U.S. DEPARTMENT OF ENERGY | Nuclear Energy

# Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

## Measurement Technologies for Prognostic Indicators for Advanced Reactor Passive Components

**Pradeep Ramuhalli**
Pacific Northwest National Laboratory

**October 12-13, 2016**

*PNNL-SA-121656*

# Project Team

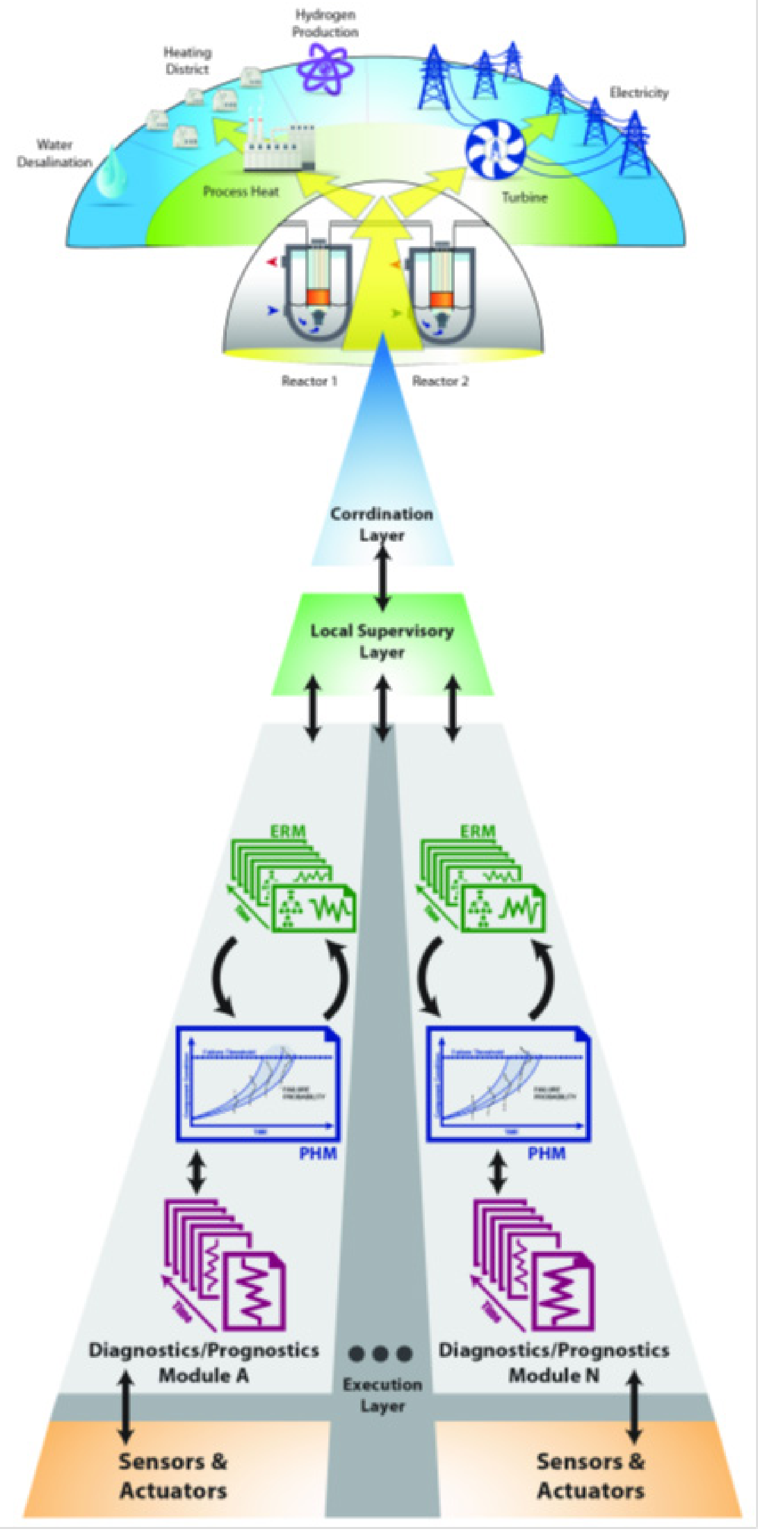
- Dr. Pradeep Ramuhalli (PI; Sensor design and data analysis)
- Dr. Morris Good (Acoustic probe design)
- Matt Prowant (NDE Measurements)
- Dr. Surajit Roy (Data analysis)
- Dr. Gerges Dib (Simulations)
- Stan Pitman (Materials testing, materials degradation)
- Dr. Charles Henager Jr. (Nuclear materials degradation)
- Patrick Valdez (Test-bed design)
- D. Wootan (SFR)
- Evelyn Hirt (Deputy PM, QA)

# Outline

- **Project Overview**
  - Objectives
  - Background
- **Technical Details**
  - Technical Approach
  - Results
- **Accomplishments**
- **Path Forward and Expected Outcomes**

# Overall Objective

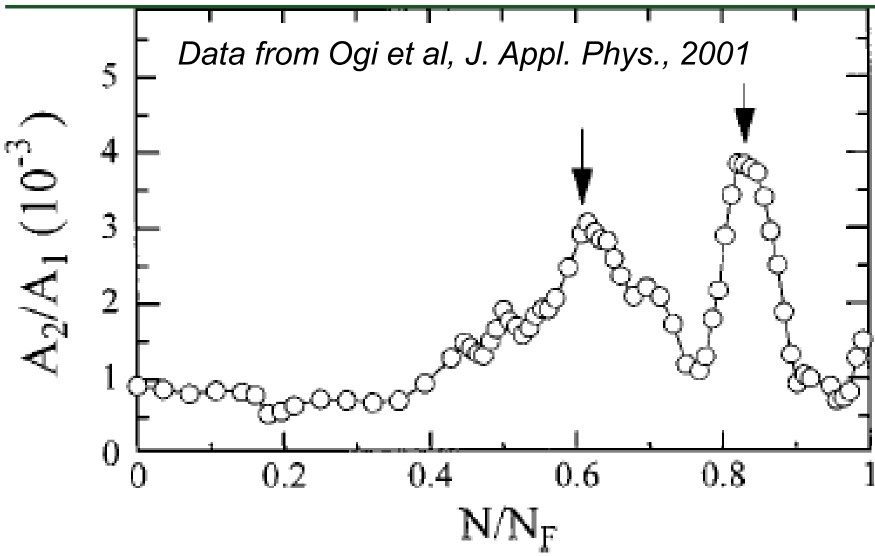
- **Technologies for increased situational awareness of advanced reactor component condition and margins to failure, enabling proactive operations and maintenance**
  - Sensors and measurement technologies for in-situ monitoring of hard-to-replace AdvRx passive components
  - Diagnostic technologies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

