Quantum Sensors in the Business of Nuclear Power Plants
Perspective for 3-5 Years

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Vision

To be a world leader in advancing science and technology solutions for a clean energy future

Mission

Advancing safe, reliable, affordable, and clean energy for society through global collaboration, science and technology innovation, and applied research.

Together...Shaping the Future of Energy®

EPRI Accelerates Technology Advancement

LABORATORIES AND UNIVERSITIES

Basic research and development

SUPPLIERS AND VENDORS

Technology commercialization

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Collaborative technology development, integration, and application

Thought leadership illuminates emerging developments, opportunities, and trends.

Technology Innovation Scouting searches globally for emerging technologies and concepts to provide insights on industry challenges and solutions.

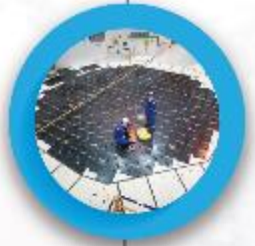
Sector R&D conducts research and demonstrations to address challenges, deploy results, and provide supporting services for existing and emerging technologies.

EPRI stimulates innovation and plays a key role in validating technology across multiple utilities, fostering widespread acceptance, and helping accelerate technology to commercial development and industry adoption

EPRI Research & Development

TECHNOLOGY INNOVATION

Driving thought leadership, advanced R&D, and technology scouting and incubation to sustain a full pipeline of solutions



Nuclear Power

Energy Supply and Low-Carbon Resources

Electrification and Sustainable Energy Strategy

Transmission and Distribution Infrastructure

Integrated Grid and Energy Services

STRATEGIC RESEARCH

Low-Carbon Resources

End-Use/ Economy-Wide Carbon Reduction

Electric System Reliability/Resilience

Electric System Flexibility

Market Transformation/ Policy/Regulatory Education

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Considerations for Deploying Quantum for Stationary Nuclear Applications

Environmental Requirements

- Temperature up to 800 °C (1472 °F)
- Ionizing radiation (gamma, neutron)
- Coolant (water, molten salt, liquid metal)
- Sensor size, Density
- Compatibility with component materials

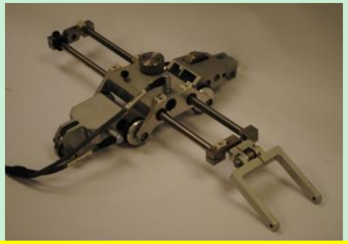
Performance Requirements

- Reliability—Plant and Sensor
- Qualification—Sensor and Delivery
  - Cables, Power
- Sensor lifetimes
  - Maximum temperature, cyclic temperature, long-term
- Cost and Standardization

Thermal Bands for Sensor Applications

Up to 200°C
Available with current technology

Manual deployment



Conventional technology—session-based scanning

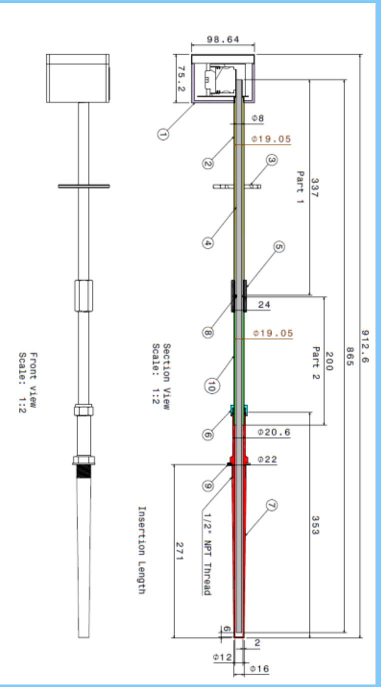
Up to 350°C – LWR
Monitor existing indications

