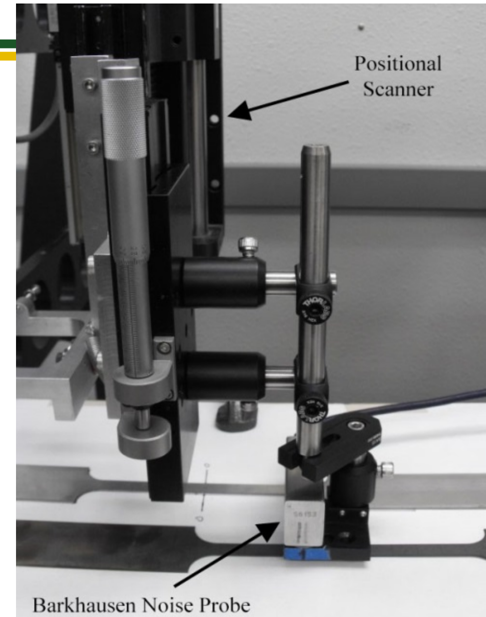
Table III-1. Summary of ISI&M Requirements

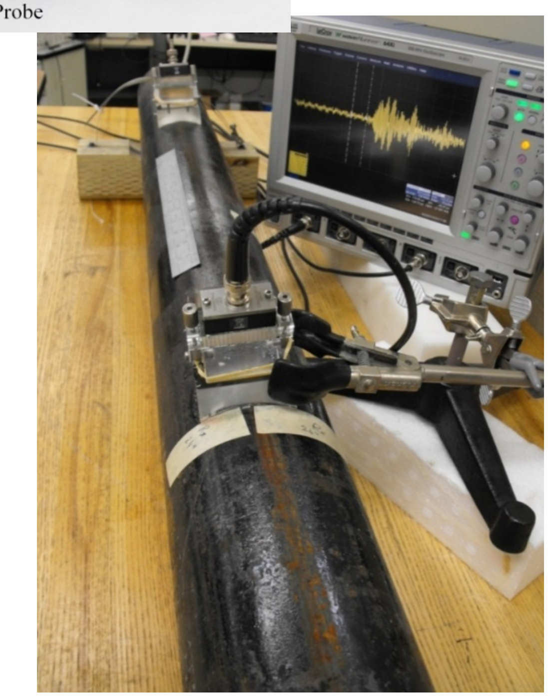
Major Components	ISI Scheduled Inspection	ISI Access	Maintenance Preventive	Maintenance Corrective	Maintenance Access
Control Rod System					
- Control Rod Drive Mechanism	Not Required	N/A	TBD	Replace part	Port [6]
- Control Rod Drive Line	Not Required	N/A	TBD	Replace	Port [6]
Reactor Internals					
Integrally Welded Structures -Core Support Structure -Core Barrel -Passive Core Restraint -Coolant Flow Ducts & Plenum -Thermal Barrier (Redan)	Visual (VTM3) [1]	Ports[3]	Not planned	Not planned	N/A
Internals attached by other than welding	Visual (VTM3) [1]				
Reactor Support - Support Skirt Welds & Bolts	Visual (VTM3) [2]	Ports & Pit [4]	NA	NA	
Reactor & Containment Vessel	Visual (VTM2) [2] CM	7" gap, Ports[5]	NA	NA	NA
Primary EM Pump	CM	N/A	TBD yrs	Replace	Port [6]
IHX	CM	N/A	Not planned	Replace	Port [6]
DRACS	CM	N/A	Not planned	Replace	Port [6]
Reactor Closure - Stationary Deck	CM,Visual(VTM3)		NA	NA	

(1) Primarily dimensional gauging and under-sodium scanning. Maybe supplemented with readily available information from continuous monitoring.
(2) Conducted using a remote operated vehicle with camera and light
(3) Access port in the reactor enclosure head for in-vessel inspection machine access.
(4) Inspection pit around the reactor support skirt
(5) Access port in the upper outer skirt of reactor containment vessel
(6) Plant design shall include provision to permit access for removal of large components. Provisions include ports in the reactor enclosure shield deck hatch and containment, and an extension to the roof to accommodate the handling and removal of large components.