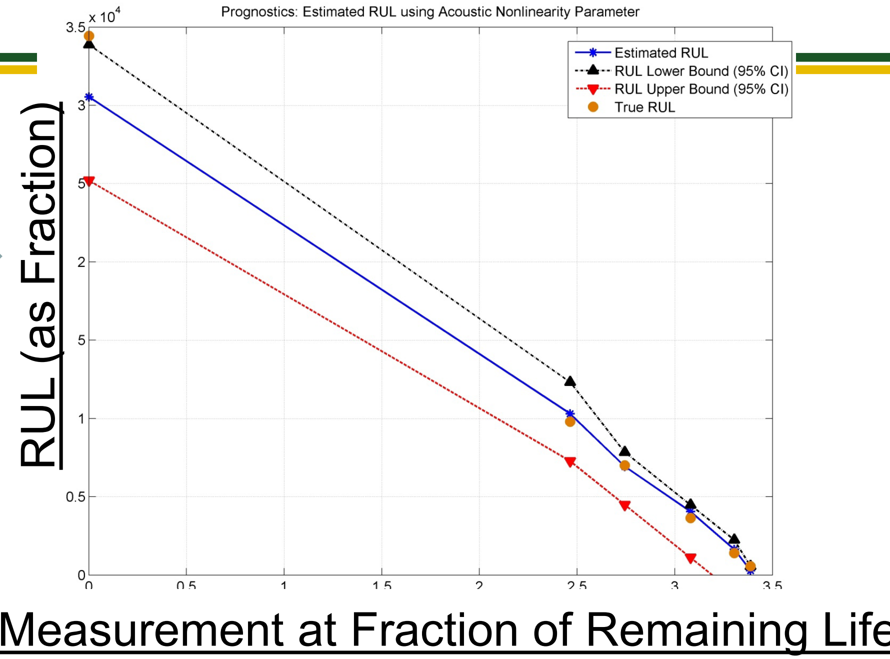


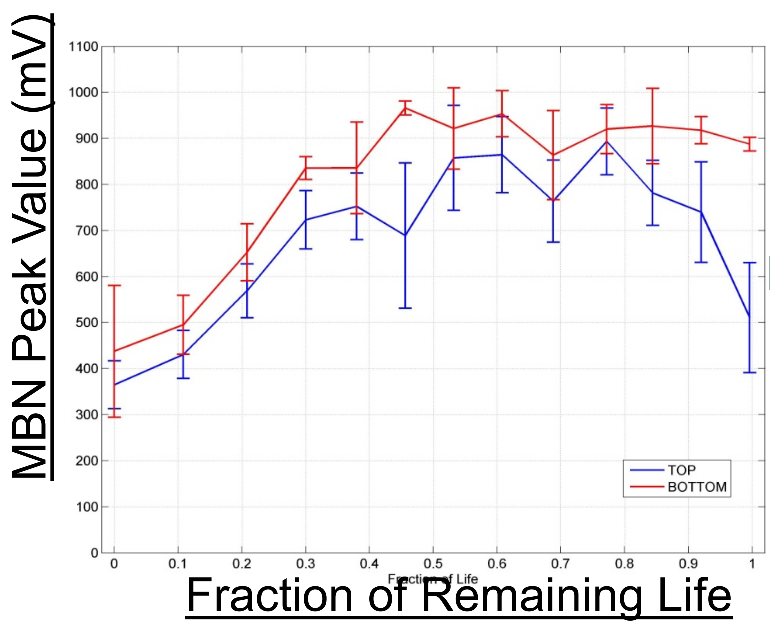
# Previous Research Addressed Statistical Tools for Damage Prognostics

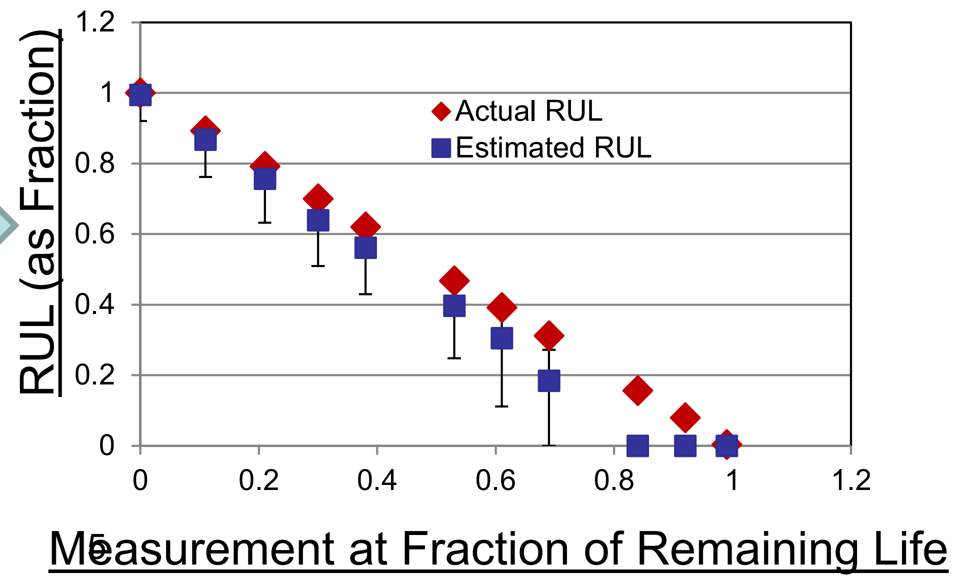
U.S. DEPARTMENT OF ENERGY

Nuclear Energy



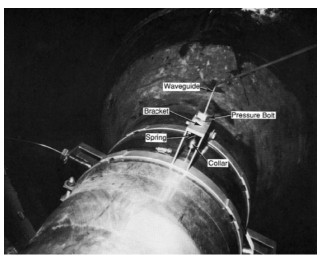



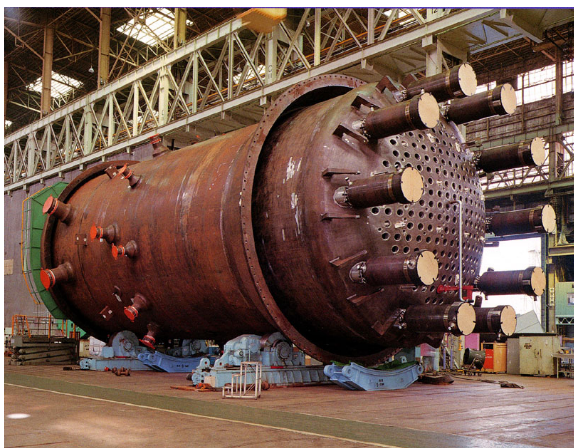



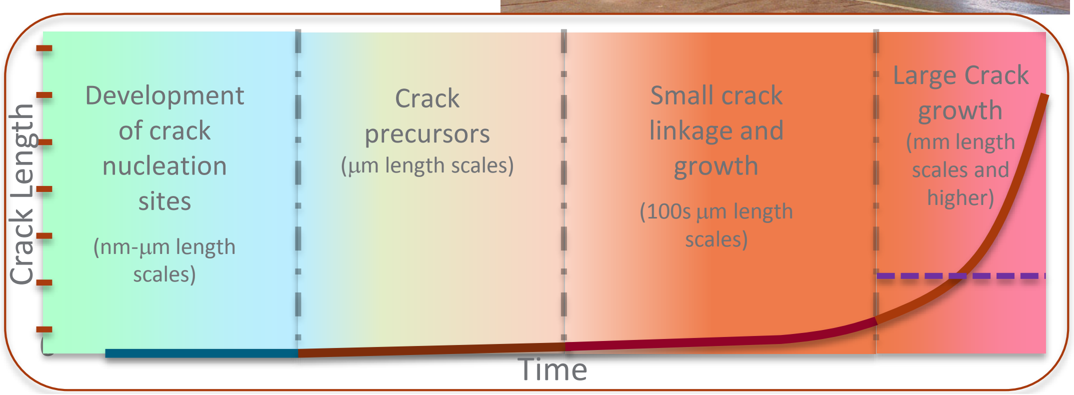
U.S. DEPARTMENT OF
ENERGY
Nuclear Energy

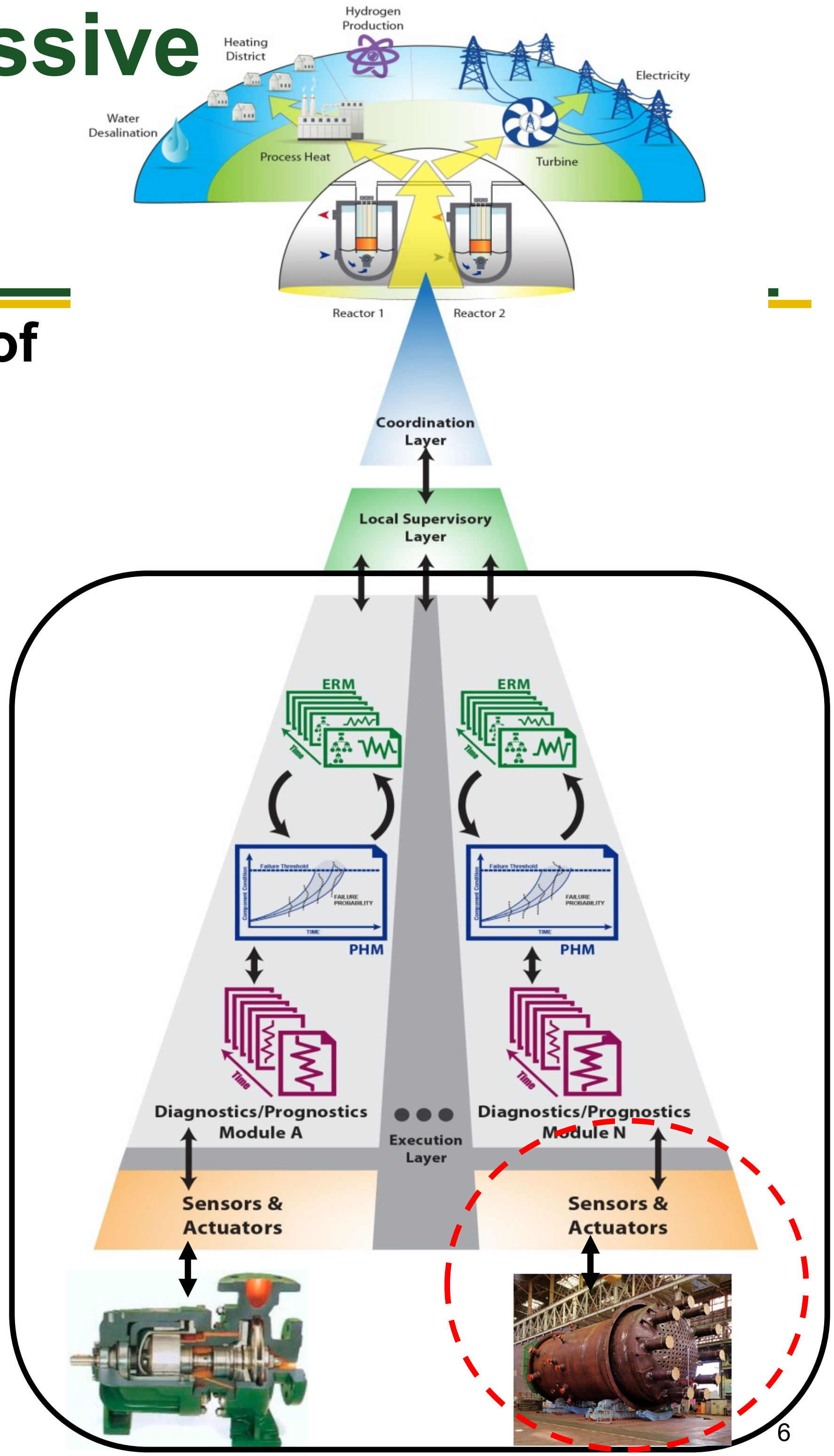
# Focus on Passive Components

- **Integrated approach aging management of critical components**
  - Incipient damage
  - Takes advantage of PNNL expertise in NDE, ISI, and Sensors/Instrumentation





