Need for Advanced NDE Methods in Non-Light Water Reactors

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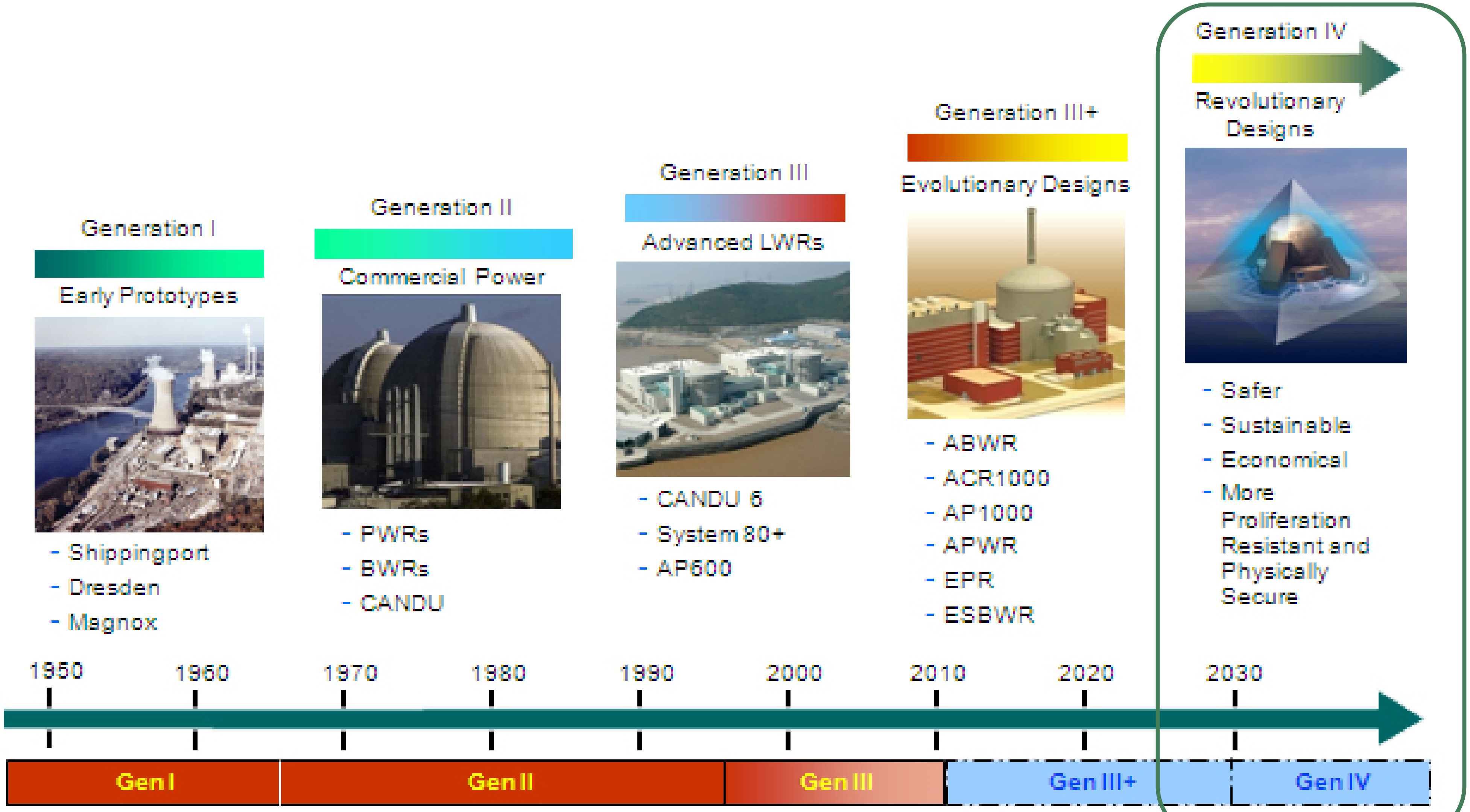
Workshop on Advanced Non-Light Water Reactors – Materials and Component Integrity

December 9-11, 2019

Outline

- Background: Advanced Non-Light Water Reactors (ANLWR)
- Needs and challenges for NDE and SHM
- Examples of recent R&D efforts
- Open research questions
- Summary

Advances in Nuclear Power Technology



Advanced Non-Light Water Reactors

http://www.gen-4.org

Nominal Operating Parameters of ANLWRs

		SFR	LFR	MSR	SCWR	GCR
Temperature (°C)	Core Inlet		290-610	550-650	350	250-587
	Core outlet	704***	465-780	700-1000	625	530-850
	Maximum	~825^{+}, 705^{++}	814^{+}	1300***, 947**	1900^{+}	1238^{+}
	Primary loop (Inlet/outlet)	338/485	405/561	570-650 /700-1000		
	Secondary Loop (Inlet/outlet)	282/443	392/541	450-600 /633-690		
Pressure Range (MPa)	Reactor Vessel	~0.1-0.2	~0.1	~0.1 – 0.5	26	~5-9
Flow Rate (kg/s)	Primary loop	174,128 (l/min)	2150-16200		1418	96-320
Neutron Flux	Peak fast fluence n/cm^2	6.8x 10^{12*} 4.0x 10^{23} (limit)	3.7 x 10^{23}	0.33-1 x 10^{21*} 3 x 10^{23**}		
	Flux (average) n/cm^2-s		2.35 x 10^{15}			
Power density (MW/m^3)	Average	17-210	69		Varies from 67-300	4-6.5

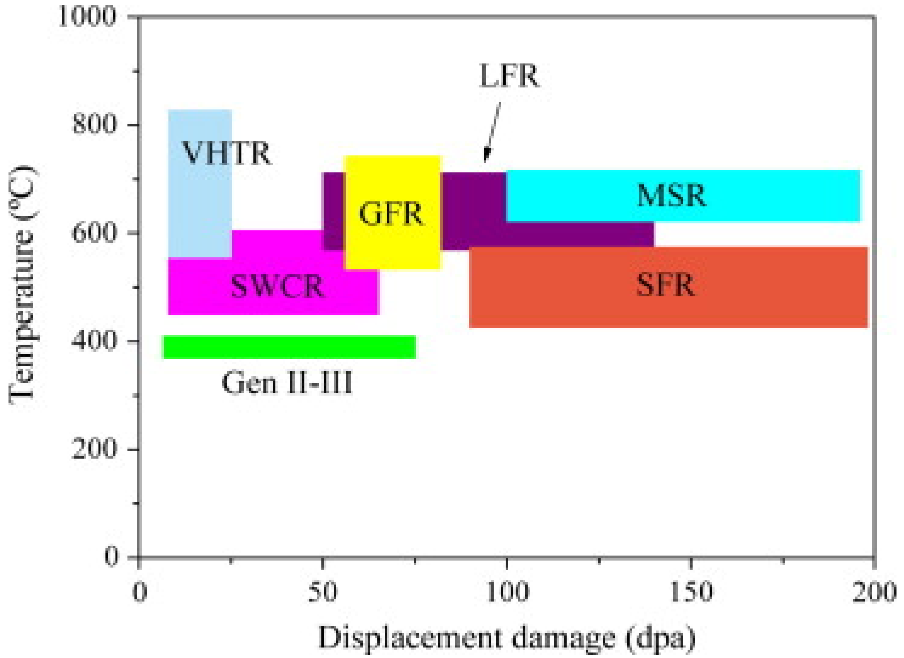
* Reactor vessel
** Graphite moderator
***Coolant maximum
$^{+}$ Fuel
$^{++}$ Reactor Vessel Wall

Operating Experience for ANLWR Passive Components

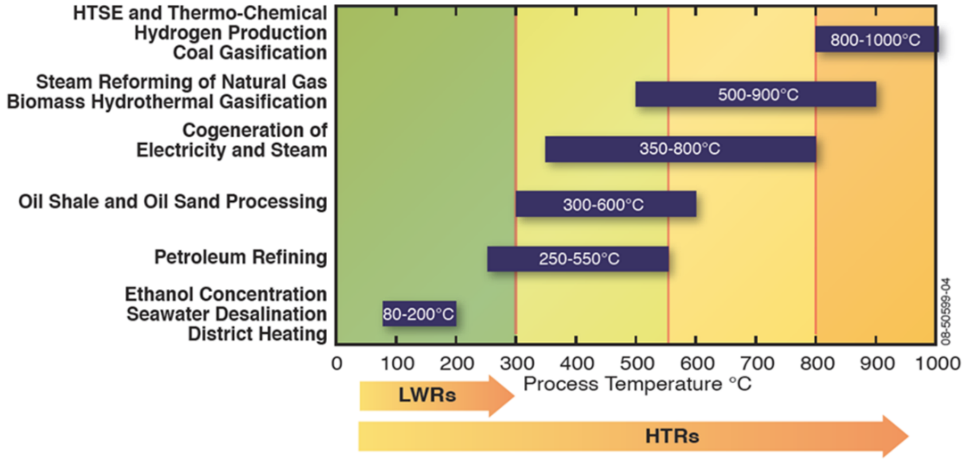
- Sodium reactors
  - Cause: Manufacturing defects, defective welds, fatigue cracking, erosion, sodium deposits, contamination, …
  - Effect: Sodium leak, sodium-water interaction, sodium contamination, level fluctuations, …
- HTR
  - Cause: Material incompatibility, moisture intrusion, manufacturing issues, …
  - Effect: cracking, chloride corrosion, failure of nut/bolts, plugging of pressurization lines, mechanical jamming, …
- LFRs, MSR
  - Cause: Material choice, high coolant velocity, coolant contamination
  - Effect: irradiation hardening, cracking, corrosion/erosion,…
- Issues identified from OE have been largely addressed through design modifications in current concepts and selection of improved materials
  - Some ANLWR operational concepts also include periodic replacement of critical passive components

Anticipated Challenges in ANLWRs

- Harsh operating environments
  - Potential for higher neutron damage levels for core structures and vessel components, and extended exposure to higher temperatures/corrosive coolant chemistry
- Extended life operation of ANLWR
  - Limited information on performance of some materials in ANLWR environments over lifetime
- Non-traditional operations possible (on-demand power, multiple missions, advanced energy conversion cycles, etc.)
  - Potential for increased stress from non-traditional operating profiles
- Possibility of extended operating intervals and online refueling between refueling outages
  - Potentially limited opportunities for periodic in-service inspection of primary system components



