Sensor Technology to Support In-Situ Measurements in High-Temperature Environments; Scouting and Performance Testing

NUCLEAR

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2024 ASI Summer Workshop:
Embedded Sensors for Advanced Reactors

8/27/2024

Presentation Outline

- Sensor categories of interest
  - Types & purposes
- EPRI approach
- Sensor prototype testing
  - Testing targets and high-level results
- Innovative sensor approaches
- Thoughts on next steps

Sensor Technology and Plant Applications

Diagnostics & Maintenance

Process, Operation

Structural Integrity, Monitoring, Twinning

Safety, Reliability, Economy

Broad measurement, general interpretation:

E.g. Pressure, Temperature, Flow etc
>> inform plant output and control room settings

More mature technology, smaller development gaps, larger support community

Specific measurement, complex interpretation:

E.g. Wall thickness, Creep, Runtime Events etc.
>> Planning, maintenance, justification

More innovative technology, larger development gaps, smaller support community

Process Control and Plant Health

	Measurand	Application Examples
I&C	Temperature	Core exit, in-core distribution, general I&C, safety, component history, event analysis
I&C	Pressure	General I&C, safety, component history, event analysis
I&C	Flow	General I&C, safety, regulatory
I&C	Chemistry	System health, maintenance strategy, event analysis, monitoring, operations adjustment, leak detection, asset protection, coolant health, adverse condition detection
I&C	Neutron monitoring	Safety, fuel integrity & security, tritium production monitoring
I&C	Fluid level monitoring	Coolant levels, confirmatory sensing
O&D	Leak detection	Fission gas, coolant vapor or liquid
O&D	Operations support instrumentation	Information to maintenance operations (e.g. under-sodium viewing)
NDE	Structural integrity	Component health, damage detection & assessment, digital twin, operations feedback, vibrations, run/repair decision making

Considerations

Changing parameters:
- High-temperature & radiation
- Compact RX sizes
- Advanced materials
- Different species/measurands to accommodate

Sensor strategy considerations:
- Updated tolerance requirements
- Redundant measurements
- Indirect measurements may be required

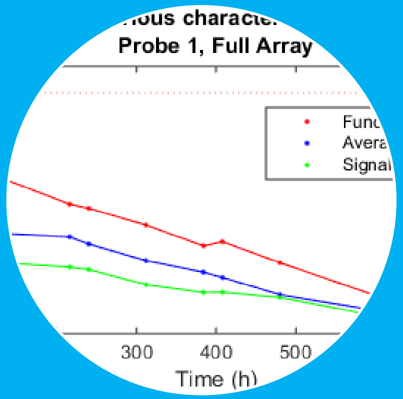
Sensor viability considerations:
- Size
- Peripheral requirements
    - power, data transmission
- Sensor maintenance
- Installation access
- Mounting and coupling
- Reliability and qualification
- Cost and standardization

Sensor Lifetime considerations:
- Sensor lifetime at high temperature
- Sensor lifetime in radiation environment
- Sensor lifetime in compound environment
- Sensor fidelity versus lifetime, drift
- Caustic Environments

Autonomous, Permanently Mounted/Embedded Sensors…	
Yesterday's UT: Manual deployment	
	Volumetric Examination (NDE) >>Run/Repair decision aid
Tomorrow's UT: Control room integration	
	Volumetric Examination (NDE)
	Flow sensing
	Temperature sensing
	Fluid Level detection
	Viscosity sensing

Other NDE sensors may also be useful for online data collection, but focus thus far is on UT.

EPRI Approach for High-Temperature Tolerant Sensors

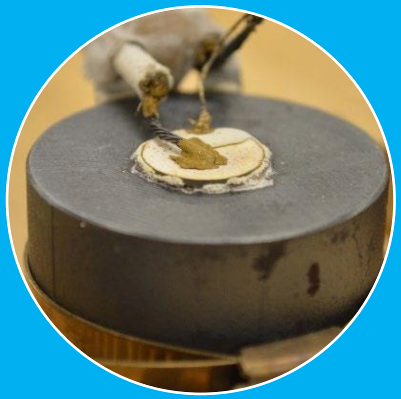


Explore sensor prototypes

- Thermal limit testing
- Thermal cycling
- Long-term thermal endurance

Guide, promote advanced sensor development

- Directly installed UT for 600 C
- UT phased array for 350 C
- Ultrasonic process sensors



Adhesive mounting and coupling

- Practical bonding & coupling
- Advanced strategy testing
- Limited irradiation testing (NSUF)

Networking with stakeholder communities

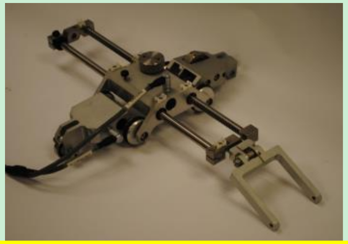
- Advanced reactor developers
- Sensor technology developers
- National Labs
- Adjacent industries
- MISSION: ***Sensors***
  - Synergy, non-redundancy, road-mapping

Conducting yearly workshops since 2021

Thermal Bands for Sensor Applications

Up to 200°C
Available with current technology

Manual deployment

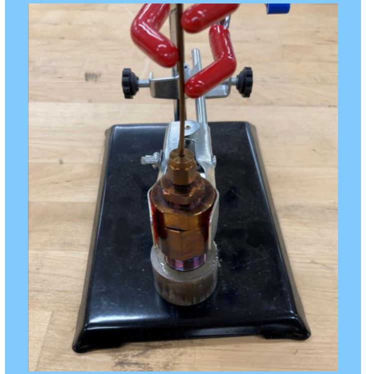


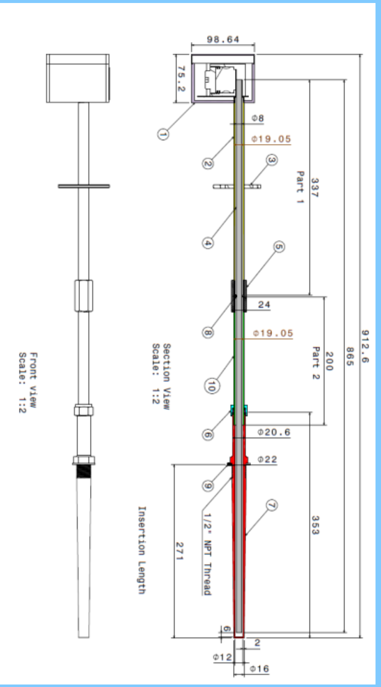
Up to 350°C – LWR
Monitor existing indications