# Measurement Technologies for Prognostic Indicators... Objectives

## Objectives:

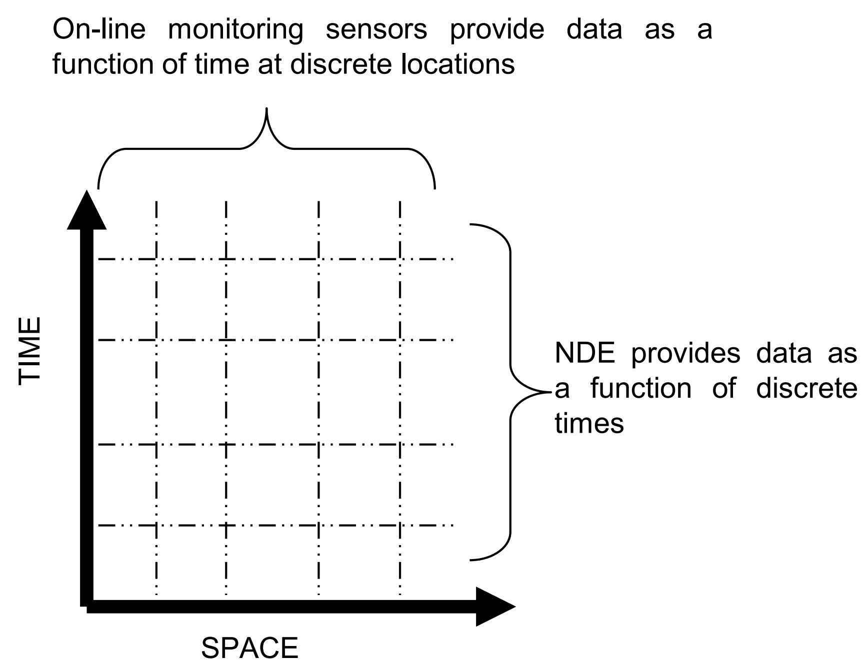
- Identify in-situ measurement technologies that support early detection of degradation modes of interest to advanced reactors;
- Complete experimental design for the evaluation of sensitivity of selected in-situ nondestructive evaluation (NDE) measurement technologies to selected AR passive component degradation modes, especially in inaccessible and hard-to-replace components;
- Begin assessment of selected in-situ nondestructive measurements for their ability to provide reliable and sensitive prognostic indicators for these degradation modes.

## Interactions with the ART program Materials Pathway experts

- Benefit from information on potential degradation modes in advanced reactor concepts
- Potential for leveraging ongoing experiments to assess NDE measurement opportunities and evaluate selected NDE measurement approaches

# In-service Inspection (ISI) vs Condition Monitoring (CM)

- **Most effective technique - continuously monitor all plant components 100% of the time**
  - Not feasible unless incorporated when plants are built
  - More continuous monitoring capabilities exist now, but still not practical for all components
  - Preferred approach for AdvRx that may have multiple-year fuel cycles, or components with very limited accessibility
- **Next best method: Examine all components periodically**
  - Not economically viable, and not enough skilled personnel
- **ISI – inspect some of the components periodically**




Fundamental differences in data structure between Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM))
(After Thompson [2009])

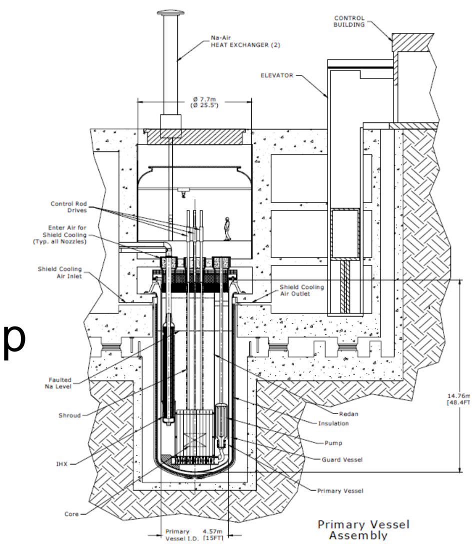
# Technical Approach

- **Component Identification**
  - ISI vs CM – what makes sense for AdvRx components?
  - Component dependent
- **Potential NDE measurement approaches for selected components**
  - Phased approach, with initial focus on SFR components
- **Experimental design and evaluation criteria**
- **Sensor and instrumentation modeling and design**
  - Leverage existing work where applicable
- **Experimental data acquisition and measurement data analysis**

# Sodium-cooled Fast Reactors (SFR) Technology: Potential Failure Modes of SFR Components

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

- **Wide variation in materials**
  - Stainless steel
  - F-M steel
- **Wide range of failure modes possible**
  - Thermal fatigue, SCC, corrosion, creep, creep fatigue, …
- **Locations vary**
  - Welds and joints
  - Bends/elbows
  - Tubing
  - …
- **NDE measurement challenges**
  - Access limitations for ISI
  - Sensor materials challenges for in-situ monitoring
  - Measurement parameter sensitivity
  - Deployment issues for in-situ monitoring



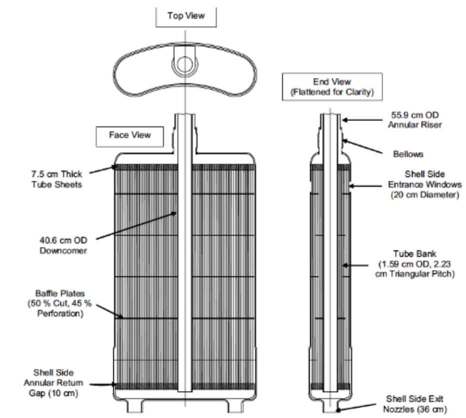




Table III-1. Summary of ISI&M Requirements

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

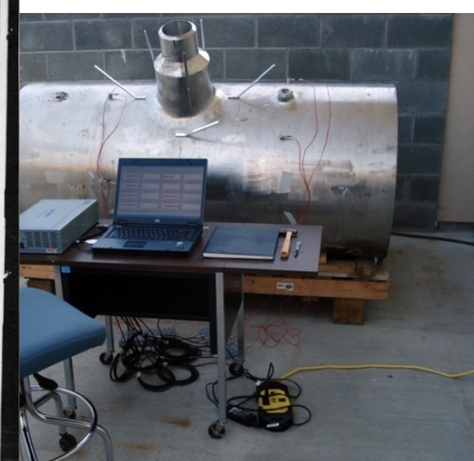
(1) Primarily dimensional gauging and under-sodium scanning. Maybe supplemented with readily available information from continuous monitoring.
(2) Conducted using a remote operated vehicle with camera and light
(3) Access port in the reactor enclosure head for in-vessel inspection machine access.
(4) 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.