J.G. Marques, Energy Conversion and Management, 2010



blog.ngnpalliance.org

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Defense-in-Depth Philosophy

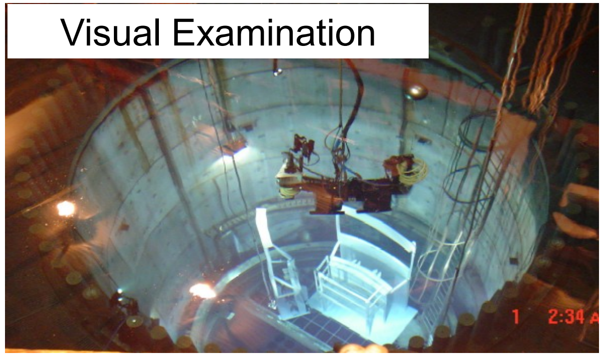
- All U.S. nuclear power plants designed, built, and operated so as to:
  - maintain structural and leak-tight integrity of components important to safety,
  - prevent or minimize accidents, and
  - mitigate the effects of accidents, should they occur.
- Defense-in-depth: Multi-layered approach to maintaining safety and high reliability
  - No one action, system, or component is depended upon to maintain safety
  - An integrated number of actions, systems, and components with multiple backups
- In-service inspection (ISI) using nondestructive evaluation (NDE) is one component of defense-in-depth
  - ISI of safety components required by 10CFR 50 through endorsement of ASME Boiler and Pressure Vessel (BPV) Code
  - ASME BPV Code specifies type of NDE inspection, frequency of inspection, and sampling criteria based on system classification (Class-1, 2, or 3)

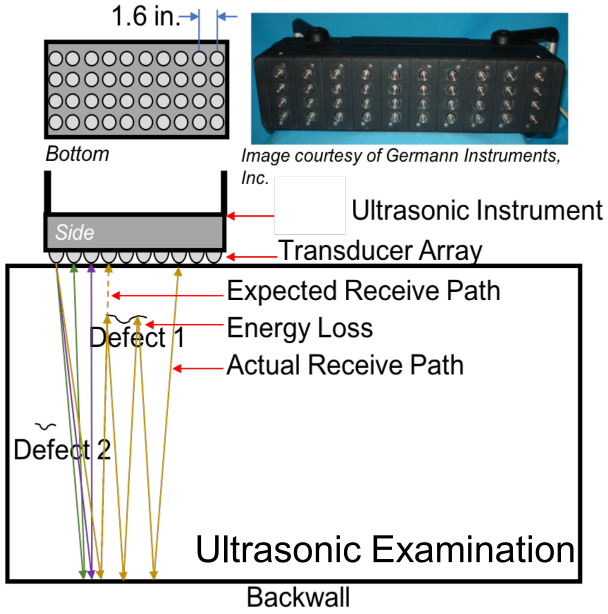
ISI Scope and Effectiveness

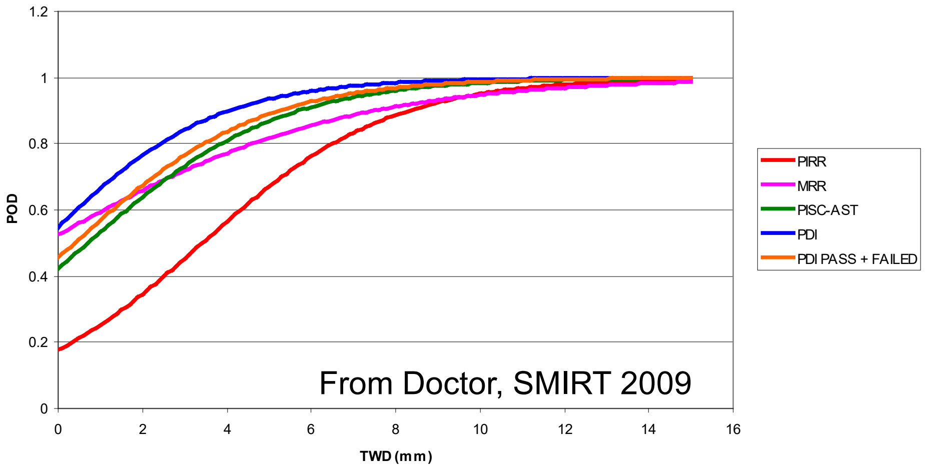
- Inspection sample sets selected to be representative
  - Populations and methods vary by safety class
- Finite periods of operation, or inspection intervals, defined
  - Current 10-year interval established by consensus and practical convenience
- Effectiveness affected by:
  - Unknown degradation progression rates – failures may occur between planned inspections
  - Variable crack initiation times
  - Degradation outside of initial inspection sample
  - ASME NDE methods applied may not always be targeted for appropriate degradation processes
- Unpredicted (or undiscovered) degradation leads to augmented ISI programs and mandated requirements exceeding those in ASME XI
  - SCC in SS and Alloy 600/82/182 welds
  - Boric acid corrosion
  - Flow-accelerated corrosion
  - Thermal fatigue
  - Other forms

NDE Methods in Nuclear Industry

- Methods endorsed by ASME BPV
  - Ultrasound, Eddy current, Radiography, Visual, Liquid penetrant testing, Magnetic particle testing
- NDE Reliability
  - For a given flaw, what is the repeatability of detection by a given technique?
  - What is the smallest flaw that can be detected by a given technique?
- NDE reliability influenced by many factors including equipment, materials and surface condition, flaw size and orientation, procedures, …







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Potential ISI Needs and Issues in ANLWR

- Wide variation in materials
  - Stainless steel, F/M steel, ceramics, graphite, Ni-base superalloys,…
- Locations vary for potential degradation
  - Welds and joints
  - Bends/elbows
  - Tubing

Components	Materials	Potential Degradation Modes	Desired Measurements
• Reactor vessel • Core structure, shields • Reflectors, absorbers, moderators • Piping and tanks • Heat exchangers, steam generators • Turbines, compressors • Valves, pumps	• Austenitic stainless steel • Ni-base superalloys • F/M steels • ODS F/M steels • Ceramics, composites, polymers • Graphite • Concrete	• Thermal and mechanical fatigue cracking • Creep/irradiation creep/creep-fatigue • Oxidation/corrosio n • Embrittlement • Stress corrosion cracking • Void swelling	• Cracking and corrosion • Creep • Coolant parameters (temperature, pressure, flow, chemistry, level) • Neutron flux • Contamination (coolant and cover gas) • Loose-parts

- Data on material performance over ANLWR lifetime is limited
  - Tests ongoing for material qualification, codes and standards development
- NDE measurement challenges
  - Potential access limitations for ISI
  - Measurement parameter sensitivity
  - Deployment issues for in-situ measurements

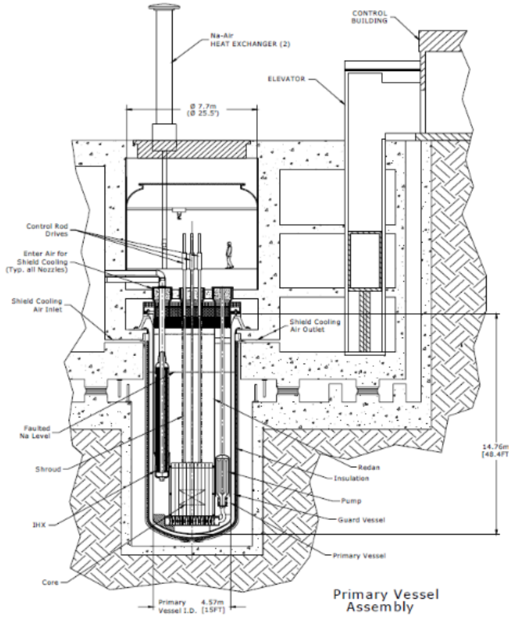
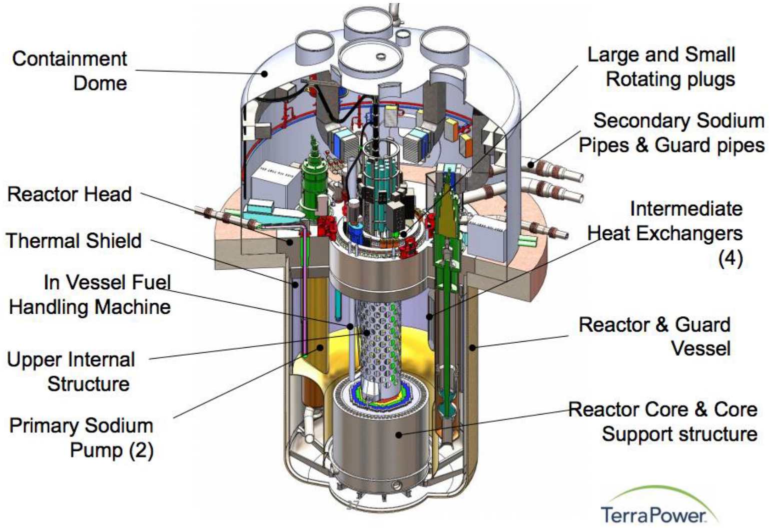
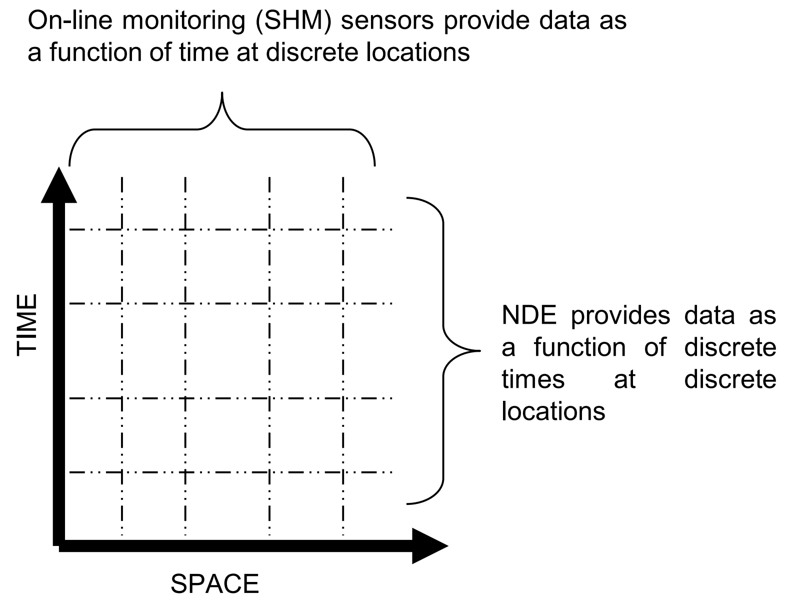