Tolerance for operating conditions

~650°C and beyond –Advanced Reactors

Autonomous operations





Conventional technology—session-based scanning

Installed LWR technology--monitoring

Forward technology—Installed in extreme environments

Current Testing and Capabilities

- Bulk-wave ultrasonics up to 1472 °F (800 °C)
- Ultrasonic Phased array up to 662 °F (350 °C)
- Adhesives up to 700 °F (371 °C)
- Sensors embedded in flexible circuitry 350 °F (180 °C)
- Ultrasonic process sensors
- NDE alternatives (strain-based FFSE)
- *Goal is to demonstrate sensors to embed under insulation*

- High-temperature infrastructure
  - Box furnaces 2192 °F (1200 °C)
  - Convection Ovens 932 °F (500 °C)
  - Hotplate 1472 °F (800 °C)
  - 20+ items, and rapidly expanding

- Testing thermal limits, cycling, and lifetimes

Phased array probe (350 °C)

Thickness monitor
in box oven (400 °C)

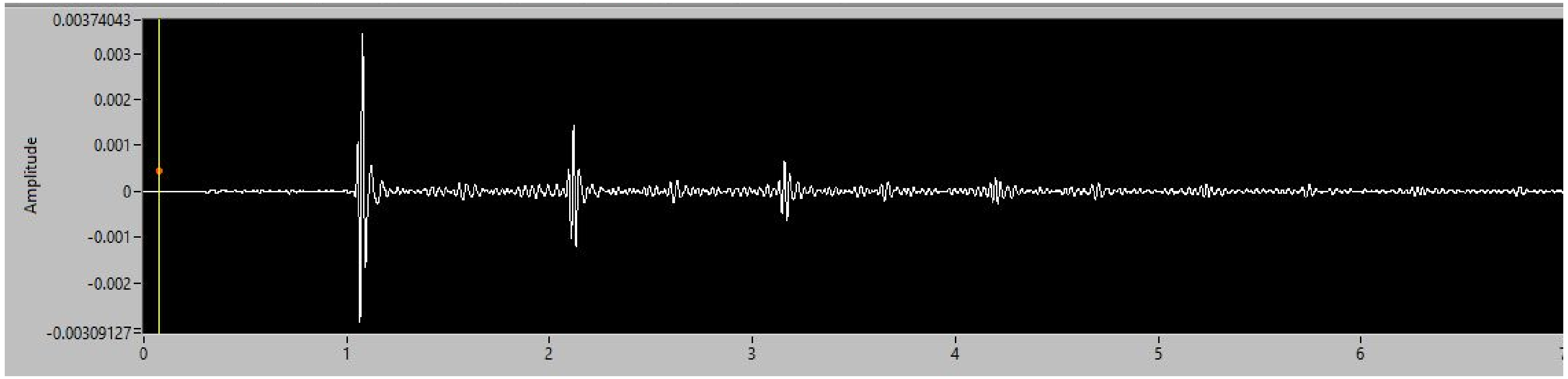
Sensors in flex circuit (180 °C)

Box furnace battery (1200 °C)

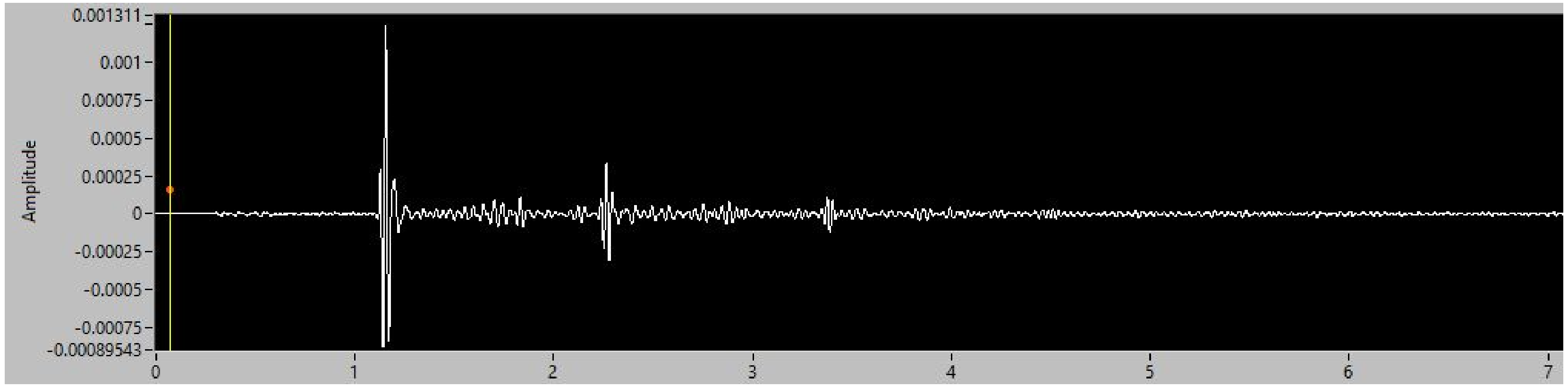
Hotplate/surface heater (800 °C)

Sample Results; Hardened Bulk Wave UT Probe

Baseline
68 F (20°C)



Signal at
932 F (500°C)