Tolerance for operating conditions

Installed LWR technology--monitoring

~650°C and beyond –Advanced Reactors

Autonomous operations



Forward technology—Installed in extreme environments

Process Control and Plant Health

<table>
<tr><th></th><th>Measurand</th><th colspan="2">Considerations</th></tr>
<tr><td rowspan="6">I&C</td><td>Temperature</td><td rowspan="9">Changing parameters:
• High-temperature & radiation
• Compact RX sizes
• Advanced materials
• Different species/measurands to accommodate

Sensor viability considerations:
• Size
• Peripheral requirements
  • power, data transmission
• Sensor maintenance
• Installation access
• Mounting and coupling</td><td rowspan="9">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

Sensor strategy considerations:
• Updated tolerance requirements
• Redundant measurements
• Cost and standardization
• Indirect measurements may be required
• Reliability and qualification</td></tr>
<tr><td>Pressure</td></tr>
<tr><td>Flow</td></tr>
<tr><td>Chemistry</td></tr>
<tr><td>Neutron monitoring</td></tr>
<tr><td>Fluid level monitoring</td></tr>
<tr><td rowspan="2">O&D</td><td>Leak detection</td></tr>
<tr><td>Operations support instrumentation</td></tr>
<tr><td>NDE</td><td>Structural integrity</td></tr>
</table>

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Structural Integrity Applications; Traditional and Emerging

Traditional

Needs and Strategies:

- ◊ Periodic Monitoring
- ◊ Uprates
- ◊ Lifetime extensions

Applications:

- ◊ Cracking
- ◊ Wall thinning
  - -Corrosion
  - -Erosion
  - -Wear
- ◊ Embrittlement

Methods:

VT, UT, RT, EC, PT, MP

VT—Visual Testing
UT—Ultrasonic Testing
RT—Radiographic Testing
EC—Eddy Current Testing
PT—Dye Penetrant Testing
MT—Magnetic Particle Testing

Emerging

- ◊ Fixed sensors
- ◊ Damage mechanism identification
- ◊ New ultimate purposes

- ◊ Cracking
- ◊ Wall thinning
  - -Thickening?
- ◊ Embrittlement
- ◊ Creep
- ◊ Residual Stress

VT, UT, ~~RT,~~ EC, ~~PT, MP~~

Strain, Surrogate, Innovative

- ◊ Smart Materials
- ◊ Machine Learning
- ◊ Digital Twinning
- ◊ Data Integration

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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

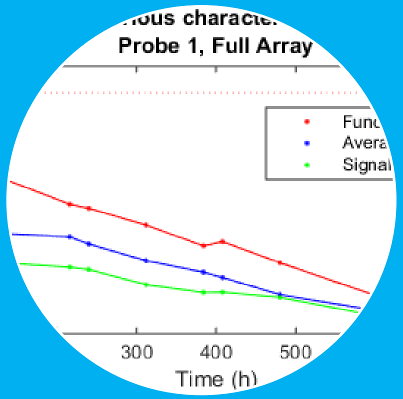
More mature technology, smaller development gaps, larger support community

Specific measurement, complex interpretation:

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

More innovative technology, larger development gaps, smaller support community

EPRI Approach for High-Temperature Tolerant Sensors

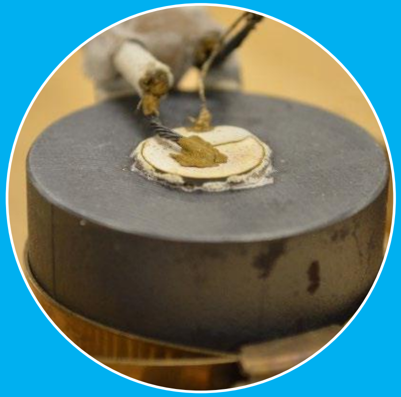


Explore sensor prototypes

- 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

Current Technology and Capabilities

Probes	Max Temperature (°C)	Max Temperature (°F)
Bulk wave ultrasound	800	1472
Phased array ultrasound	350	662
Adhesives	371	700
Sensors in flexible circuitry	180	350
Ultrasonic process sensors	1000	1832
NDE alternatives	700-1000	1292-1832