Figure III-2. Primary Plant Systems



ISI for Reliable Degradation Detection

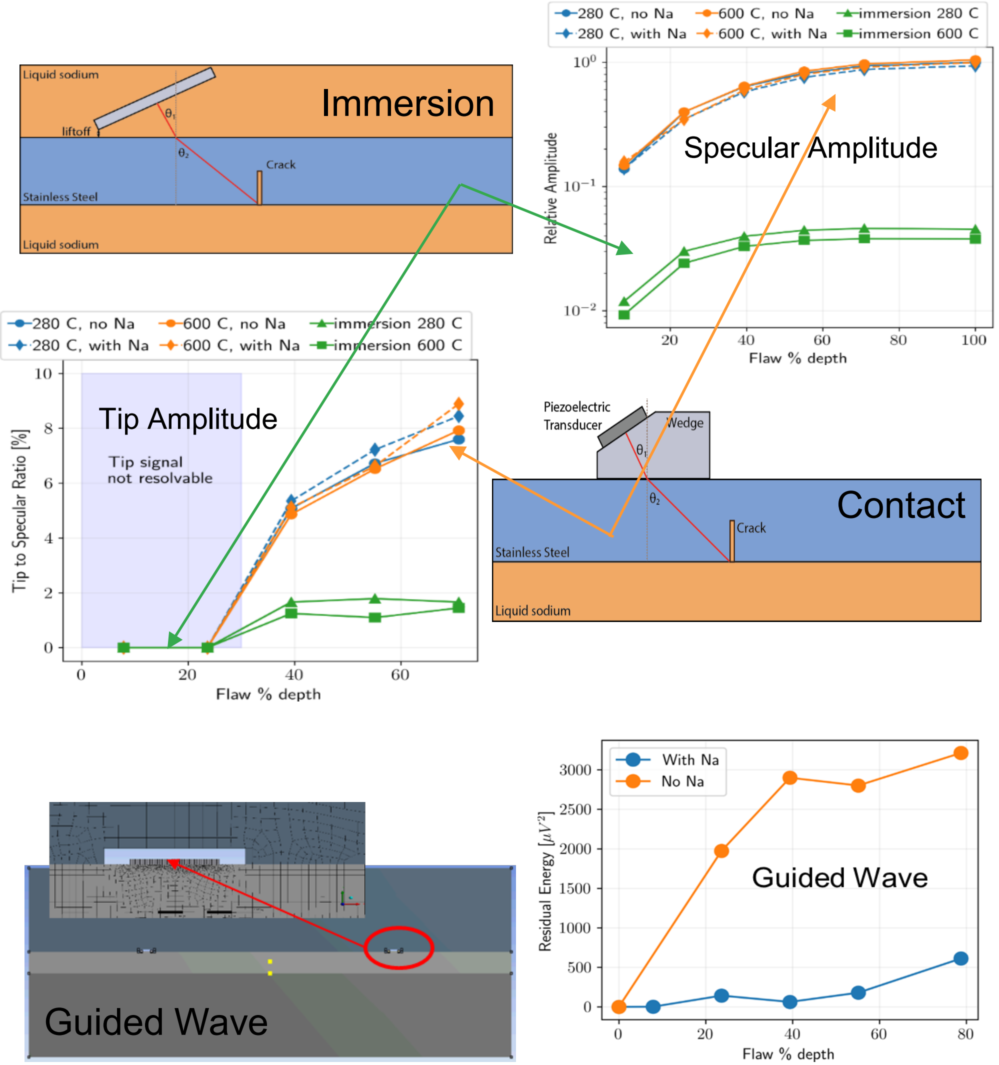
- Most effective technique - continuously monitor all plant components 100% of the time
- Next best method would be to examine all components during each refueling outage (or periodically)
  - Not economically viable – plants would spend more time being inspected than making power
  - Would require very large population of skilled NDE and crafts personnel; especially for many plants in simultaneous outages
- Structural health monitoring (SHM), which continuously monitors a subset of components, may need to be considered for ANLWRs that may have longer refueling cycles
  - Component selection based on contribution to risk, and perhaps limited accessibility



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

Simulation Studies Can Provide Insights Into Inspection Performance

- ➢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 detection and sizing 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



Source: Dib et al, IWSHM (2018)

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SHM Systems for Nuclear Power May Require High Temperature, Rad-tolerant Sensors

- Materials selection is key
  - Example: Prior research has shown viability of AlN and BiT composites for high-temp, in-reactor ultrasonic measurements

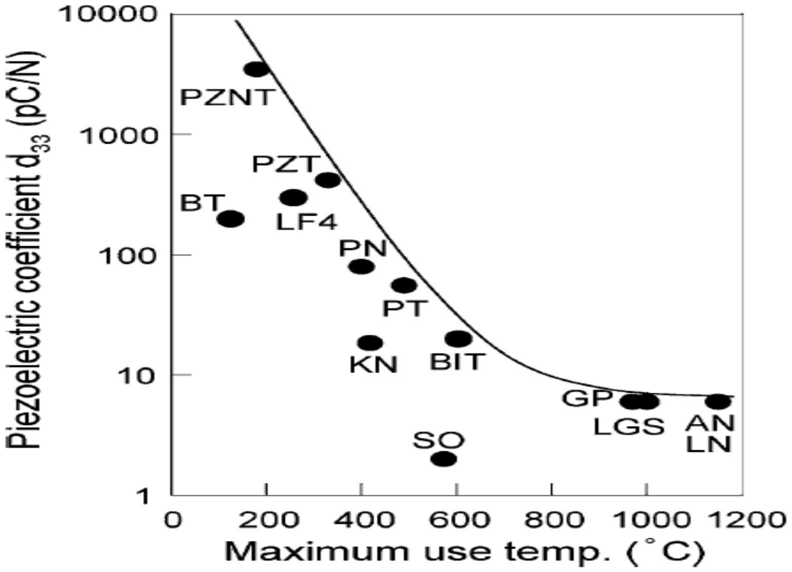
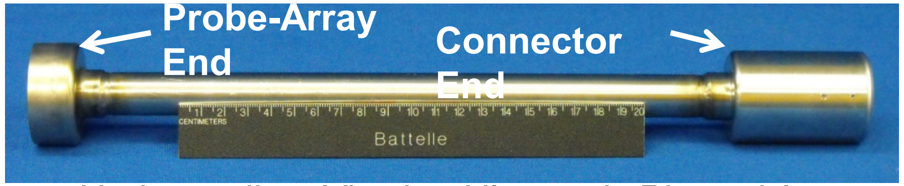
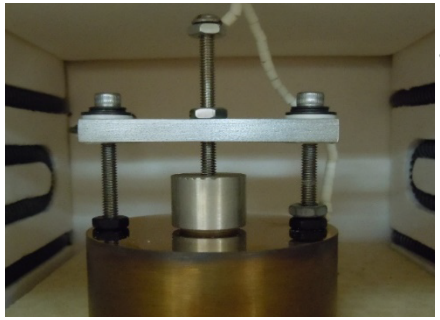
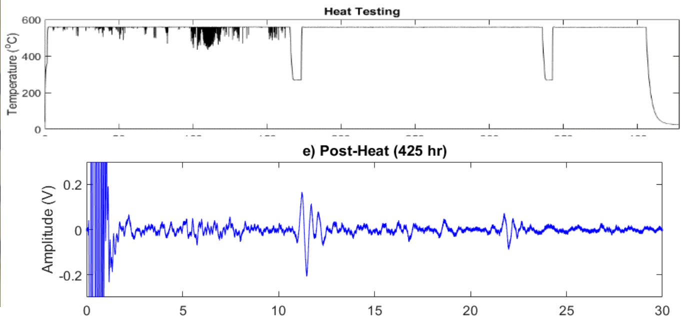


Figure . Relationship between piezoelectric coefficient d_{33} and the maximum use temperature (for most materials, T_C) for piezoelectric ceramics. Reproduced from M. Akiyama, et al, *Advanced Materials* **21** (5), 593-596 (2009).

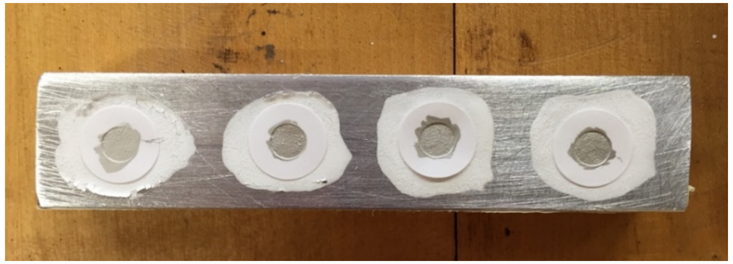


Under-sodium Viewing Ultrasonic Phased Array (Larche et al 2017)





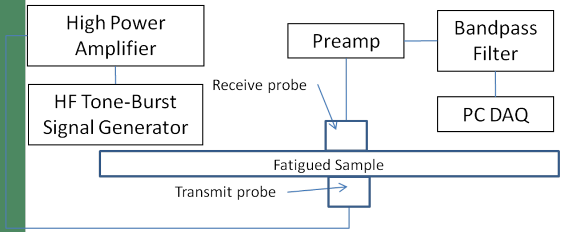
High temperature (>550^{o}C) Monolithic Ultrasonic Transducer (Ramuhalli et al 2018)

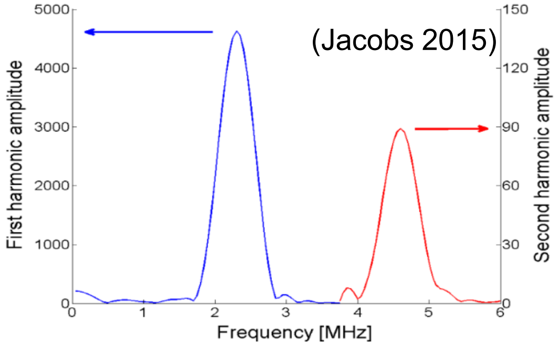


Sol-gel High-Temperature Composite Transducers

(courtesy C. Lissenden, B. Tittman)

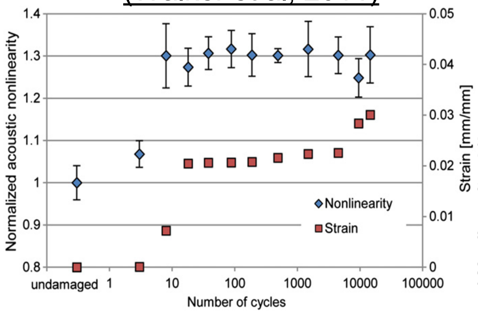
Advanced NDE Methods are Being Investigated for Early Detection and Monitoring of Degradation



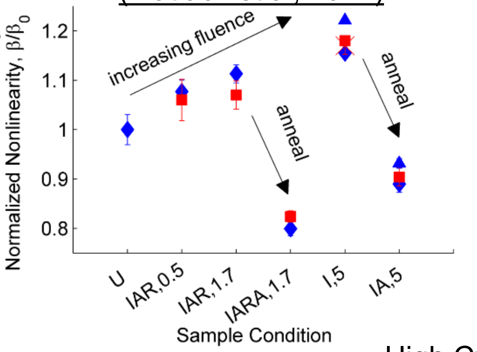


Nonlinear Ultrasonics

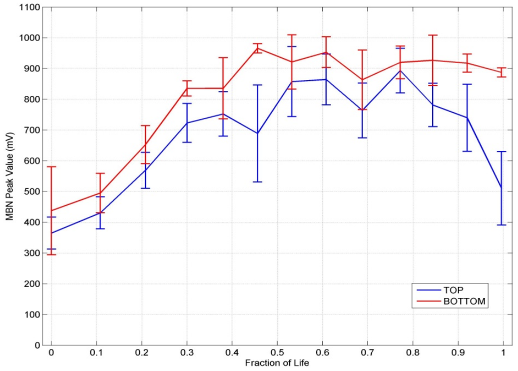
Low Cycle Fatigue (A36 Steel)
(Walker et al, 2011)