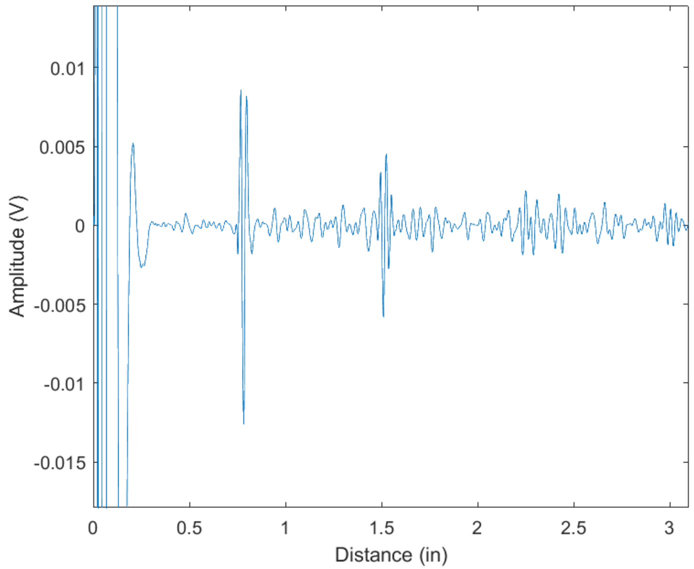


Data from thermal cycle #4

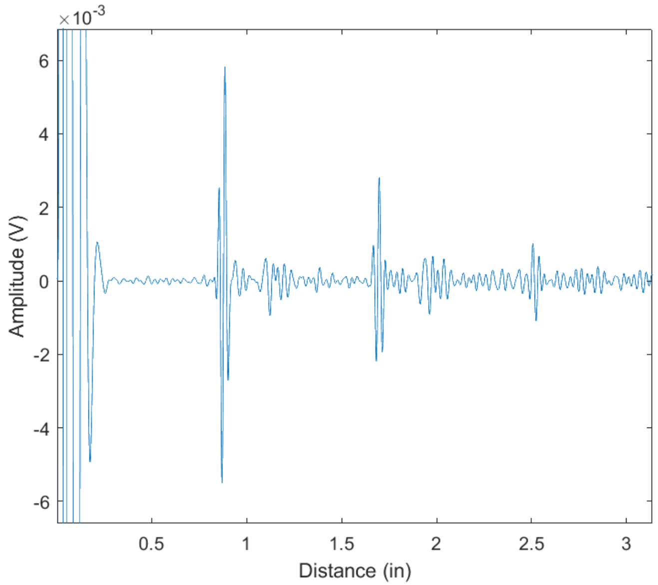
Results of testing with temperature held constant at 932 F (500 C) are stable thus far