# Monitoring for Materials Degradation: Structural Health Monitoring (SHM)

- **In-situ online monitoring**
  - Monitoring hard-to-access or high-risk regions
  - Flaw growth monitoring
  - Component/system-scale monitoring
- **Acoustic emission only currently sanctioned technique for online monitoring of materials degradation by the ASME BPV Code**
  - Flaw growth monitoring only (flaw must be characterized using other methods)
  - Guided ultrasonic waves being discussed for inclusion in Code
- **Many other methods being researched**
  - Guided ultrasonic waves
  - Electromagnetic methods
  - Vibration monitoring
  - …



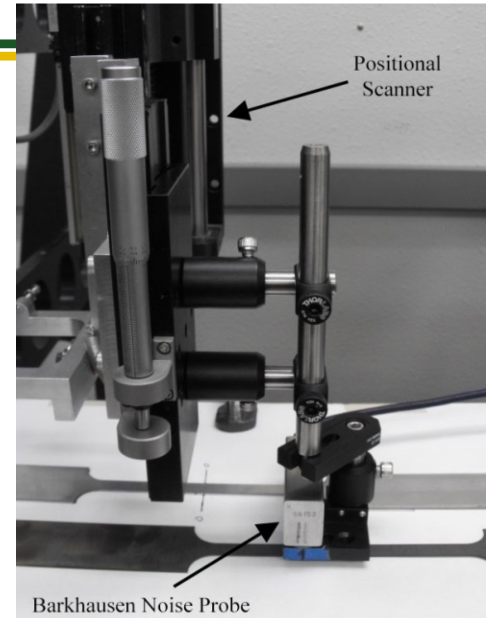
**AE System Circa 1993**

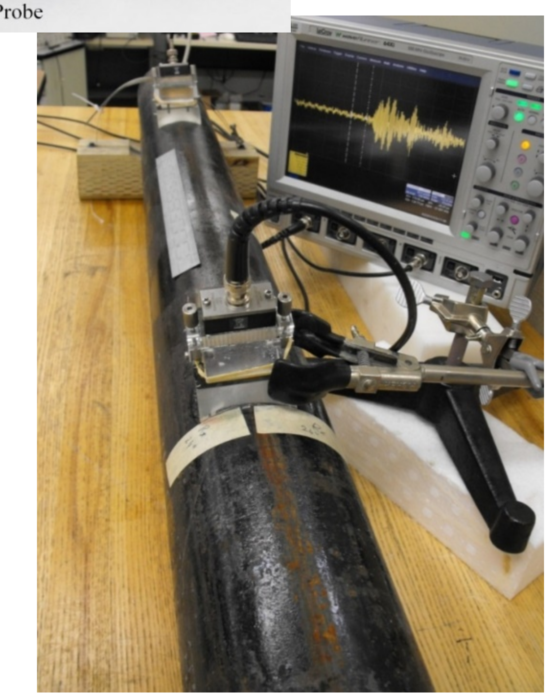


**AE System Circa 2010**

# NDE Methods Under Consideration

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

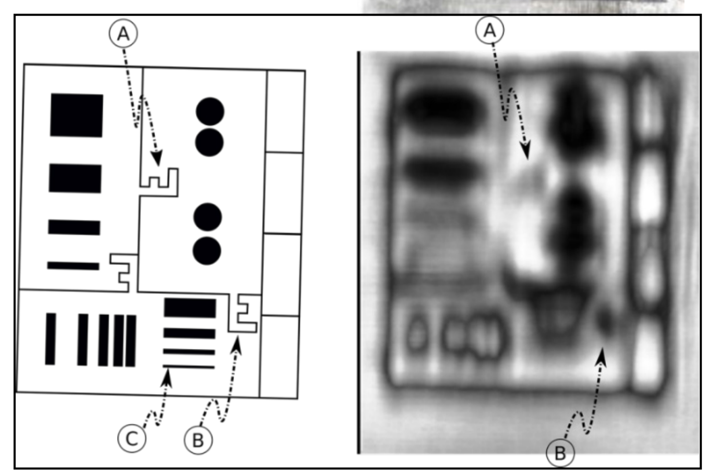


# Sensor Concepts - I

## Periodic ISI

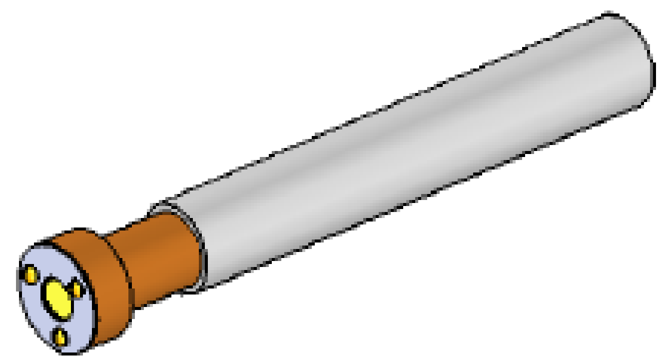
- Takes advantage of opportunities during periodic refueling outages
- Applicable to in-vessel and ex-vessel components
  - SFR: In-vessel/in-component temperatures ~250C, Na environment
  - SFR: Ex-vessel temperatures generally < 250C
- Sensor concepts
  - Ultrasonic: adapts USV technology: Focus on bulk wave inspection for cracking
  - Electromagnetic: Magnetic and eddy current inspection of tubing (may require draining coolant)
  - Quantification of sensitivity (smallest flaw detectable) and reliability (probability of detection)
  - Sensor delivery is an issue that will need to be addressed



# Sensor Concepts - II

## In-situ continuous monitoring

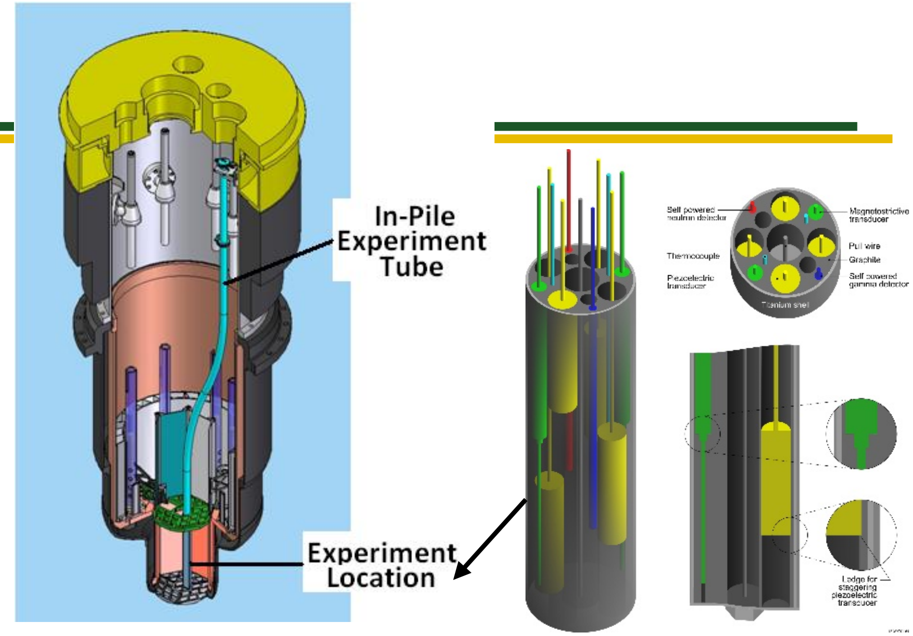
- Monitor components that are hard to access during periodic outages
- Applicable to in-vessel and ex-vessel components
  - SFR: temperatures ~500-550C, Na environment possible for in-vessel sensors
  - Large area monitoring vs targeted (high risk area) monitoring
- Sensor concepts:
  - Ultrasonic: Wide area monitoring using guided ultrasonic wave modes (active or in listen-only mode)
  - Electromagnetic: Targeted area monitoring only at this stage
  - Quantification of sensitivity (smallest flaw detectable) and reliability (probability of detection)
  - Sensor material selection is an issue that will need to be addressed



Example of Concept High Temperature Ultrasonic Sensor for In-Situ Monitoring

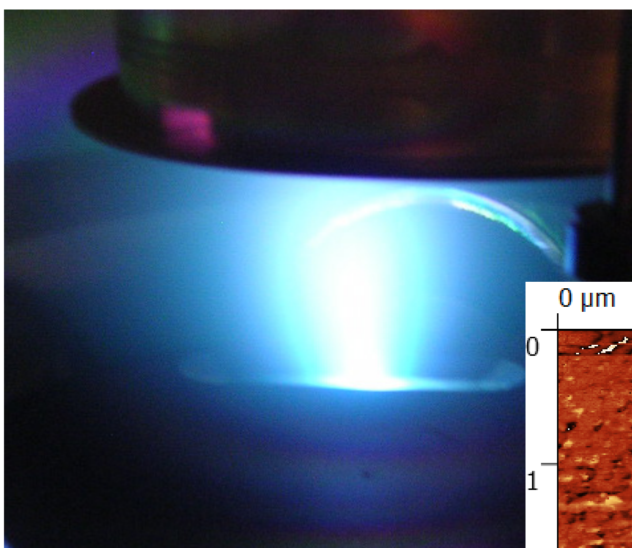
# Ultrasonic Sensor Material Selection Leverage Prior Work

- **NEUP: High temperature piezoelectric sensors for ultrasonic measurements**
- **NEET: Piezo material survivability under irradiation**
- **PNNL LDRD: New sensor materials**