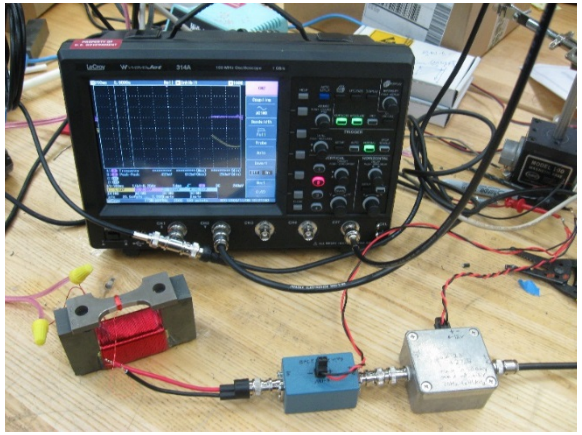


Irradiation (A533B Steel)
(Matlack et al, 2014)



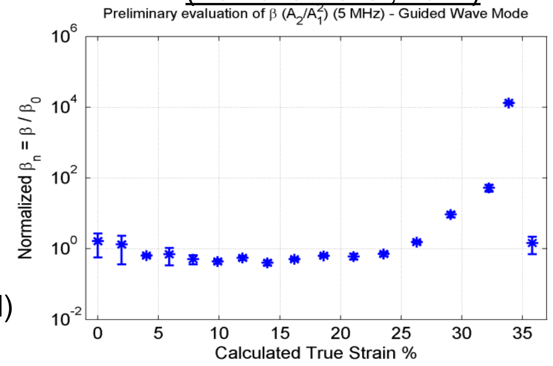
MBN (Tensile Strain, 410 Steel)
(Ramuhalli et al, 2015)



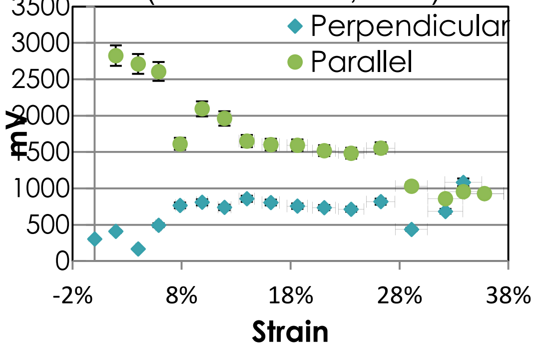


Magnetic Barkhausen Noise

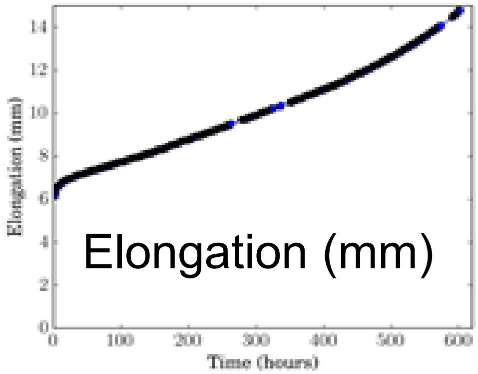
High Cycle Fatigue (304 SS)
(Ramuhalli et al, 2014)

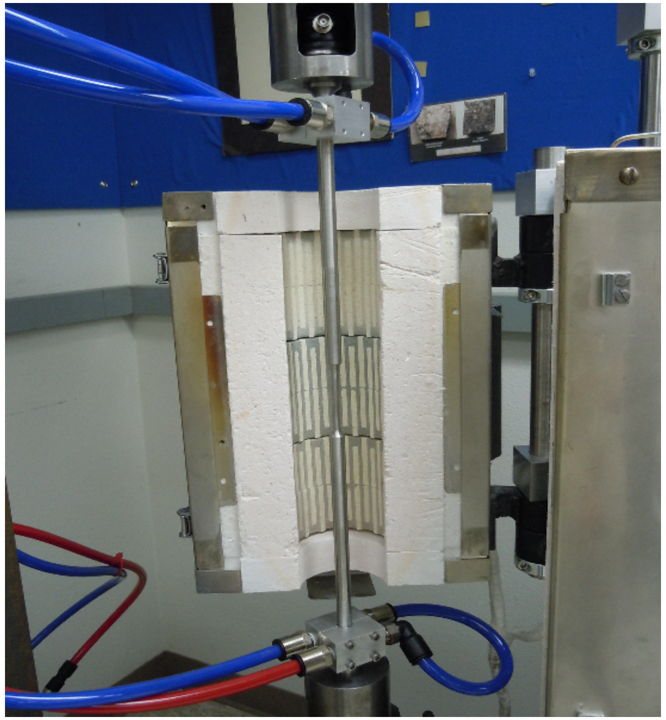


MBN Peak (Tensile Strain, 410 Steel)
(Ramuhalli et al, 2015)

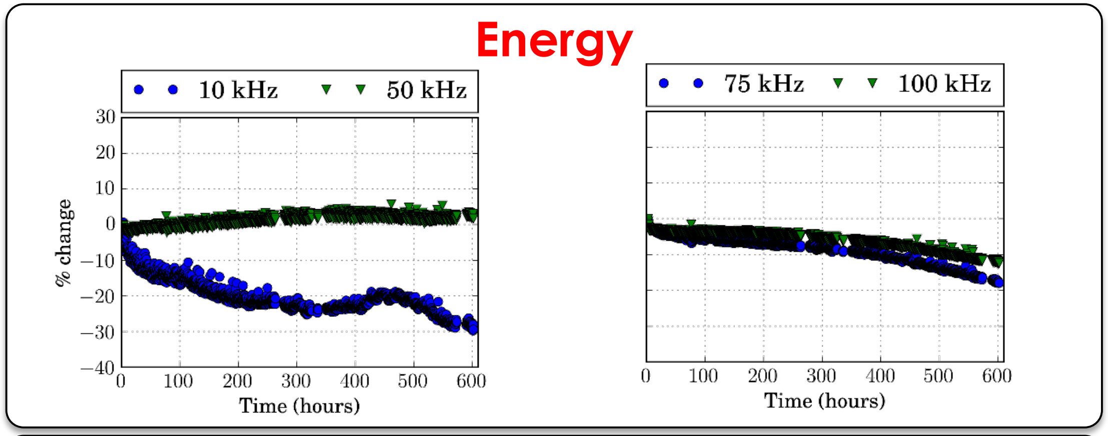


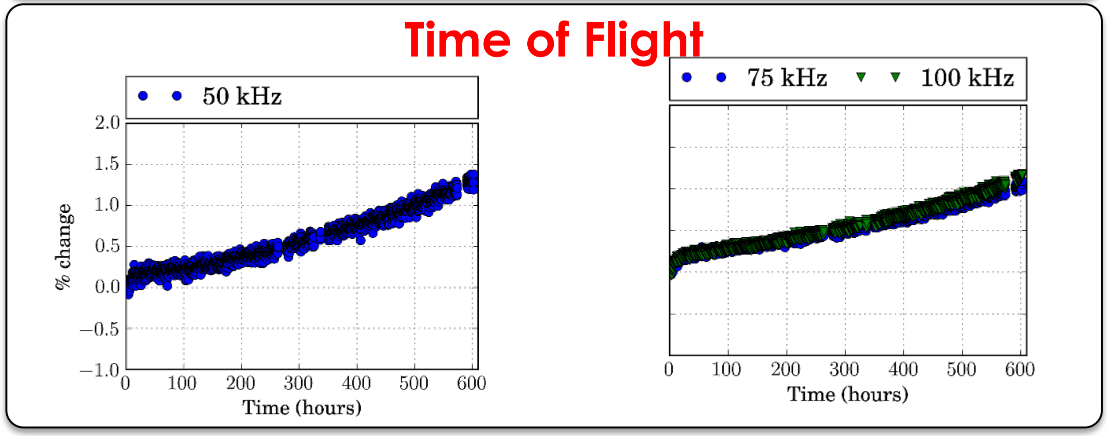
SHM/NDE Measurements May Provide Necessary Sensitivity to Other Degradation Modes





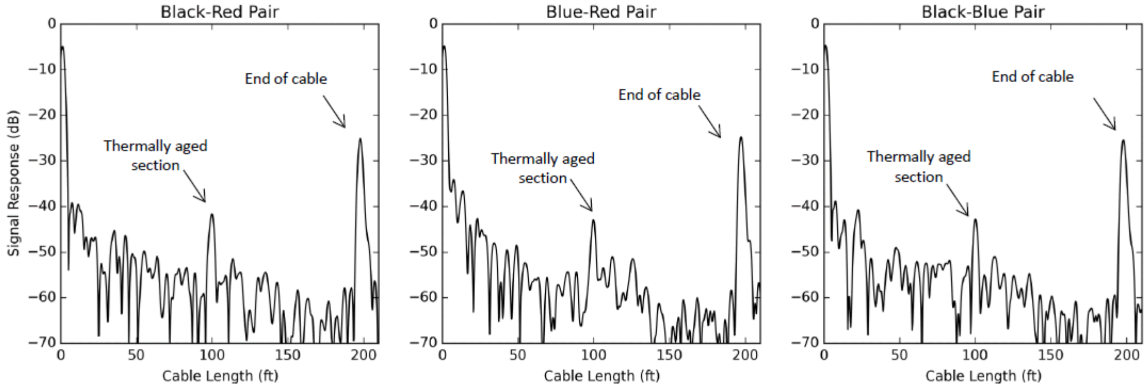
High Temperature (600°C) Creep Test Setup with In-Situ Ultrasonic Guided Wave Monitoring