Representative bulk wave probe rated to 550 °C

Sample Data from High-Temperature UT Prototype

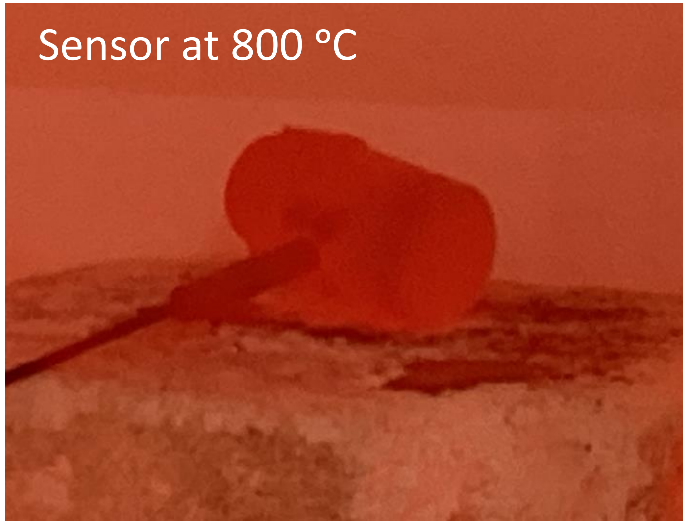


Baseline (ambient) signal:
12.5 mV reflection, 20:1 SNR



Signal at 1472 °F (800 °C)
after 5 thermal cycles:
6 mV reflection, 37:1 SNR

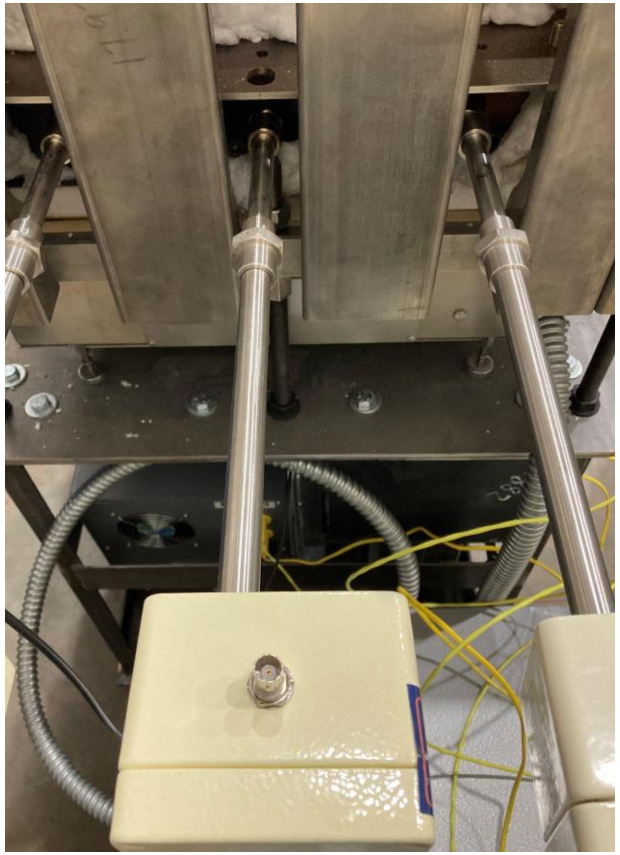
Sensor after 800 °C cycling

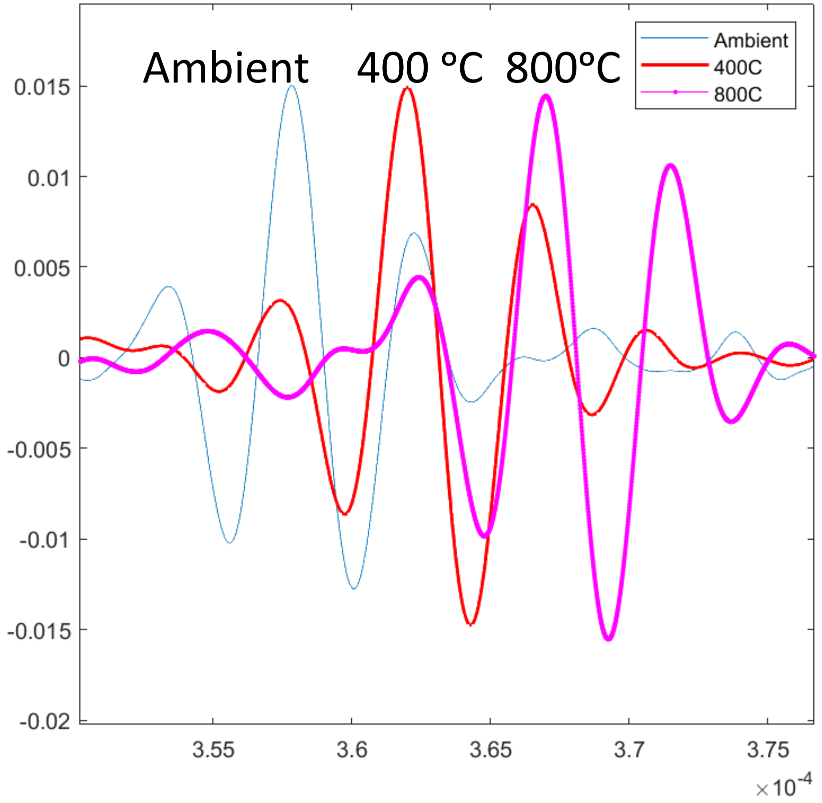


Sensor at 800 °C

Ultrasonic Thermometer

- Ultrasonics based thermometer for mounting in hot media
- Sensor remains cool while standoff is inserted into measurement area
- Probe requires piping and insulation penetration
- This probe is rated for 1832 °F (1000 °C), and may prove drift-free





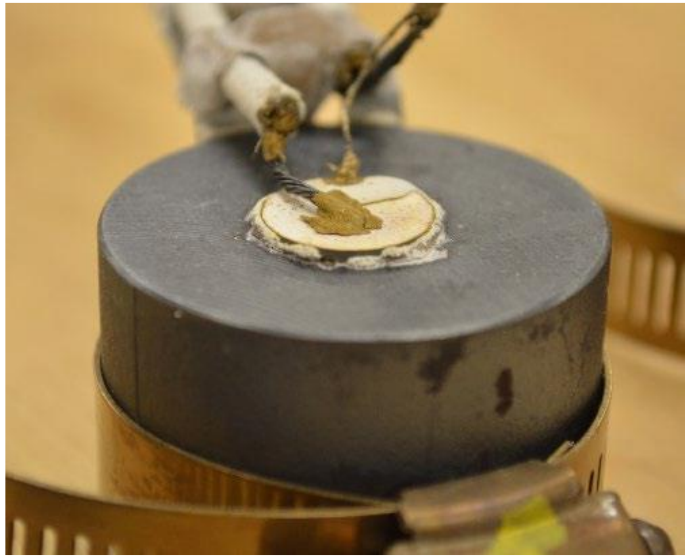
Signal as a function of temperature (demonstrating appreciable phase shifting)

Consideration of Attachments for Permanent installation

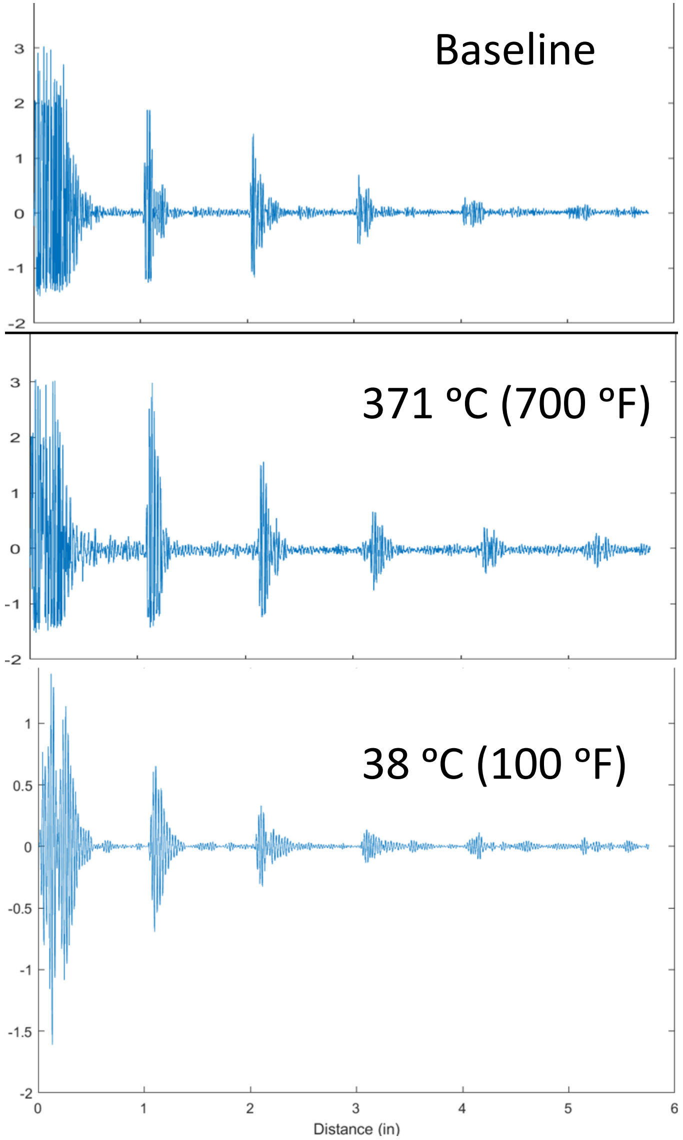
Method	Coupling	Advantages	Disadvantages
Clamping	Pumped couplant or metal foil—could use new materials	Non-invasive	Low sensor density, Not always viable
Bolting to component	Pumped couplant or metal foil—could use new materials	Strong attachment, Medium sensor density	Invasive
Welding to component	Facilitated by weld	Very strong attachment, good sensor density	Invasive, may cause new HAZ
Brazing to a component	Facilitated by welding a third material	Strong attachment, good sensor density	This mechanism is not currently demonstrated
High-temperature Adhesive	Facilitated by adhesive	Non-invasive, Good sensor density	Lower bond strength, Suitable materials are not always available