NDE Methods Considered

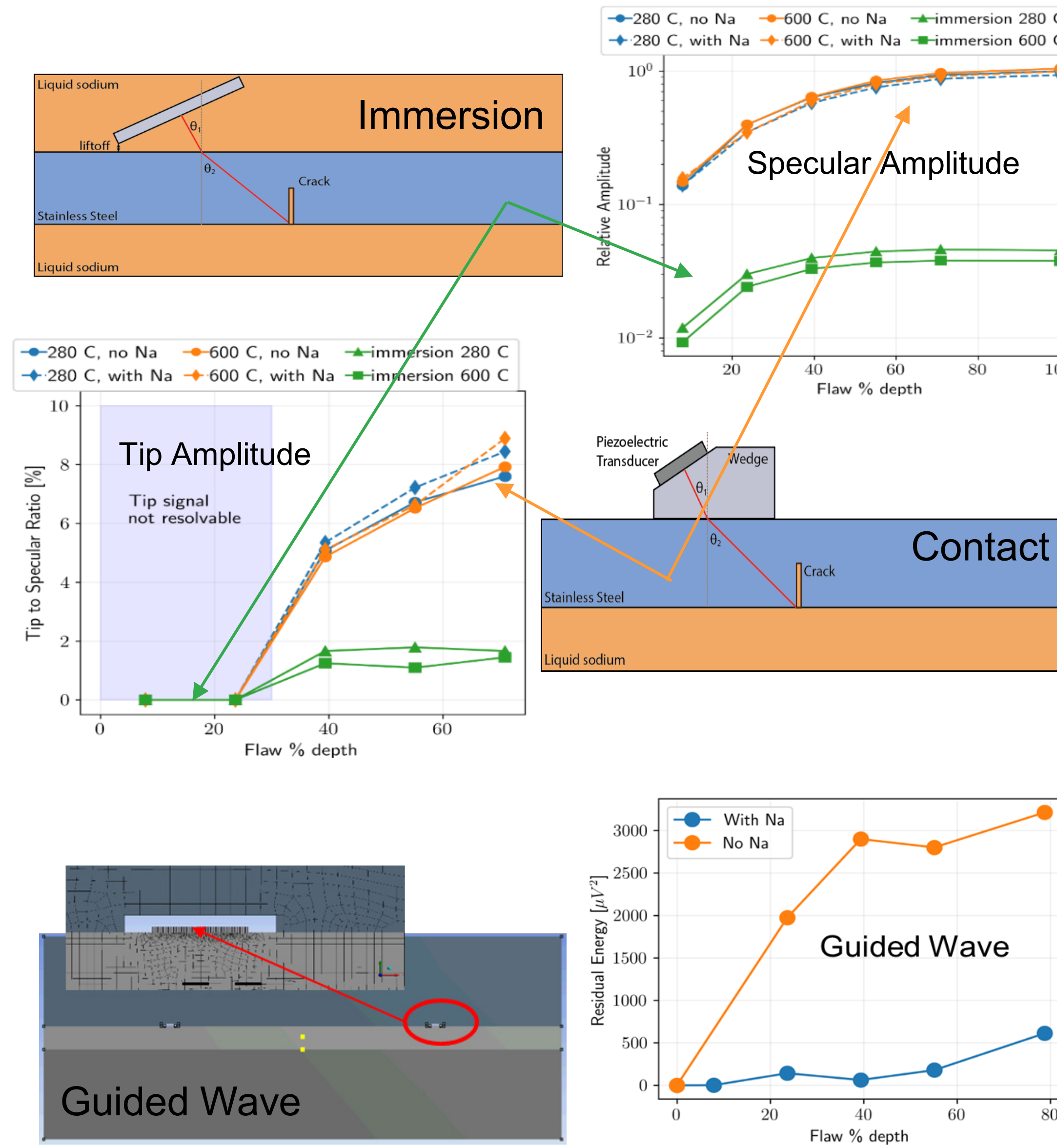
- **Generally widely applied for ISI in nuclear power and other applications**
- **Modifications necessary to support advanced reactor needs**
- **Acoustic**
  - Linear and nonlinear ultrasonics
  - Bulk and guided modes of operation
  - Acoustic emission
- **Electromagnetic**
  - Eddy current
  - Magnetic Barkhausen
- **Optical**
  - LDV for vibration monitoring





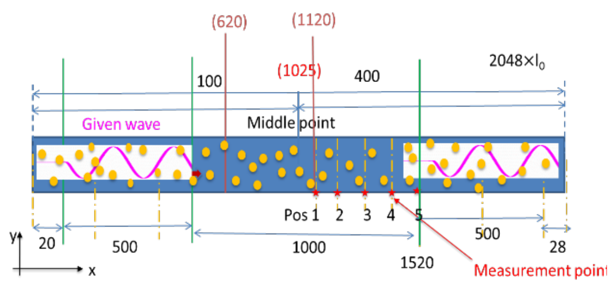
Simulation Studies Provided Key Insights on Prognostic Indicators