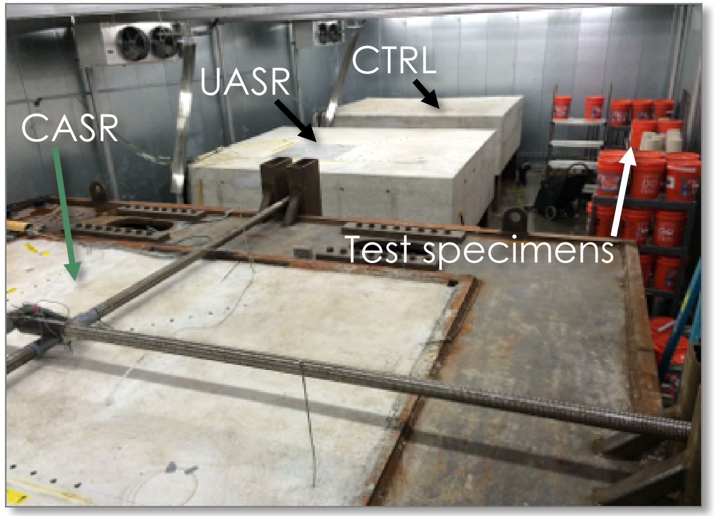


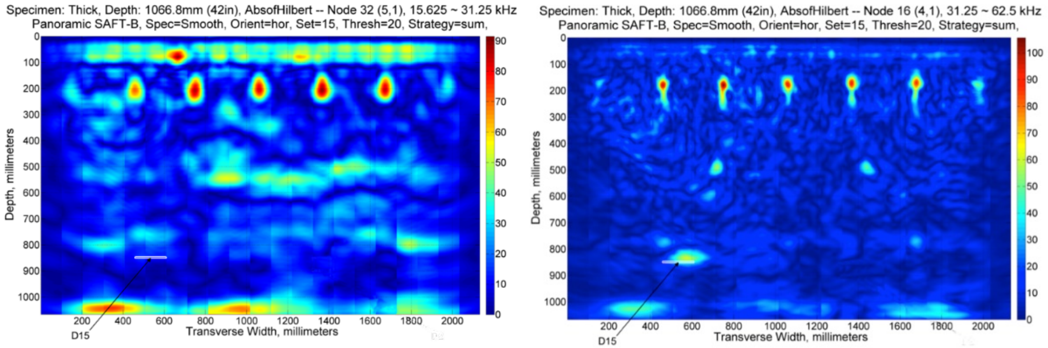
Source: Dib et al, (IWSHM 2018)

NDE and SHM Methods for Non-Metallic ANLWR Components are Likely Needed



W. Glass et al (2017)

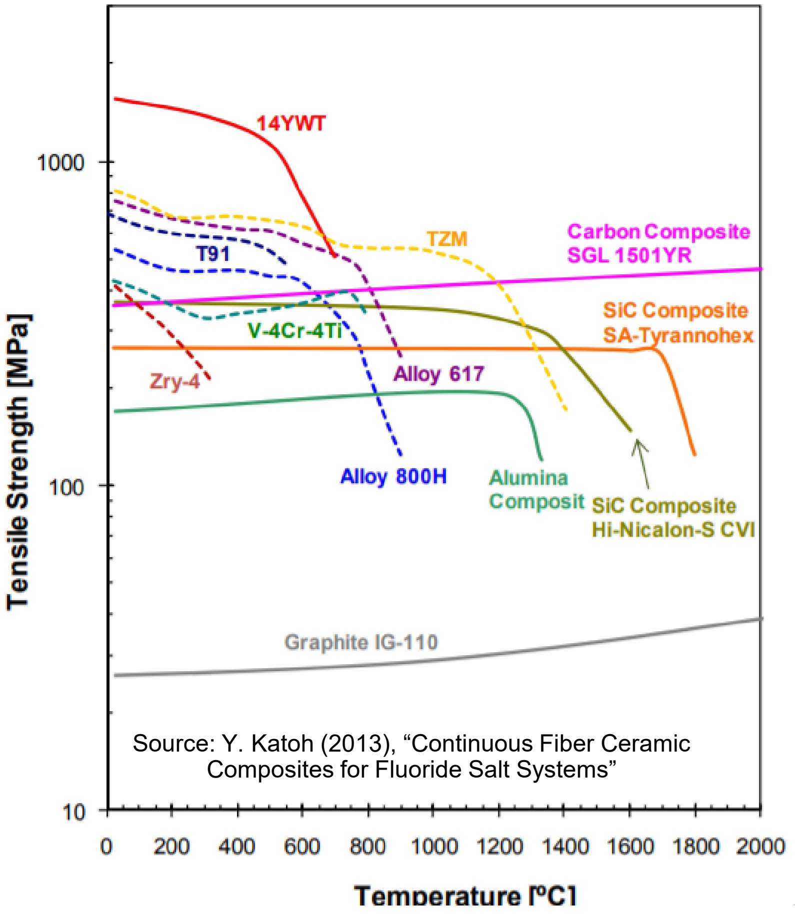




D. Ezell (2019), "High Fidelity Ultrasonic Imaging of Concrete"

NDE techniques for characterizing polymers and concrete for LWRs can likely be adapted for use with ANLWRs

NDE and SHM Methods for Non-Metallic ANLWR Components are Likely Needed



Source: Y. Katoh (2013), "Continuous Fiber Ceramic Composites for Fluoride Salt Systems"

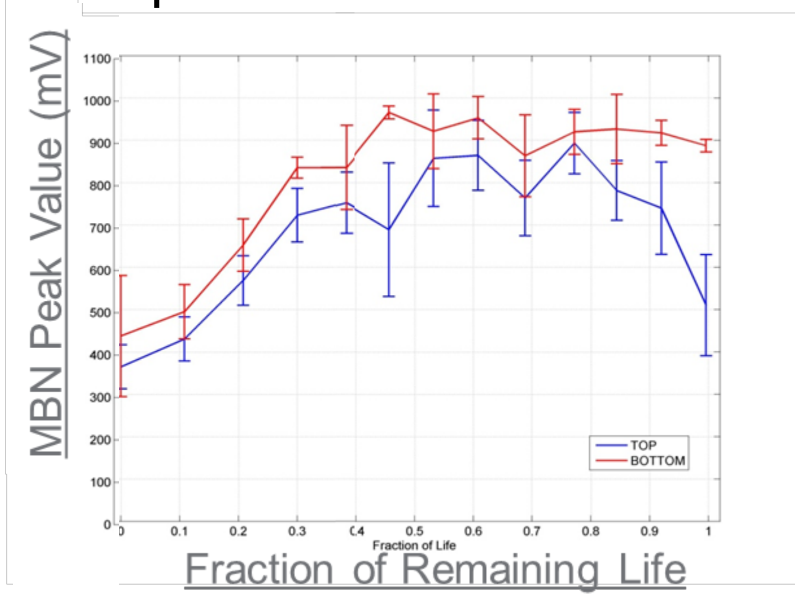
Bottom graphite stud of MSRE before (large photo) and after (inset) operation

Source: ORNL-TM-4174

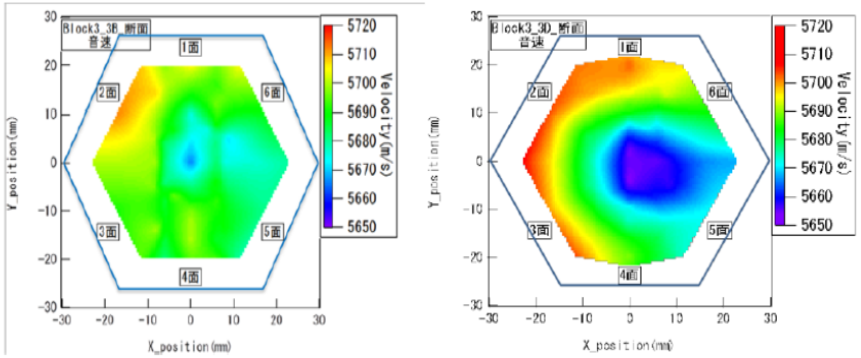
New techniques will be needed for inspecting/monitoring and characterizing materials such as SiC/SiC composites and graphite

Measurements Are Also Usually Easier than Interpretation

- Most NDE methods for microstructure characterization provide relative and not absolute information
  - Classical inverse problem: non-uniqueness
- Correlative analyses provide vital insights into measurement change with degradation
- Approaches for quantifying material state from NDE/SHM measurements and its remaining life are needed



MBN Peak Value Change with Tensile Strain in 304 SS
(Ramuhalli et al, 2015)



Density and Ultrasonic Velocity Change with Dose in Stainless Steel Blocks
Garner et al, INL/CON-14-33001, 2015

Characterizing Reliability of Advanced NDE and SHM methods Will be Necessary

- Diversity in materials and material microstructure; fabrication history
- Harsh environments seriously challenge available sensors and instrumentation
- Delineating effects of multiple stressors
- Insufficient information for inverse models and damage accumulation models
- Damage threshold for failure (especially if defining degradation with respect to precursors)

Ongoing Research

- Reliability of SHM and NDE, for mechanisms other than cracking
  - Measures of degradation severity or component health are needed
  - Measurement uncertainty quantification and its effect on reliability
  - Concurrent damage mechanisms – detection sensitivity and selectivity
  - NDE/SHM of AM manufactured materials for ANLWR reactor applications
- Sensors and instrumentation survivability
  - Online calibration of aging sensors for in-situ monitoring to correct measurement drift
  - Optimal sensor placement for in-situ monitoring
- Inverse methods for quantifying material condition from NDE/SHM, estimating remaining service life
  - Models relating material changes to measured quantities, and models for assessing component health change over time
  - Failure/Acceptance criteria – define acceptable and rejectable damage thresholds. Traditionally defined for cracks using fracture mechanics calculations to determine minimum acceptable flaw size that does not compromise structural integrity – how do we extend this concept to other mechanisms?
- Human factors
  - Inspection and data analysis can vary with operator
  - Resulting analysis information will need to be presented to operators

Summary

- NDE plays (and will continue to play) a critical role in defense-in-depth for nuclear power plants
- Many NDE methods are qualified for use in assessment of safety-critical passive components in LWRs
- As ANLWR concepts mature, new challenges to assessing degradation level and growth rates are foreseen; Research (nationally and internationally) is addressing many of these challenges
  - Sensing: what, where, and how to measure; sensitivity & fidelity; applications to non-metals and AM materials
  - Sensors and instrumentation for in-vessel/in-containment use
  - Inverse models for rapid, robust data analysis
  - Qualification of sensors and instrumentation, systems, methods, and procedures and personnel
  - Data and testbeds for testing and qualifying methods and developing analysis methods are necessary