Mounting and coupling UT probes is an area for improvement

Basic Adhesives Testing Setup and Example Results



Example sensor setup for live thermal testing



Live sensor signal characteristics for promising adhesive test

Failed adhesive
(cracking on substrate surface)

Testing involved 30+ unique samples, both in simple and compound application. Several combinations show promise thus far 371 °C (700 °F).

EPRI

Non-Traditional Component Health Interrogation Methodology

Sensor Innovation

- Advanced Reactors present advanced objectives as well as some advanced challenges
  - Driver for innovation:
    - *Innovation is a must for successful implementation, a benefit to all*

Opportunity:	*Driver:*	*Innovation:*
Fitness-for-Service evaluations have traditionally been resolved through extensive session-based NDE techniques and downstream engineering analyses– Can this be made better?	What if current technology has insufficient head-room to accommodate new applications? Can conventional methodology accommodate future reactor designs? • Harsh environments • Access limitations • New damage mechanisms • New monitoring approaches	Strain gauge technology is not typically included in fitness for service evaluations, but is sufficiently mature for extreme environments, can be deployed remotely. So… Can this technology bring new potential to the emerging fleet?

Strain Sensing Technology for Fitness for Service Evaluation (FFSE)

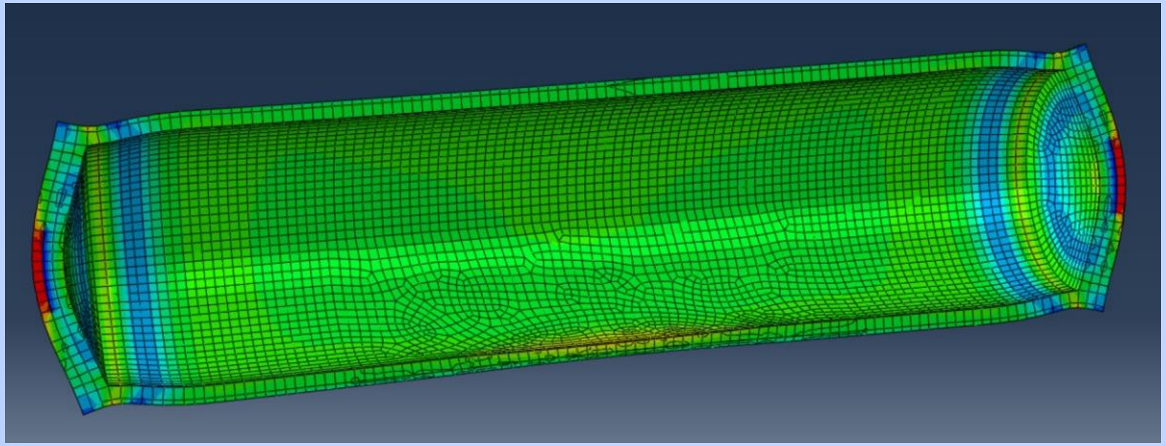
- High-temperature tolerant electrical resistivity strain gauges are available
- Fiber optics present substantial promise for surviving high-temperature and high radiation, and can be sensitive to strain
- Strain measurements can be very sensitive, and may depend on underlying conditions of component structure
- For pressurized systems, insights may be gained by directly observing the behavior of the component under load, thus inferring the ability of the component to resist the operational loading.

Test bed for studying feasibility of strain-based FFS

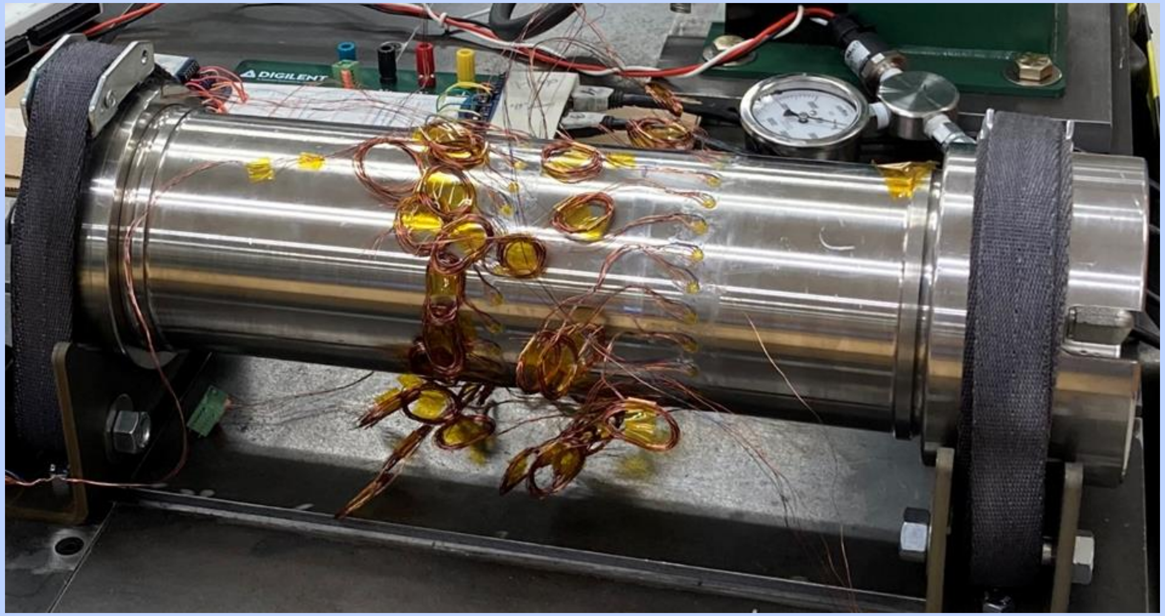
EPRI

Feasibility Testing (pressurized mockup at room temperature)