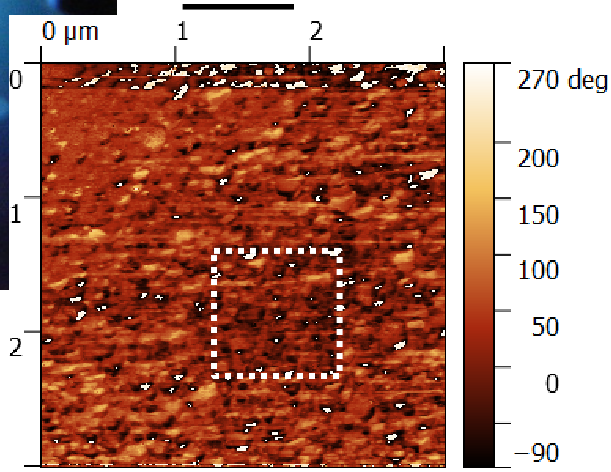

*Courtesy Dr. J. Daw (INL)*

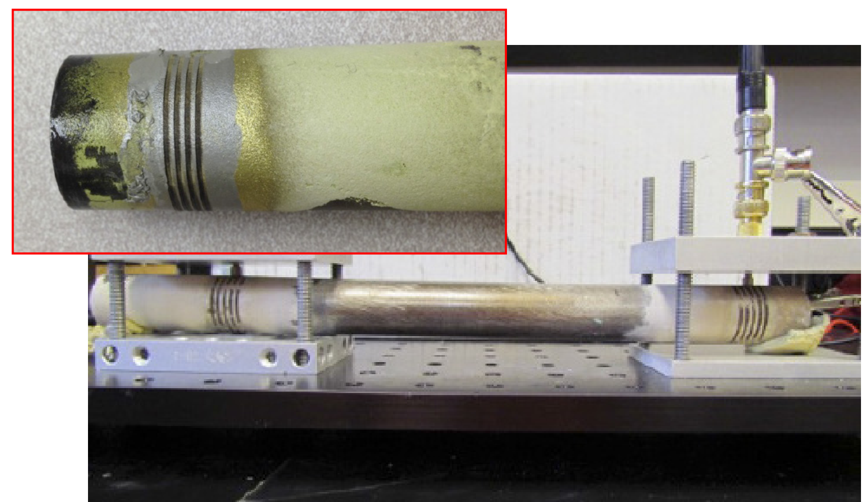
**Pulsed laser deposition (PLD)**



*Courtesy Dr. T. Kaspar (PNNL)*

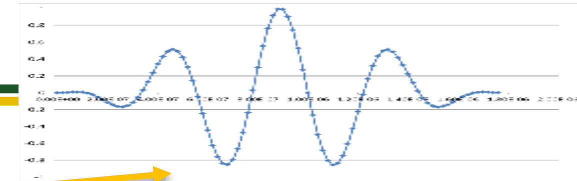
**PFM**

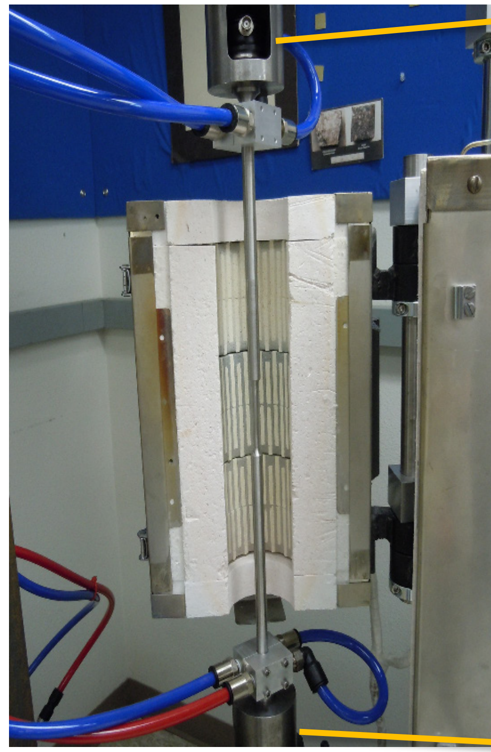


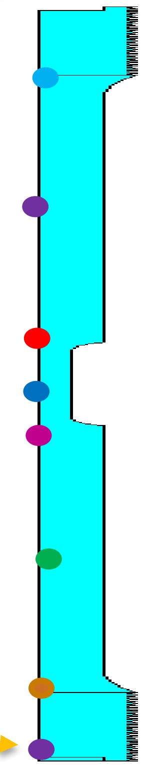



*Courtesy Dr. C. Lissenden and Dr. B. Tittmann (Penn State University)*

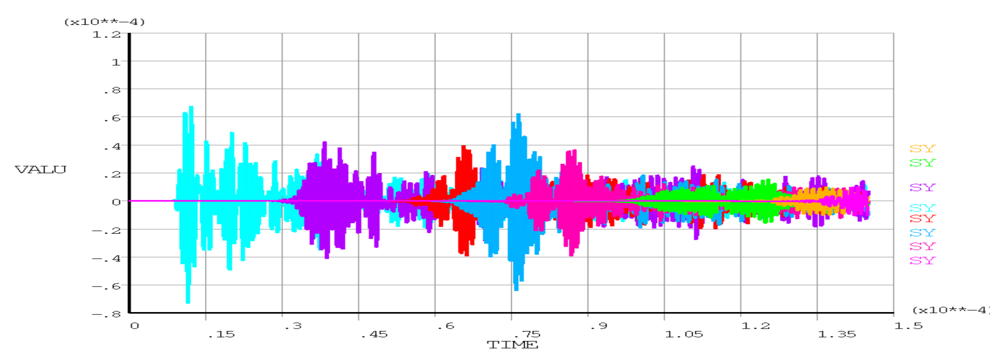
# Simulation Modeling





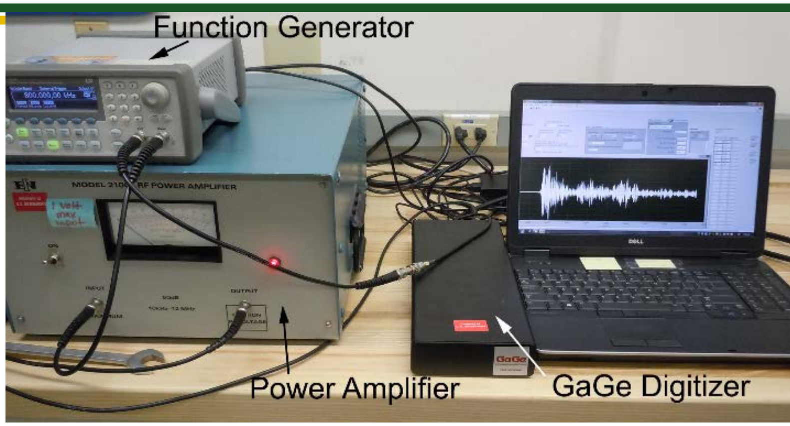


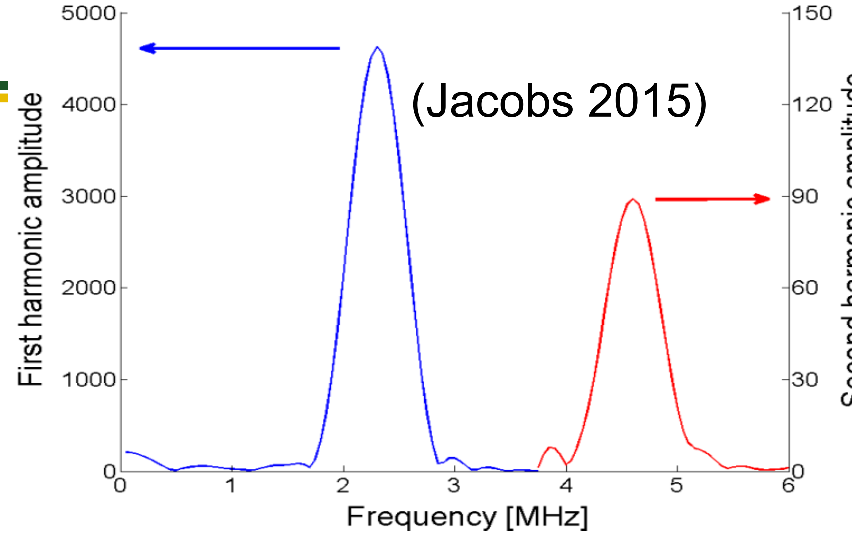
- **Simulation studies being used to support experimental design**
  - Design optimization for sensors
  - Deployment options
  - Sensitivity estimates under ideal conditions