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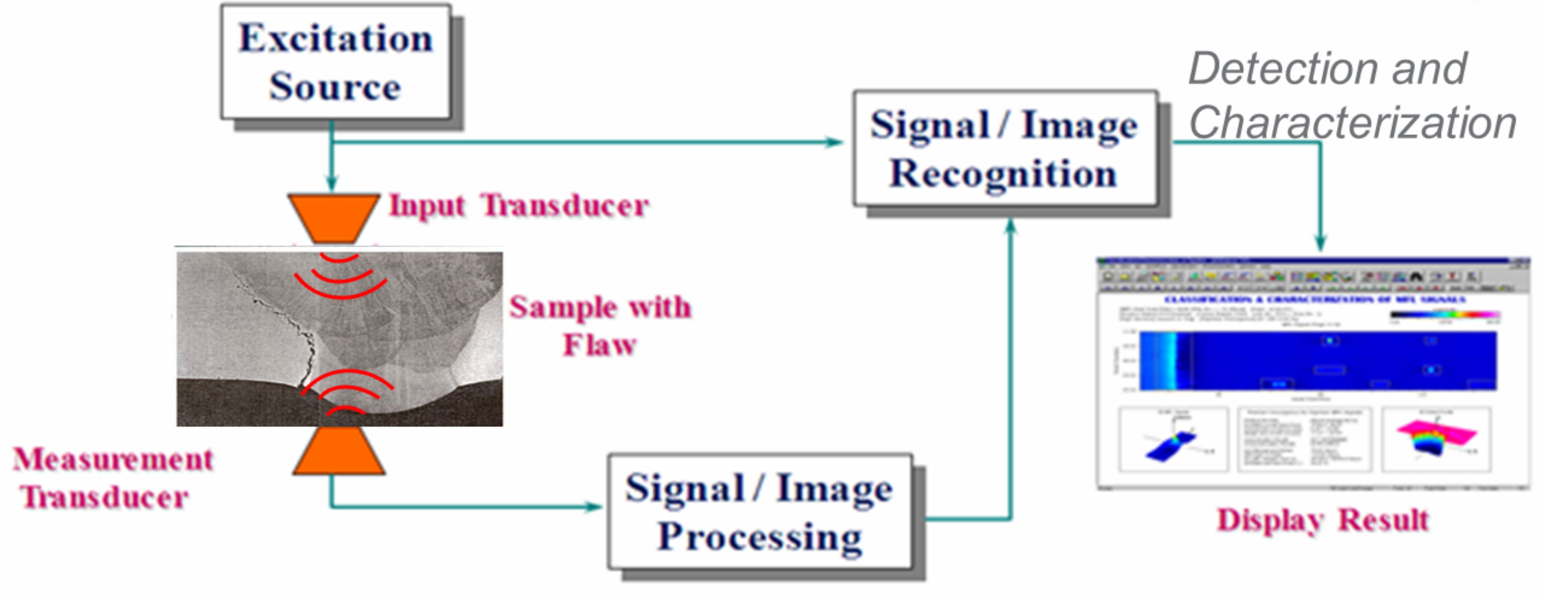
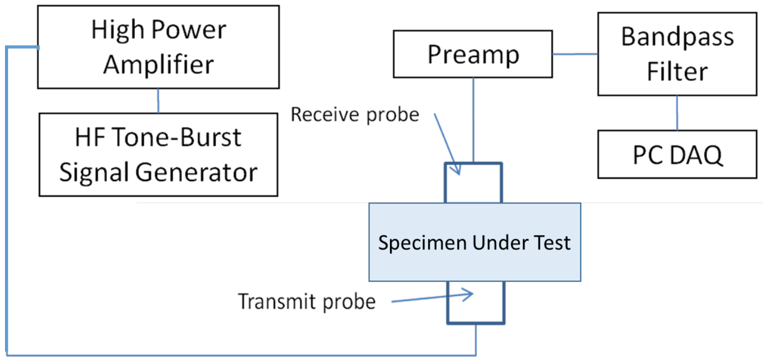
- Oak Ridge National Laboratory is managed by UT-Battelle for the US Department of Energy.

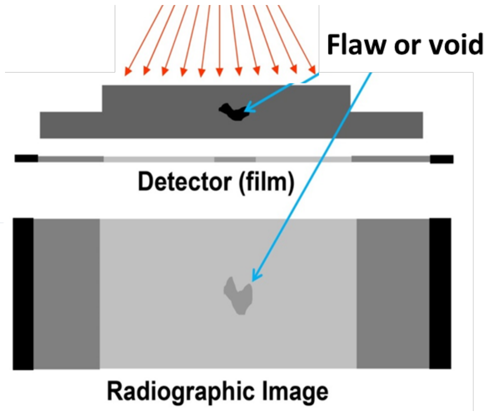
Questions?

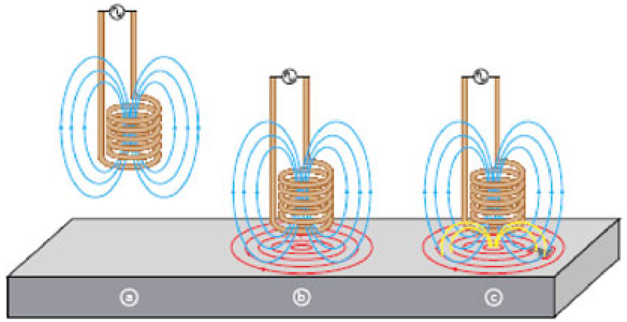
Extras

Nondestructive Evaluation (NDE)

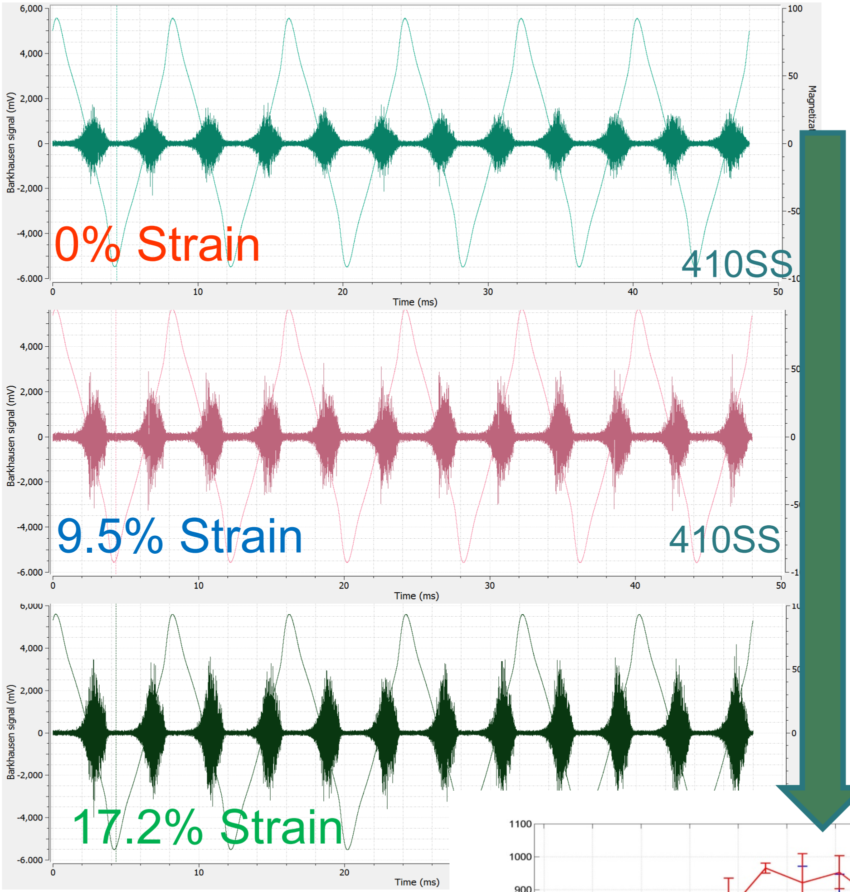


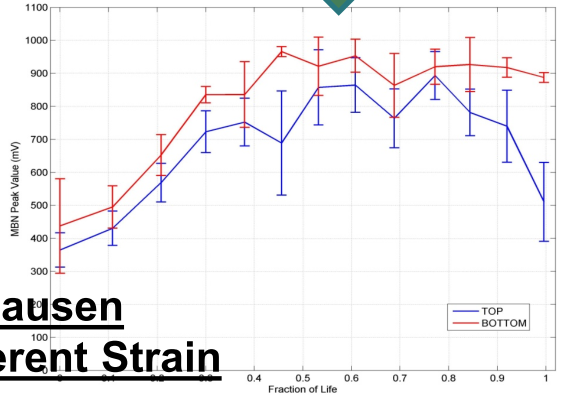




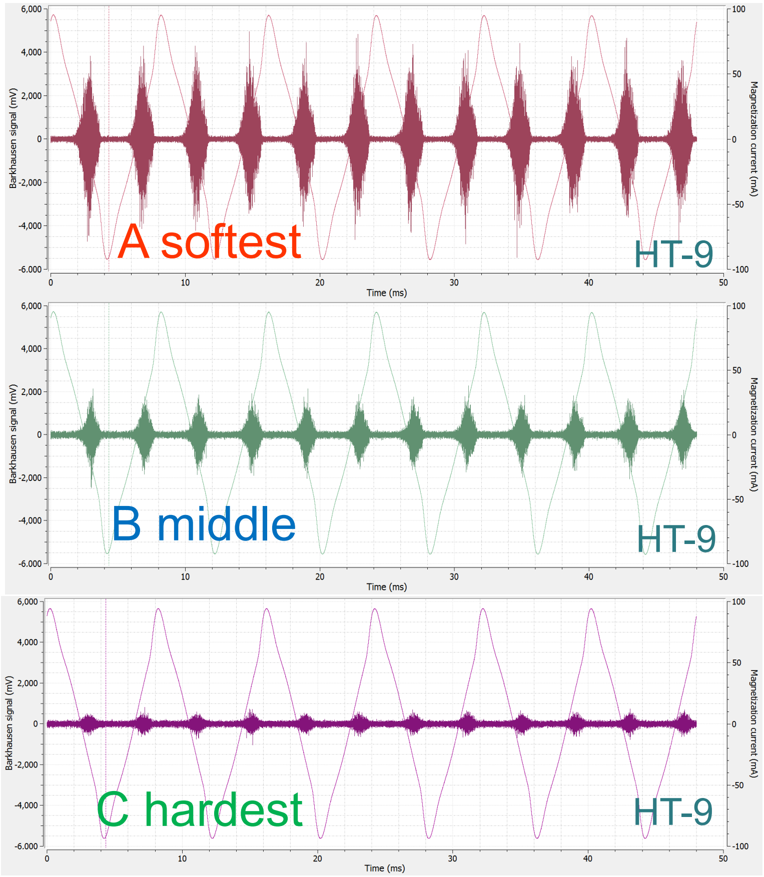


Example: Magnetic Barkhausen Noise Measurement – Effects of Stressors



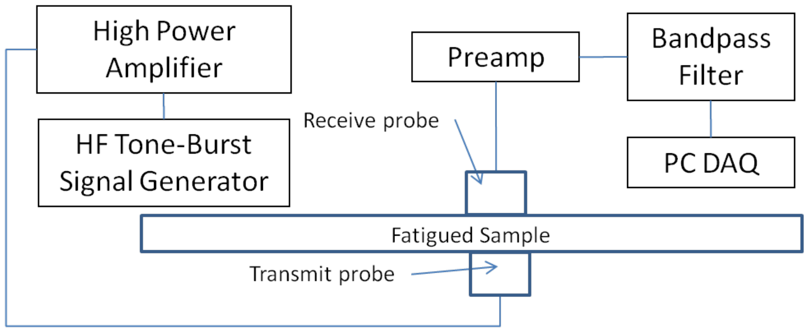


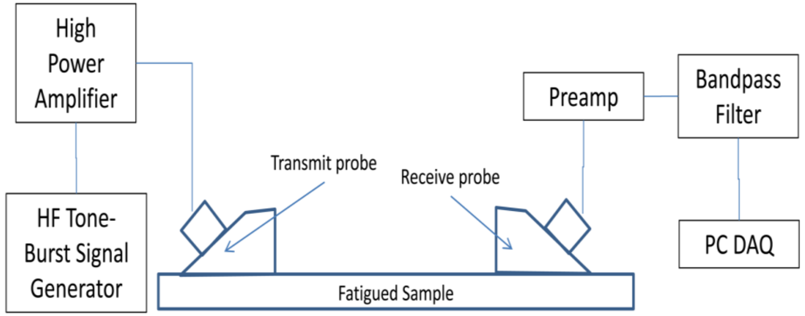
Magnetic Barkhausen measurements (Different Strain Levels)