- In 2022, a feasibility study was done to explore the sensitivity of surface strain measurements in detecting various levels of underlying wall thinning in piping mockups.
  - Flow-accelerated corrosion type damage was selected for the initial tests
  - Mockups with various levels of damage ranging from 0 mm (control) to a maximum depth of 2 mm (~28% of wall thickness) were outfitted with electrical resistivity strain gauges and pressurized to 2500 PSI.

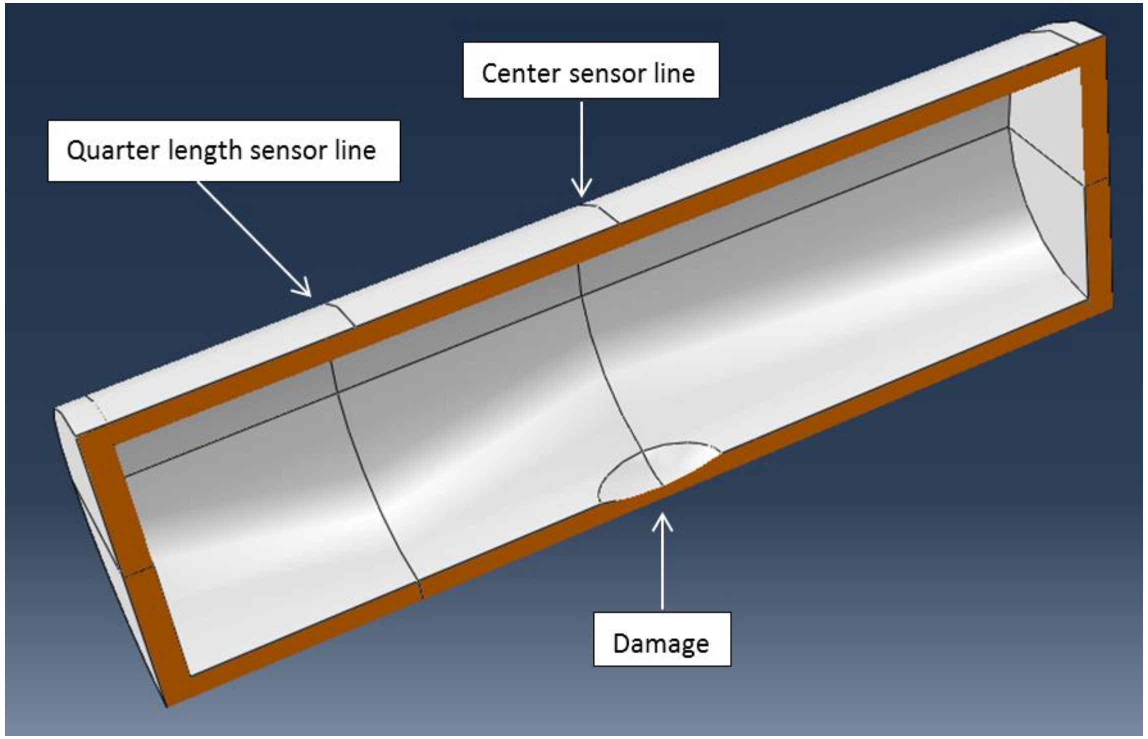


Representative modeling of pressurized pipe spool

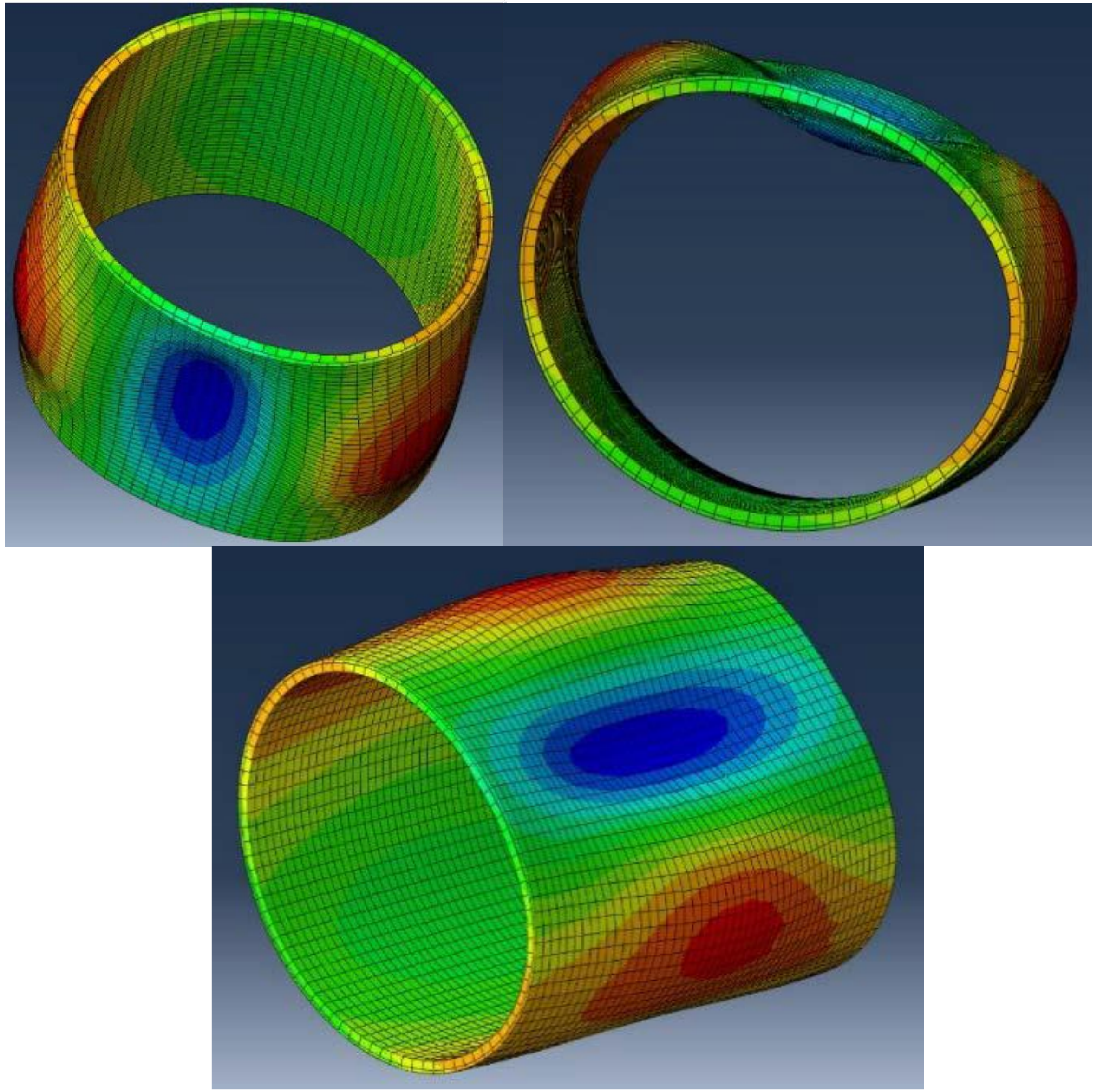


Pressure tolerant mockup for feasibility testing

Finite Element Method Modeling (deformation)

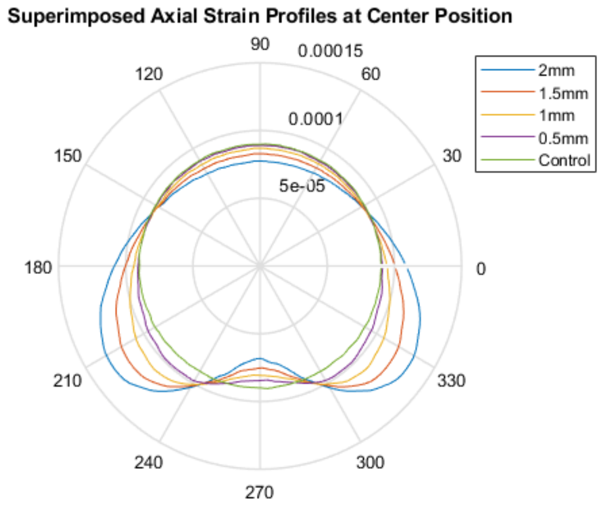


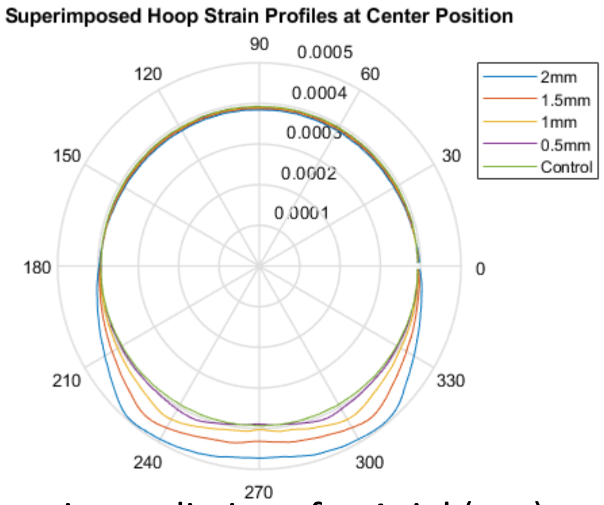
CAD model of example damage showing simulated strain sensor extraction regions



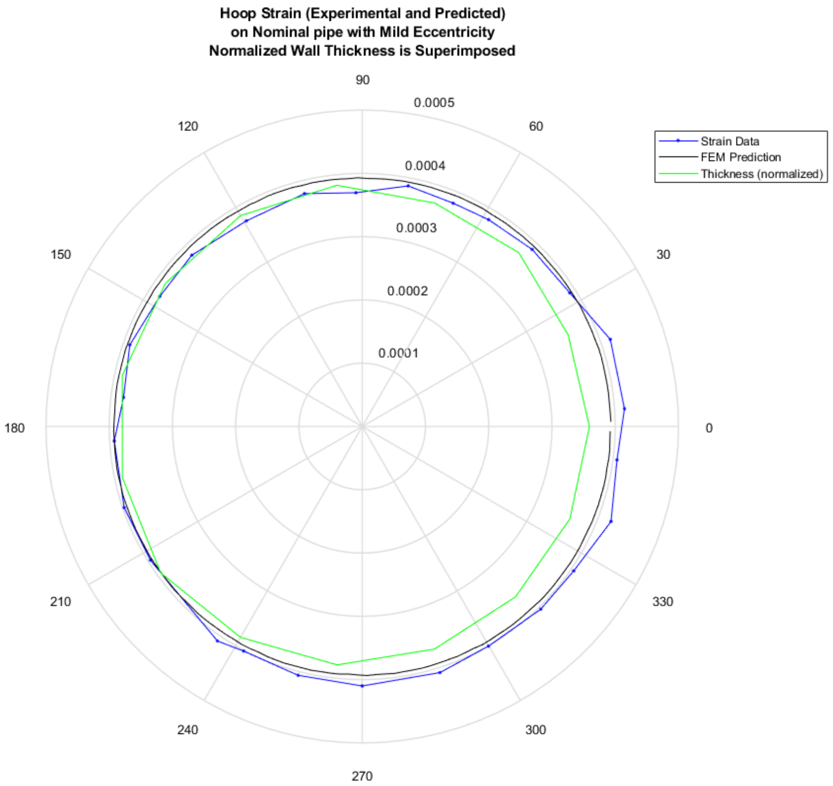
Exaggerated Deformation Profile Prediction