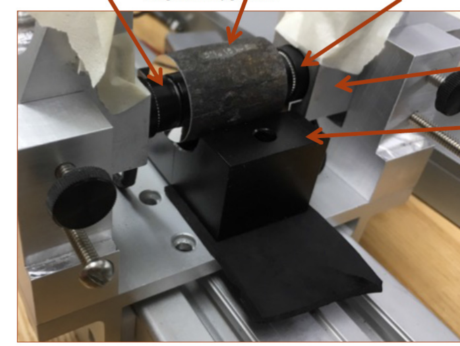
- **Potential for highest sensitivity from contact probes using bulk wave inspection**
  - Immersion systems limited in ability to detect and size cracking
  - Guided waves: sensitivity may be a challenge
- **Potential for prognostic capability on crack growth in SFR environments using ultrasonic measurements**
  - Temperature effects on detection and prognostic ability appear to be limited
  - Studies indicate other factors (orientation, grain structure, presence of Na, etc.) have greater effect



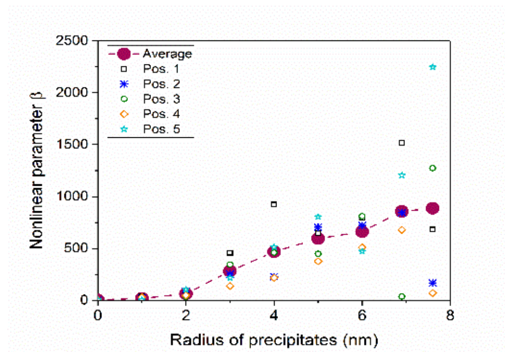
Harmonics in Ultrasound may Provide Additional Sensitivity to Earlier Stages of Degradation

- **Sensitive to microstructural changes due to degradation**
  - Precipitates size and number density
  - Dislocation loop density

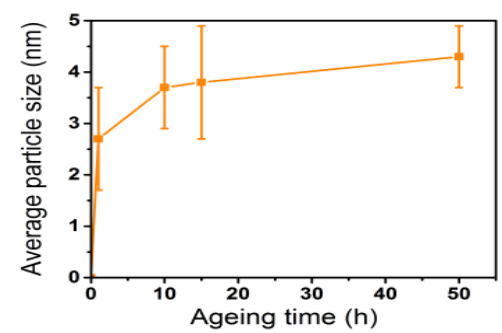




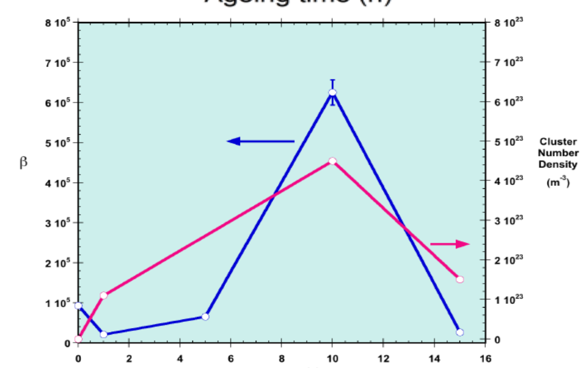
- **Interpretation of measured response challenging and is an open question**



Model Predictions



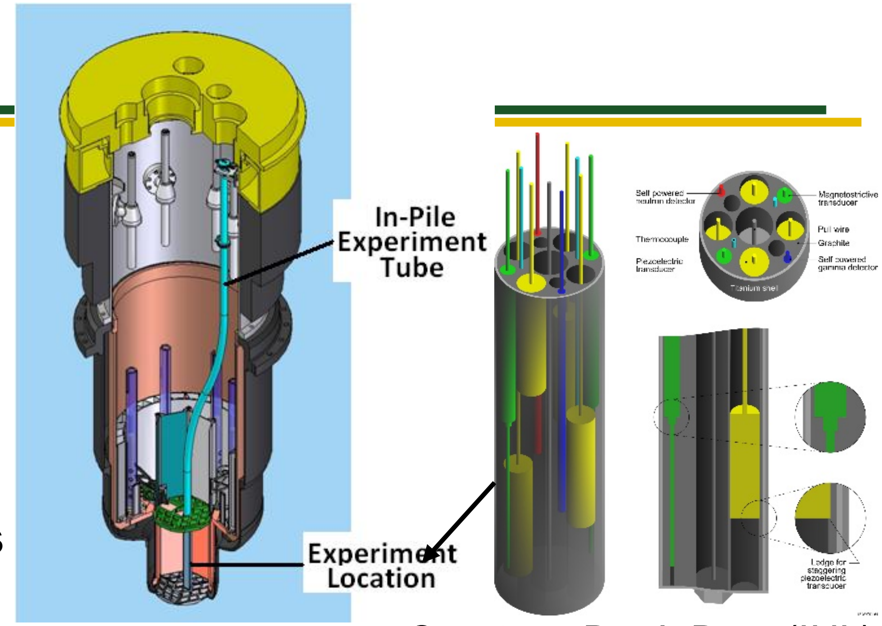
- **Use in remaining life assessment will require long-term monitoring**