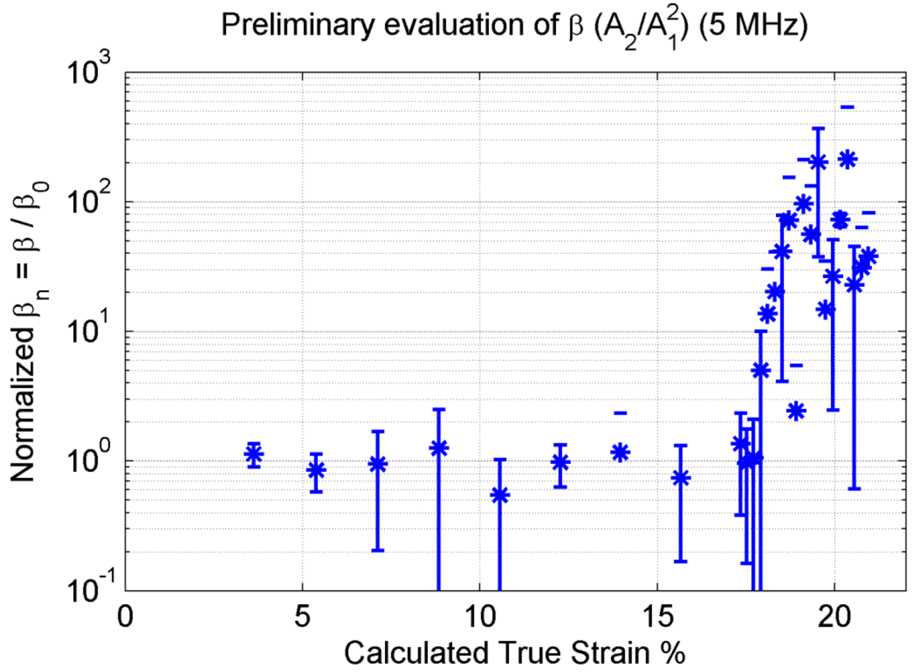


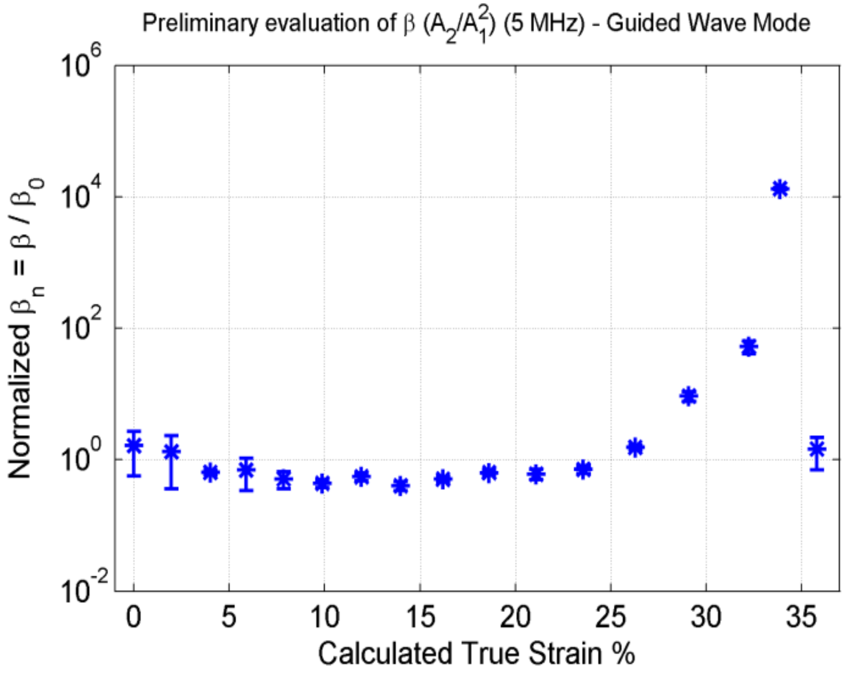
Magnetic Barkhausen measurements (Different Hardness Levels)

Even How We Make The Measurement Can Impact The Result!



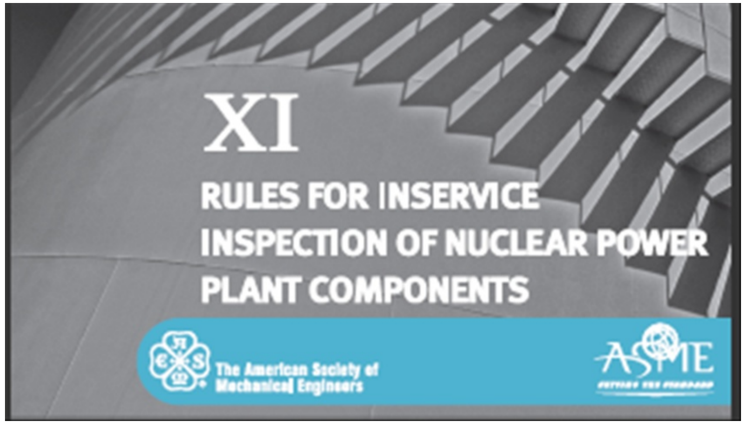






Online Monitoring for Materials Degradation: Structural Health Monitoring (SHM)

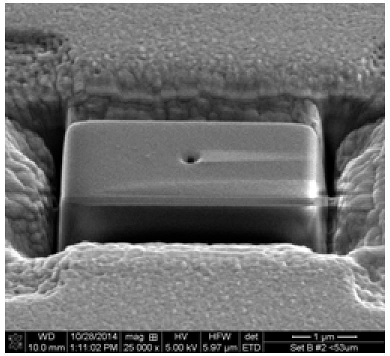
- In-situ online monitoring
  - Monitoring hard-to-access or high-risk regions
  - Flaw growth monitoring
  - Component/system-scale monitoring
- Acoustic emission only currently sanctioned technique for online monitoring of materials degradation by the ASME BPV Code
  - Flaw growth monitoring only (flaw 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
  - …
  - Advances in technology are **positively** impacting the development of OLM for materials degradation!



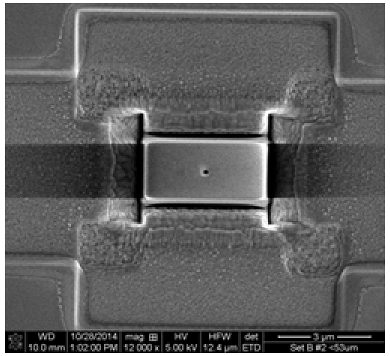
AE System Circa 1993

AE System Circa 2010

Coupled Materials Evolution-Measurement Models May Help With Mechanistic Understanding

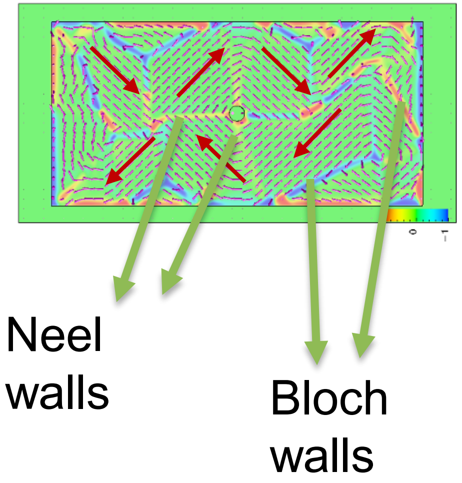


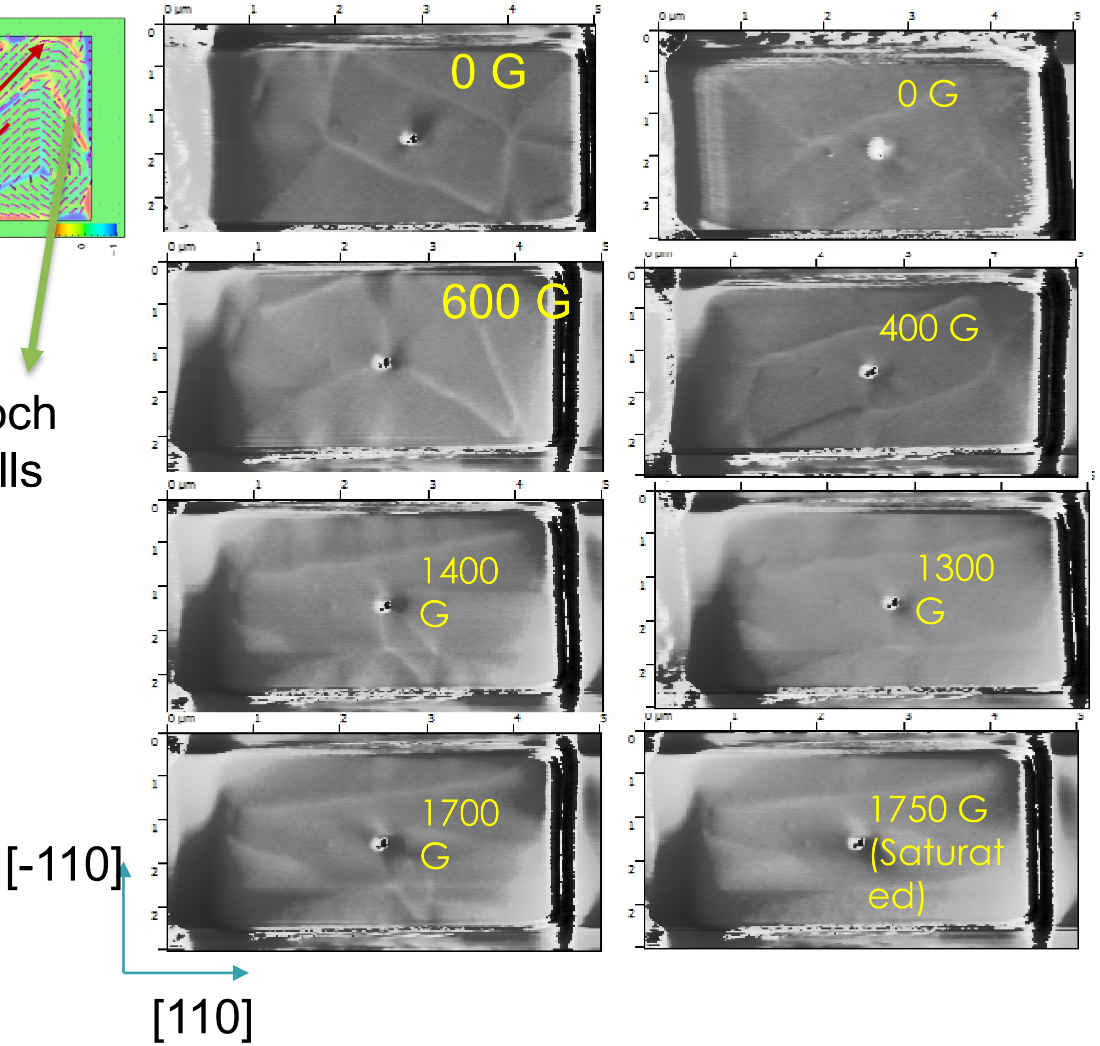
SEM image: Side view



SEM image: Top view

Simulation (at 0G)