Finite Element Method Modeling (strain)





FEM strain predictions for Axial (top) and Hoop (bottom) strains at center of mockup



Control mockup strains with superimposed wall thickness measurements (normalized)

High-Level Observations:

- *Agreements between experimental data and profiles predicted via FEM modeling were very encouraging*
- One mockup had mild eccentricity (~+4, -6% maximum thickness versus minimum thickness) which proved insightful
- Several modules of further exploration are underway:
  - Damage in elbows with welded straight legs
  - Cracking sensitivity study
  - Elevated temperature testing
  - Feasibility of applicability to low pressure components

These include sparse sensor studies

Next Steps

MISSION: ***SENSORs***

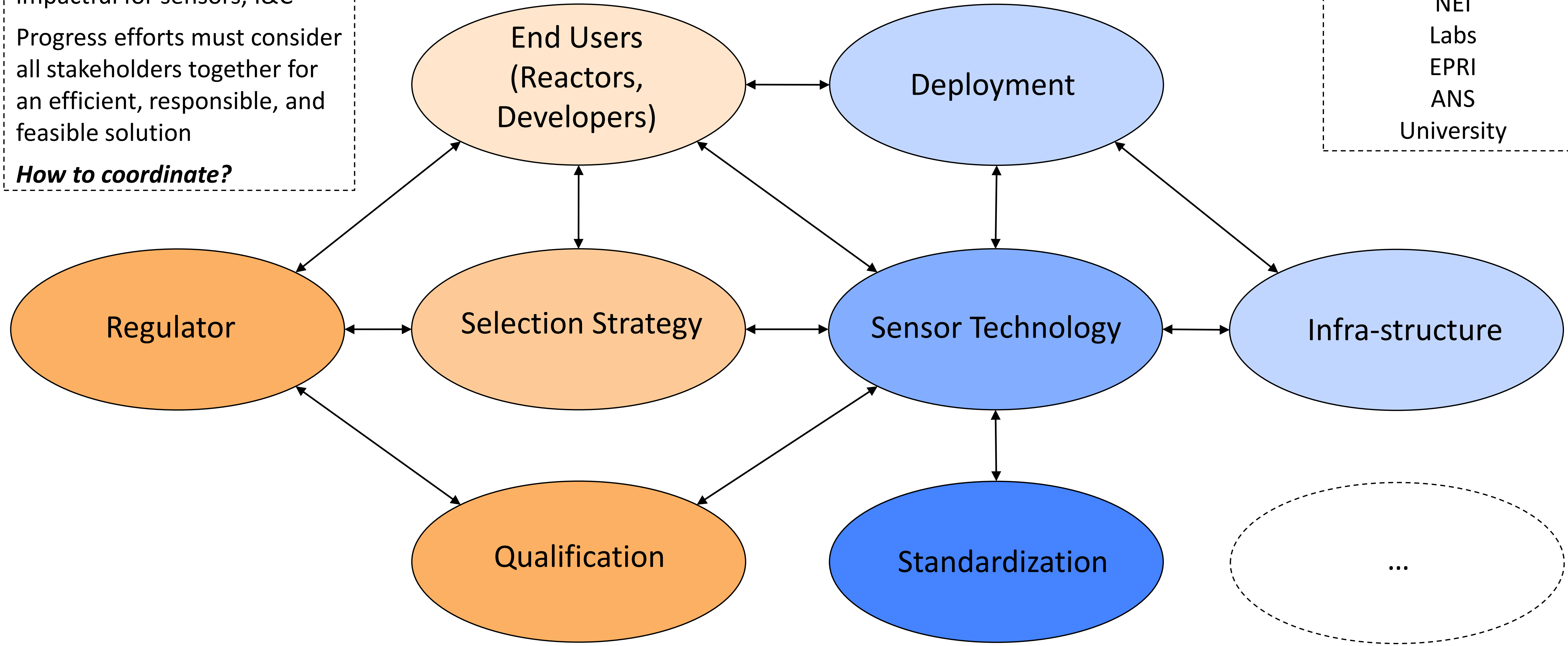
Sensor Experts Network to Support Operation of new Reactors

Many stakeholder groups are impactful for sensors, I&C

Progress efforts must consider all stakeholders together for an efficient, responsible, and feasible solution

How to coordinate?

Support Groups:
NEI
Labs
EPRI
ANS
University



Final Remarks

- Readying sensor technology for advanced reactor applications is important but not trivial
  - Integrated control systems, autonomous operations, digital twinning & data analytics (and more) drive new efficiency targets
  - Advanced challenges bring new capability requirements
  - Some conventional sensor types may have physics overhead limitations for relevant temperatures (Currie points, evaporation limits, etc) and radiation levels
    - Where physics overhead does exist, sensor development can take time and bring surprises
    - All aspects of a proposed solution must be tested
  - Complimentary aspects of sensor deployment must also be considered/developed
- Improvements aimed at advanced reactors also benefit the rest of the industry
- Standardization and developmental coordination are important

Selections from Relevant Recent Publications

- 3002026401_Sensors for High Temperature Applications
  - 12/2023
- 3002026548_Sensors for Extreme Environments Wireless Dry_Cask Storage Internals Monitoring
  - 10/2023, free to the public
- 3002026618_The State of Sensors for Advanced Reactor Applications
  - 8/2023
- 3002023836_Feasibility of Monitoring Fitness for Service by External Component Strain
  - 2022 (4x follow-on efforts)
- 3002018479_Sol-Gel Spray-On Technology for High-Temperature Ultrasonic Sensors
  - 2020, free to the public

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