Measurement Data

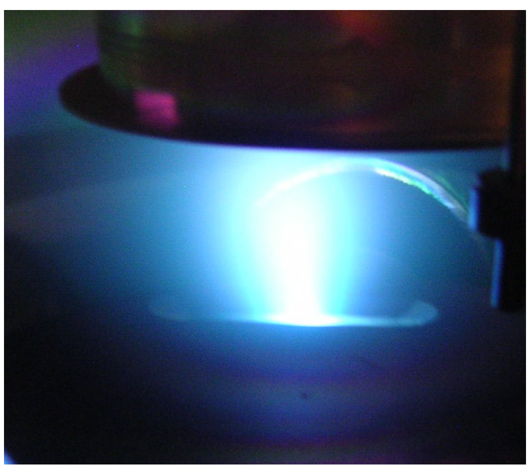
Parallel In-Situ Sensor Design and Fabrication Pathways Leverage Prior Research

- **NEUP: High temperature piezoelectric sensors and in-field fabrication methods**
- **NEET: Piezo material survivability under irradiation**
- **ART: Under-sodium viewing**
- **PNNL LDRD: New piezoelectric sensor materials**
- **Materials selection and design modifications found to be necessary to account for higher temperatures and structural components requiring monitoring**



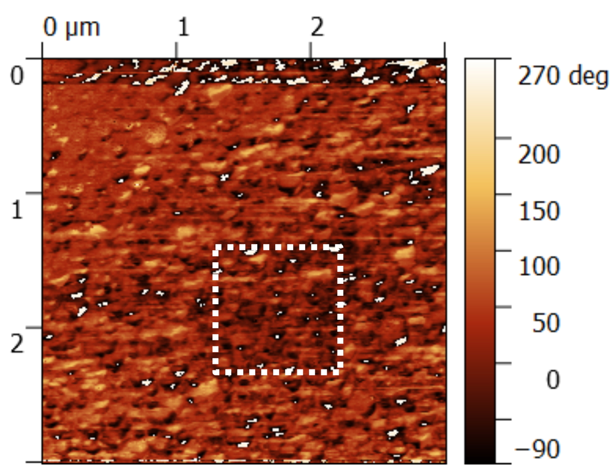
Courtesy Dr. J. Daw (INL)

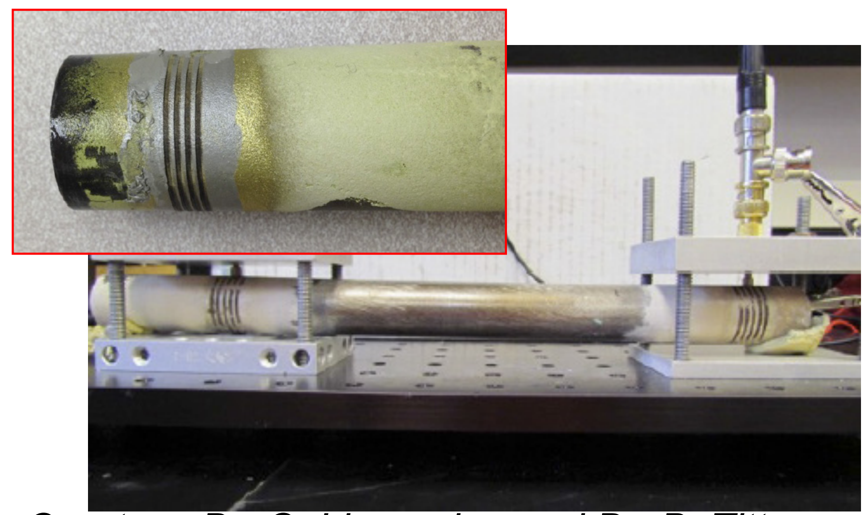
Pulsed laser deposition (PLD)