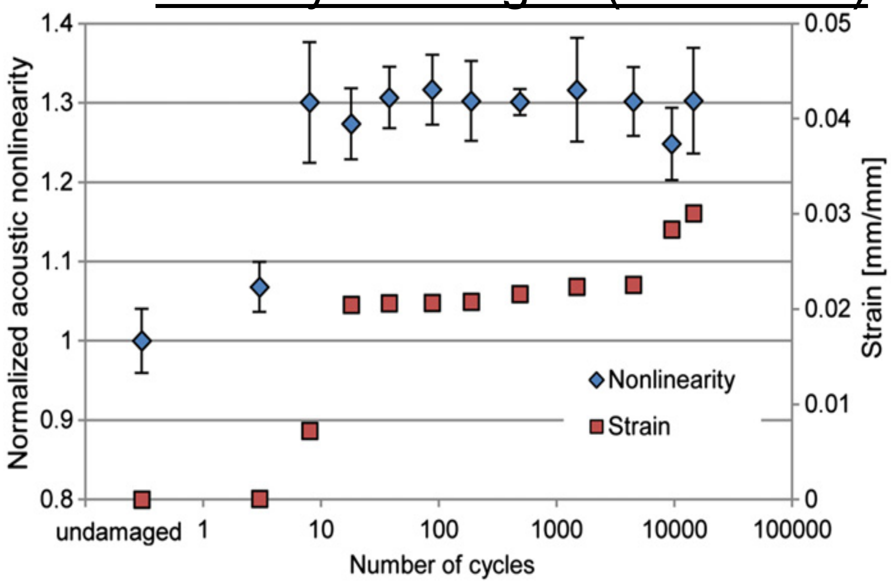
# Parameters Measured are Being Evaluated for Earlier Detection and Monitoring





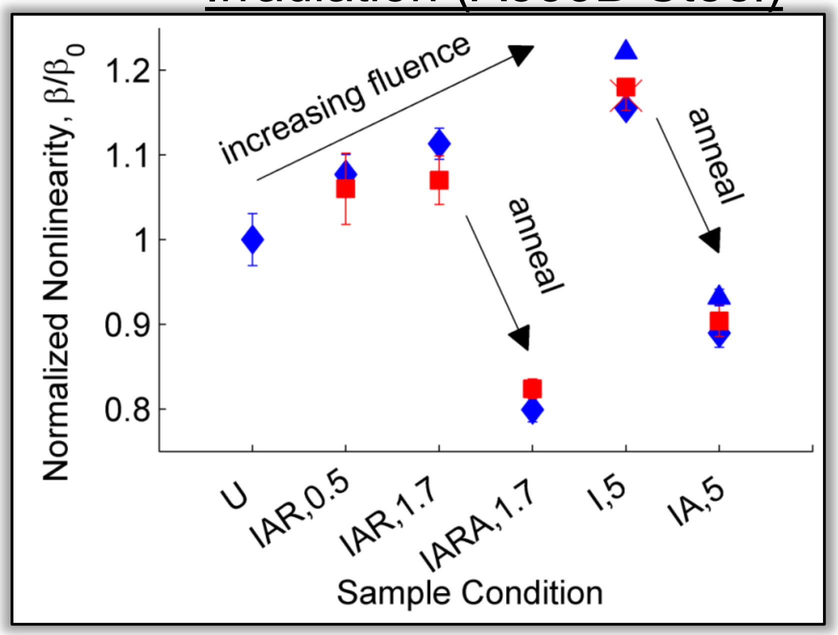




Low Cycle Fatigue (A36 Steel)




(Walker et al, 2011, NDT&E Int)

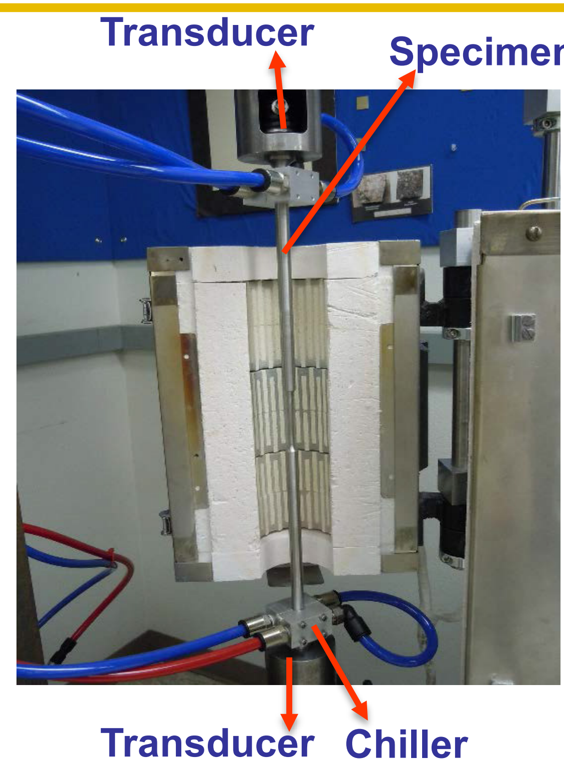
Irradiation (A533B Steel)

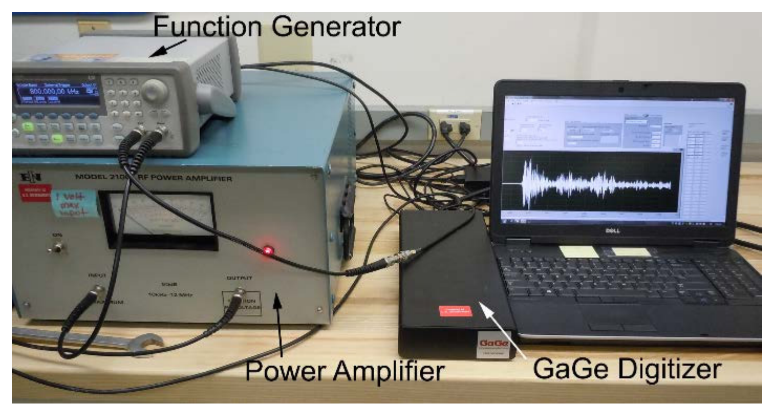



*Matlack et al., JNM, 2014*

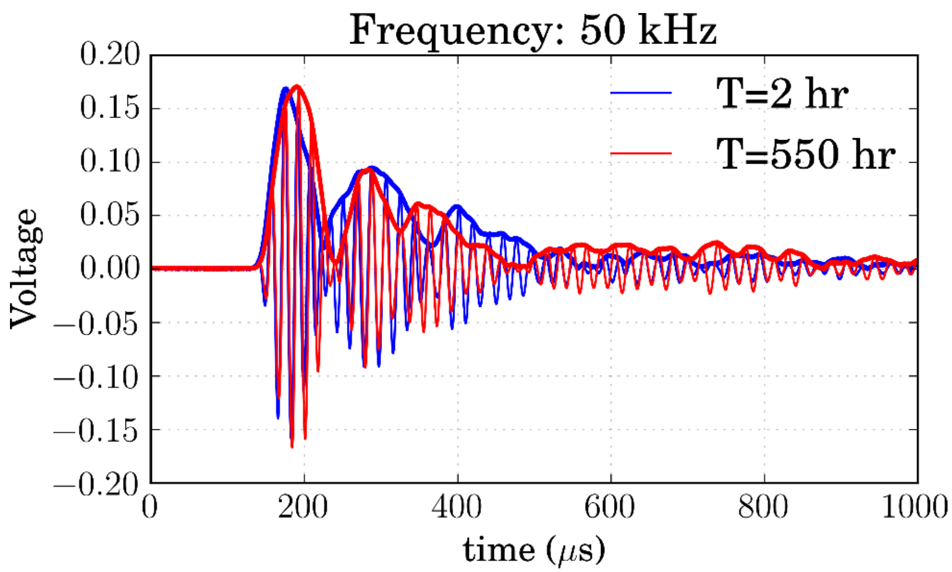
# In-situ Measurement Parameter Sensitivity - Example

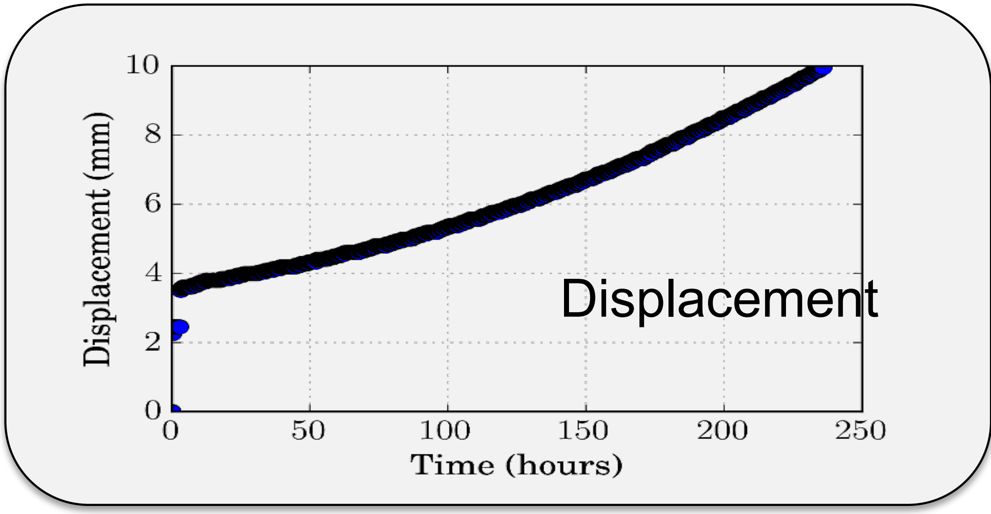
- **Nonlinear ultrasound monitoring of thermal creep**
  - Effort initiated in late FY2015 and continued into early FY2016
- **Objective – Determine if nonlinear measurements provide sufficient sensitivity to degradation in hard-to-access locations**
- **Ultrasonic guided wave mode of operation**
- **Commercial transducers kept below their temperature limits through active cooling**