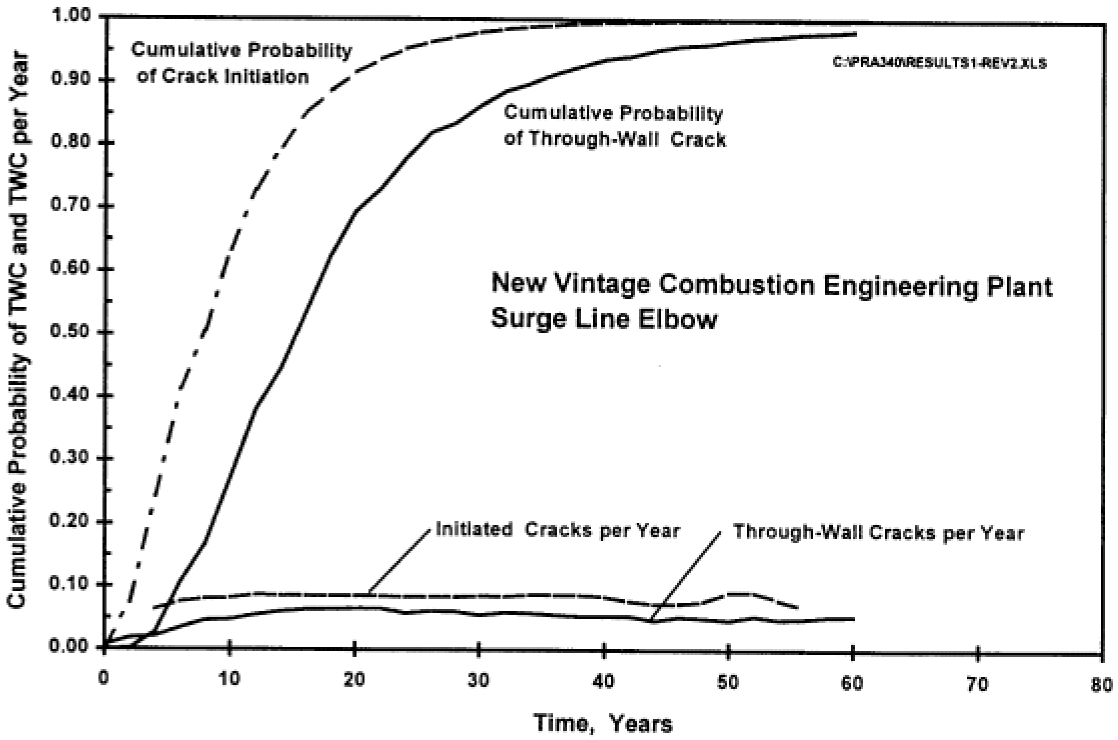




Probabilistic Failure Analysis May Also Include Crack Initiation

- Crack initiation probabilities calculated using empirical data
  - Models usually augmented using statistical analysis

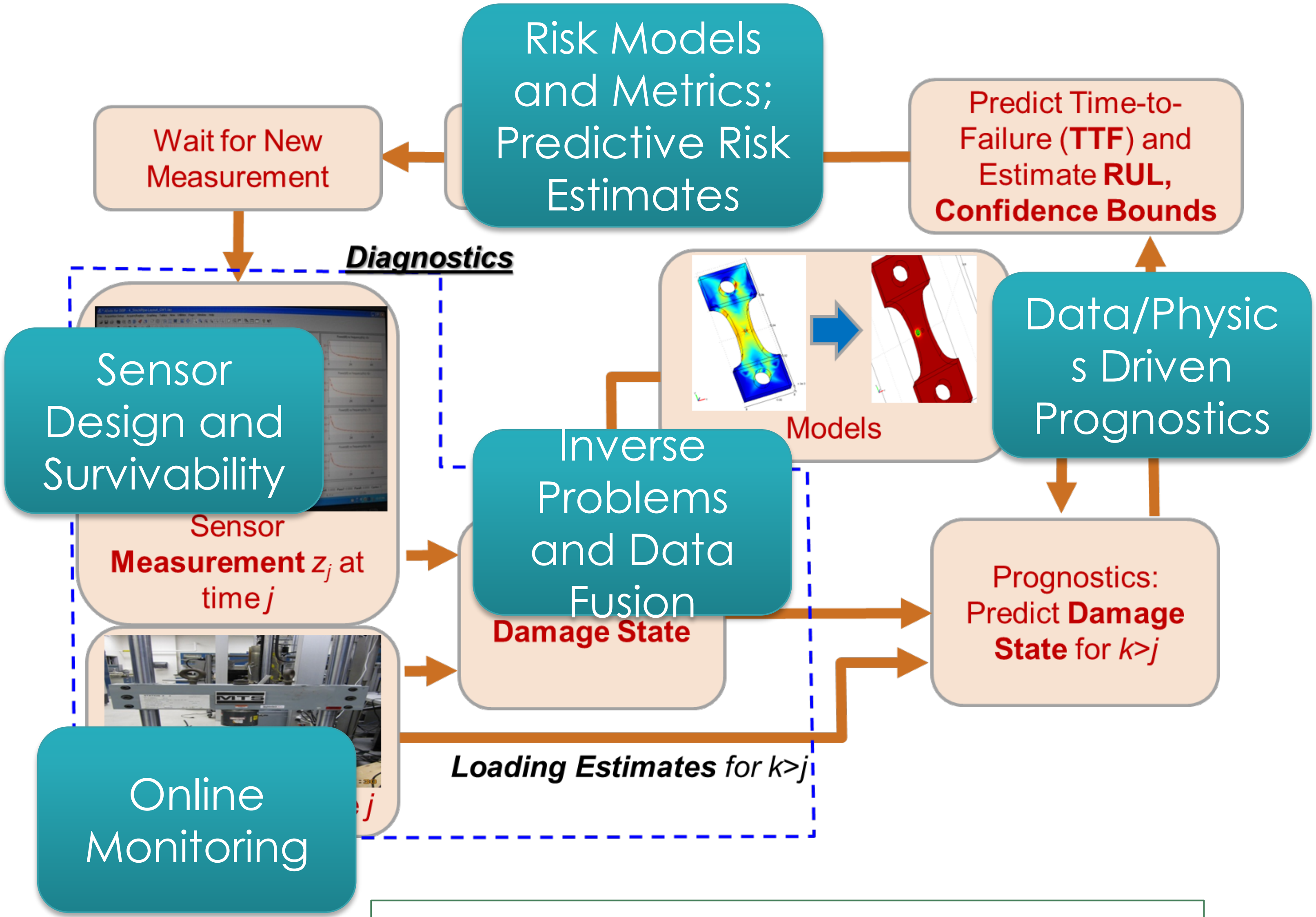
$$\ln[N_i(x)] = (6.857 - 0.766I_w) - (0.275 - 0.382I_w)I_s + 0.52F^{-1}(x) - (1.813 + 0.219I_s) \ln(\varepsilon_a - 0.080 - 0.014I_s + 0.026F^{-1}[1 - x]) - 0.00133T(1 - I_w) + 0.1097S^*T^*O^*\varepsilon^* - \ln(4)$$



<u>Calculated Probabilities of Crack Initiation and Through-wall Crack</u>

F.A. Simonen et al. / Nuclear Engineering and Design 208 (2001) 143–165

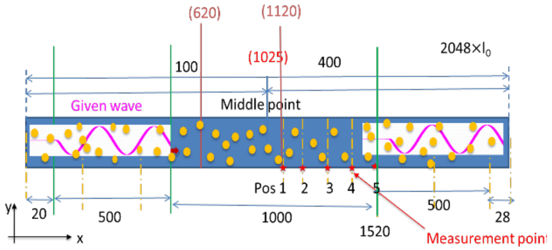
Integrating Measurements with Analytics for Prognostics & Decision Making

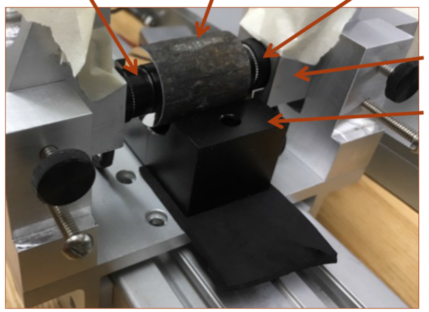


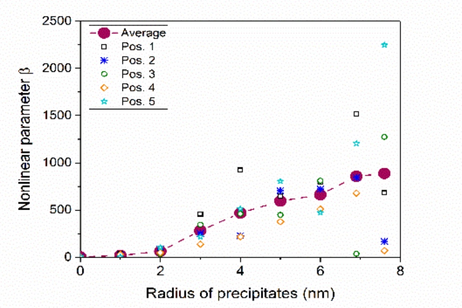
Systems Reliability and Resiliency

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

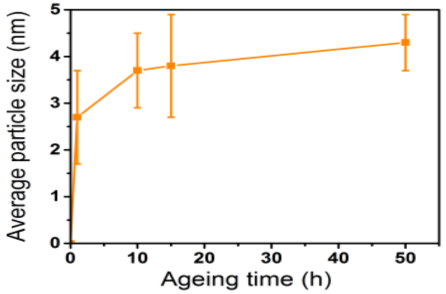
- Sensitive to microstructural changes due to degradation
  - Precipitates size and number density
  - Dislocation loop density
- Interpretation of measured response challenging and is an open question
- Use in remaining life assessment will require long-term monitoring

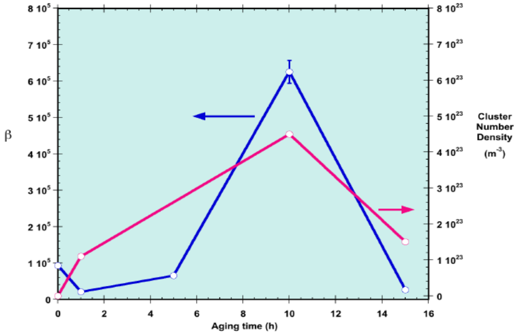






Model Predictions





Measurement Data

OAK RIDGE National Laboratory