Courtesy Dr. T. Kaspar (PNNL)

Piezoresponse Force Microscopy

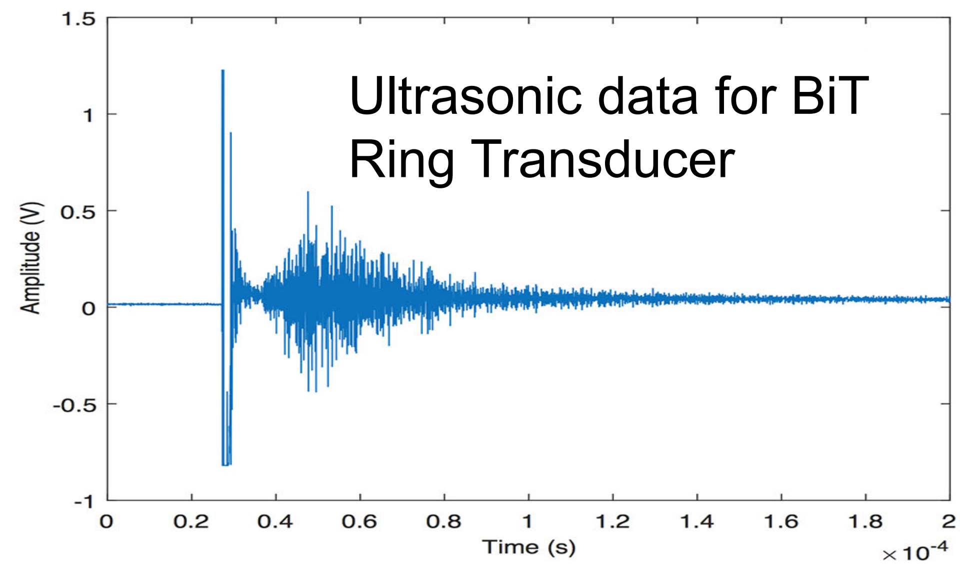




Courtesy Dr. C. Lissenden and Dr. B. Tittmann (Penn State University)