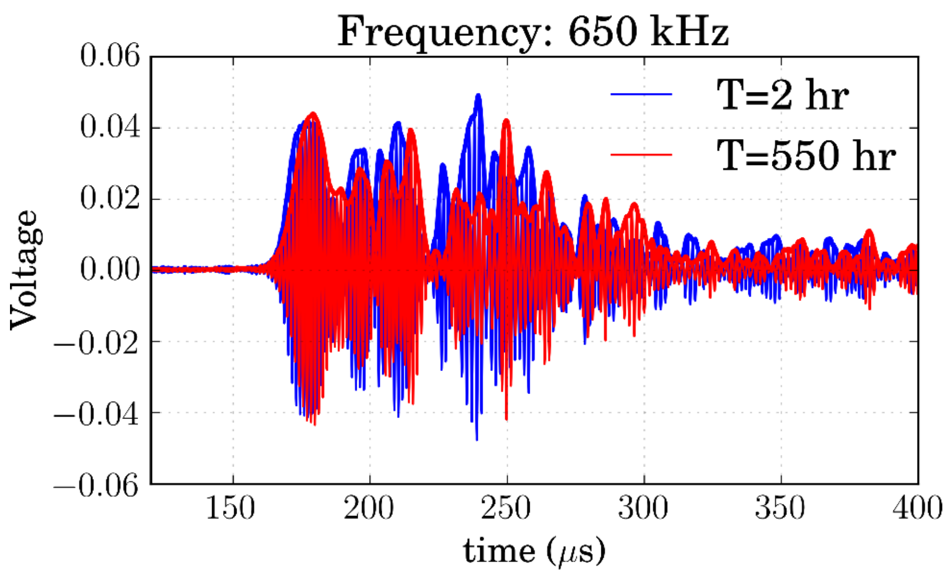


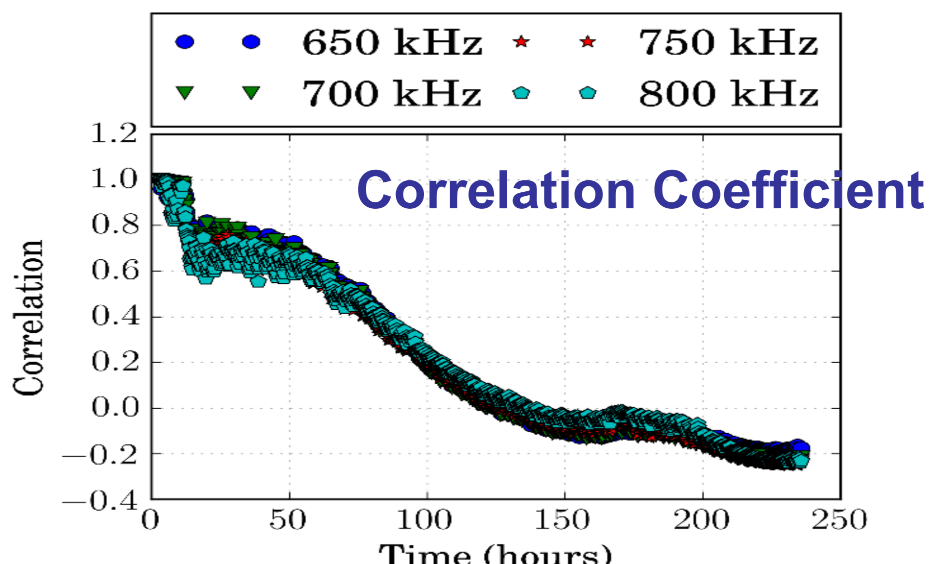



# Example of Measurements and Linear Analysis



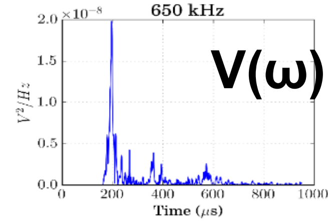



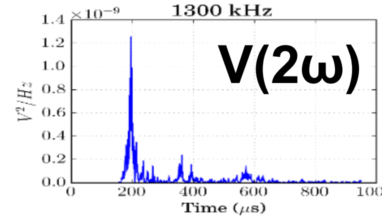



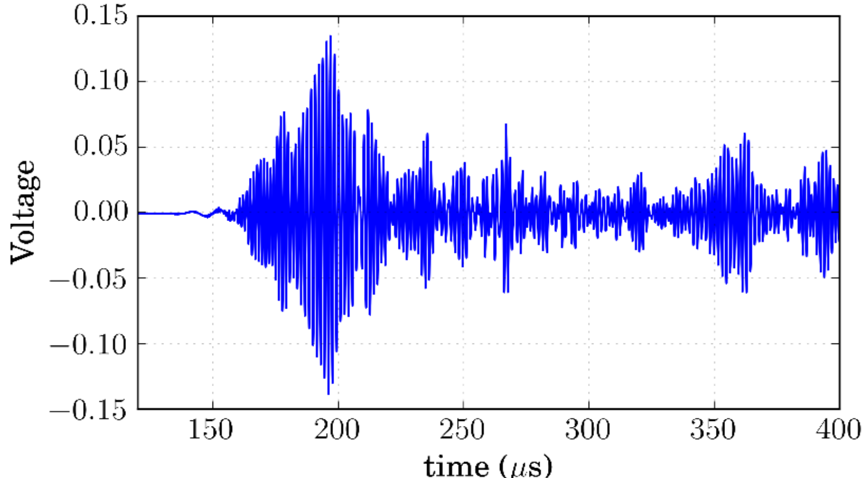
U.S. DEPARTMENT OF ENERGY

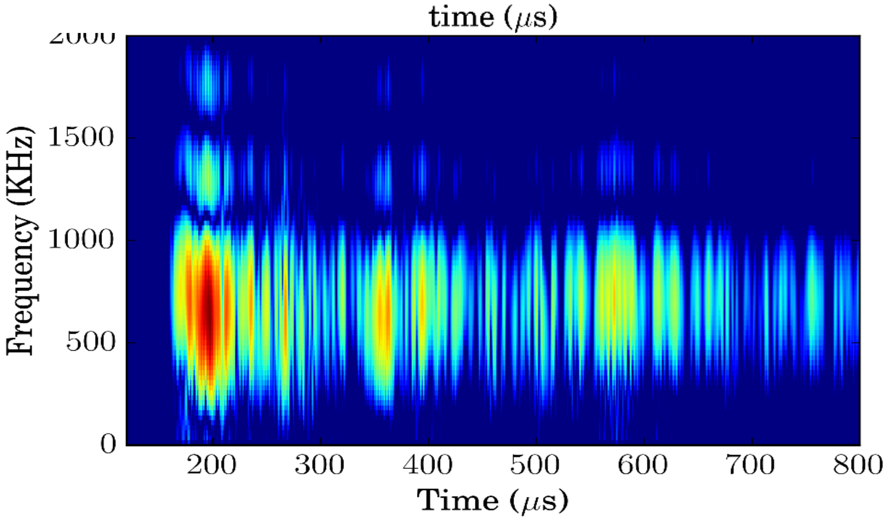
Nuclear Energy

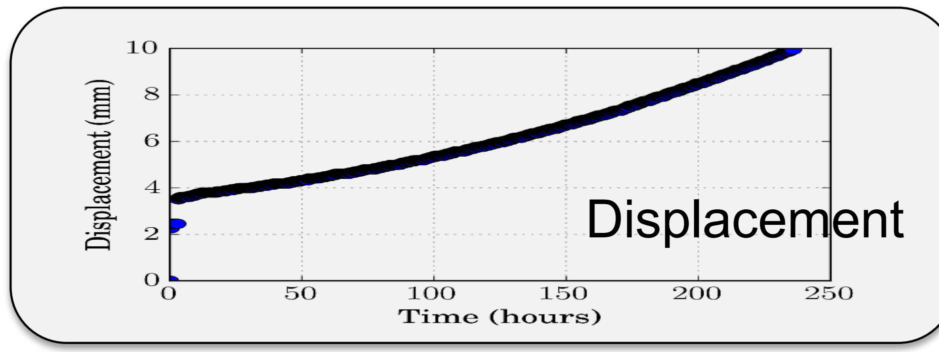
# Example of Measurements and Nonlinear Analysis