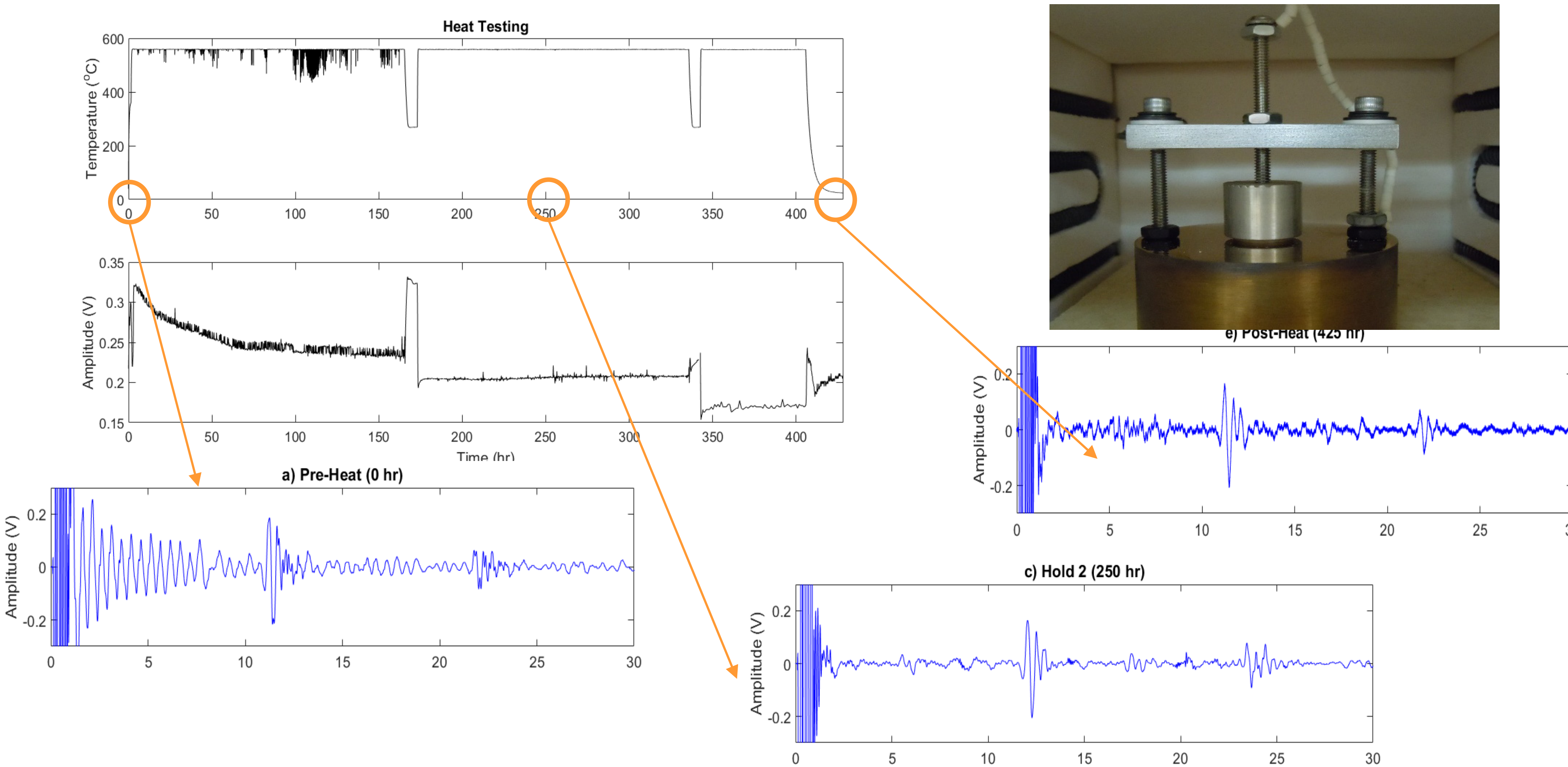
Field-Fabricated Transducers

- Research conducted at Penn State (Dr. C. Lissenden and Dr. B. Tittmann)
- Transducers "painted on" specimens
- Enable in-situ monitoring, though methods for environmentally sealing probe may be needed
- Initial tests conducted on sensor survivability at high temperature



Ring Transducers

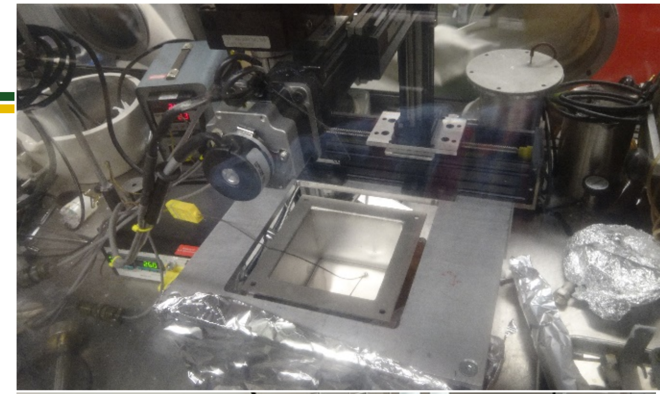
Contact Probe for Inspection and Monitoring: Materials Compatibility and Survivability Tests



Selected Materials perform well at temperature; Design modification for addressing potential thermal cycling issues.

Next Steps

- **Complete fabrication and testing of transducers**
  - Evaluate design using long-term tests (hold at temperature, thermal cycling) and in-sodium testing
- **Complete reliability assessment for inspection modes for in-sodium and ex-sodium components**
- **Assess prognostic ability from measurements for cracks and other degradation mechanisms**



Summary

- **Research focused on addressing high-impact technical gaps for assessing passive component condition in advanced reactors**
  - Sensors and measurement parameters for in-situ monitoring of critical, hard-to-replace passive components in advanced reactors
  - Simulation modeling and experiments being applied to assess measurement reliability and prognostic ability
- **Outcomes enable**
  - Tools for early warning of potential degradation in inaccessible passive components leading to failure in advanced reactor environments
  - Methods to assess passive component reliability while compensating for limited knowledge of physics of failure mechanisms in advanced reactor environments
- **Outcomes support**
  - Improved reliability and economics for advanced reactors

Project Team

- **PNNL:**
  - Dr. Pradeep Ramuhalli (PI), Dr. Morris Good, Matt Prowant, Michael Larche, Dr. Gerges Dib (Simulations), Amy Qiao, Stan Pitman, Dr. Charles Henager Jr., Patrick Valdez, David Wootan, David Baldwin, Matt Edwards, Evelyn Hirt
- **Collaborators: Dr. Cliff Lissenden, Dr. Bernhard Tittmann (Penn State University)**