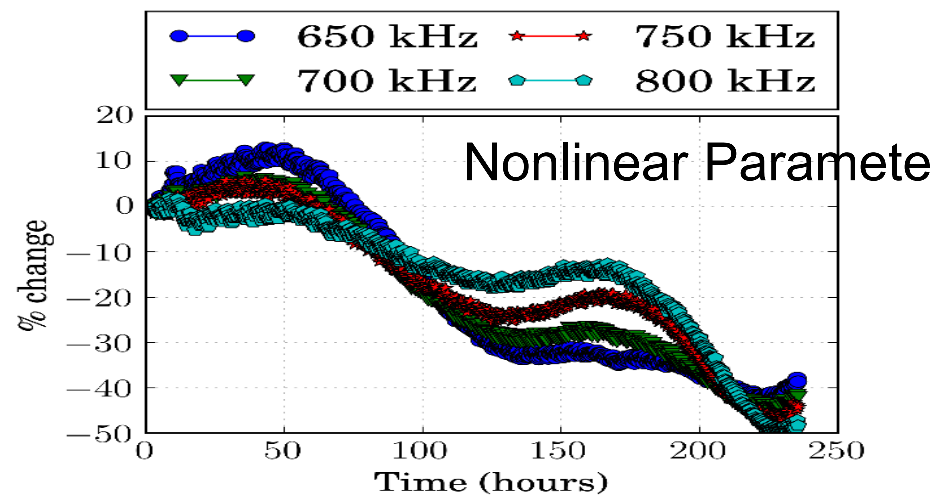



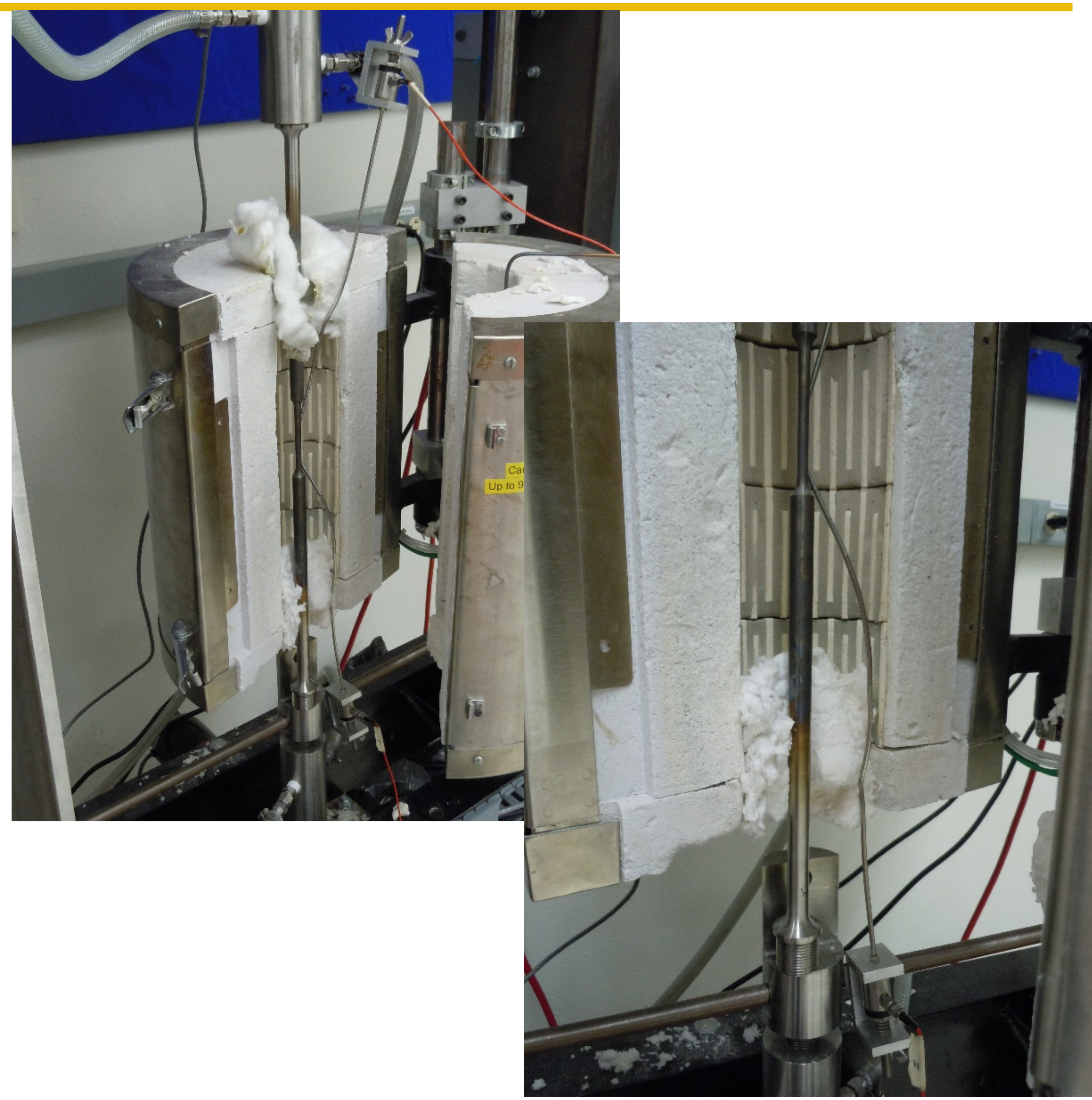



# Other In-situ Measurements

- **In-situ arrangement being modified to include**
  - Acoustic emission monitoring
  - Eddy current monitoring
- **Acoustic emission**
  - Measure stress wave emissions from crack initiation and growth
  - Waveguides to locate probe away from challenging environment
- **Eddy current**
  - Probe location planned near gage section
  - Probe design ongoing



# Path Forward

- **Develop prototype measurement systems for in-situ monitoring of critical passive components**
  - Test and evaluation in representative environments, including at high temperatures and in liquid Na
  - Focus on quantifying sensitivity and reliability of measurements
- **Address key engineering challenges in implementing in-situ monitoring systems in advanced reactors**
  - Modification of sensor design, novel sensor materials, techniques to compensate for measurement variability
- **Determine if (and how) measurement sensor technologies can be adapted for in-situ monitoring in HTRs**

# 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**

# Accomplishments – Publications and Presentations

- Meyer RM, JB Coble, EH Hirt, P Ramuhalli, et al (2013). "PHM Requirements for Passive Components in Advanced Small Modular Nuclear Reactors." Presented at *2013 IEEE PHM Conference*, Gaithersburg, MD, June 2013.
- Meyer RM, P Ramuhalli, et al (2013). "Research and Technology Gaps in Development of PHM for Passive AdvSMR Components ." Presented at *Review of Quantitative NDE*, Baltimore, MD, July 2013.
- Meyer RM, P Ramuhalli, et al (2013). "Prognostics Health Management for Advanced Small Modular Reactor Passive Components." Presented at *Annual Meeting of the PHM Society 2013*, New Orleans, LA, 2013.
- Meyer RM, P Ramuhalli, et al (2013). "Technical Needs for Prognostics Health Management of Passive Components in Advanced Small Modular Reactors." Presented at *2013 ANS Winter Meeting and Exposition*, Washington, DC, November 2013.
- Meyer RM, P Ramuhalli, et al (2014), "Progress Towards Prognostic Health Management of Passive Components in Advanced Small Modular Reactors (AdvSMRs)." Presented at IEEE *Int'l. Conf. on Prognostics Health Management 2014*, Cheney WA.
- Roy S, P Ramuhalli, et al (2015), "Probabilistic Model Selection for Prognostics of Thermal Creep in Advanced Reactors." Presented at *ANS NPIC-HMIT 2015, 2015*.
- Roy S, G Dib, P Ramuhalli, et al (2015). "Progress Towards Prognostic Health Management of Passive Components in Advanced Reactors – Model Selection and Evaluation". Presented at *2015 IEEE Int'l. Conf on PHM*, Austin, TX.
- M. Prowant, G. Dib, S. Roy, L. Luzi, P. Ramuhalli, "Nondestructive Measurements for Diagnostics of Advanced Reactor Passive Components.", ICAPP2016, San Francisco, CA, 2016.
- Roy S, P Ramuhalli, G Dib, MS Prowant, EH Hirt, and SG Pitman, "A Bayesian Model Selection Method for High-Temperature Creep Damage Prognostics," *IEEE Trans. Reliability*, 2016 (In Review).
- G. Dib, S. Roy, M. Prowant, P. Ramuhalli, J. Chai, "In-situ nonlinear ultrasonics for monitoring material degradation", IEEE UFFC, 2016 (in review).
- C. Walker, P. Ramuhalli, M. Good, B. Fuchs, M. Prowant, "Nonlinear ultrasonic measurements for quantifying creep damage in model alloys," Submitted to *ANS NPIC HMIT 2017*.

# 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
- **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