Phased array probe (350 °C)

Thickness monitor in box oven (400 °C)

Sensors in flex circuit (180 °C)

EPRI Thermal Testing Capabilities	Number of items	Temperature (°C)	Temperature (°F)
Box furnaces	16	1200	2192
Convection ovens	4	500	932
Hotplate	1	1000	1832
Creep frames	60	1100	2012

Box furnace battery (1200 °C)

Hotplate/surface heater (800 °C)

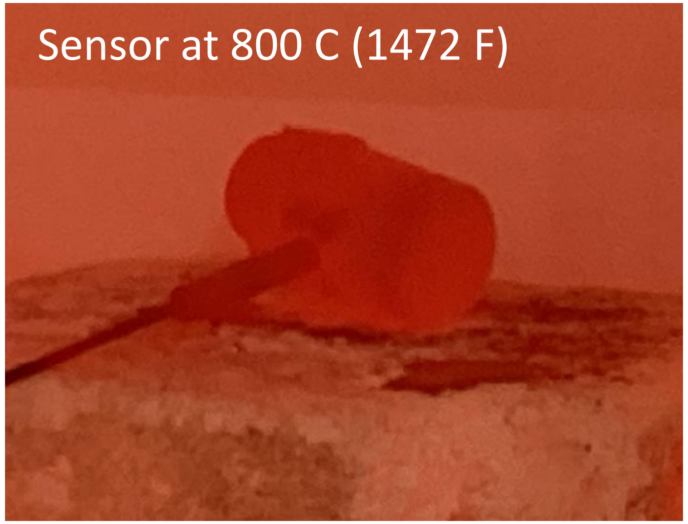
Consideration of Attachments for Permanent installation

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

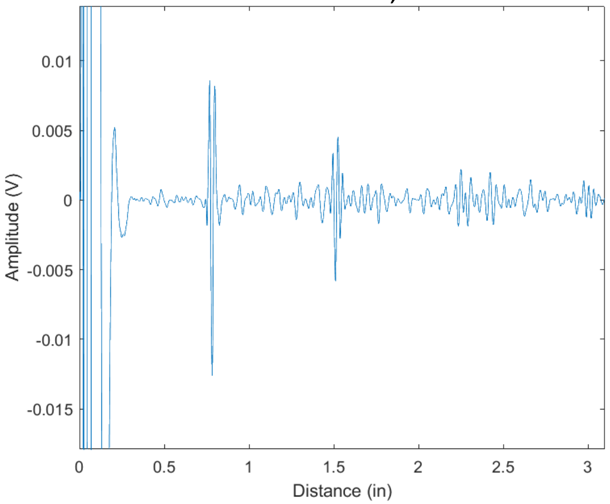
Example Data from Ultrasonic Thickness Monitor and Thermometer

Sensor after cooling from 800 C (1472 F)

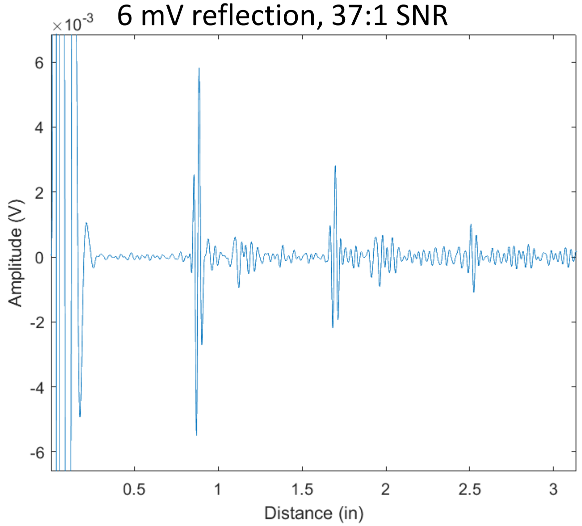


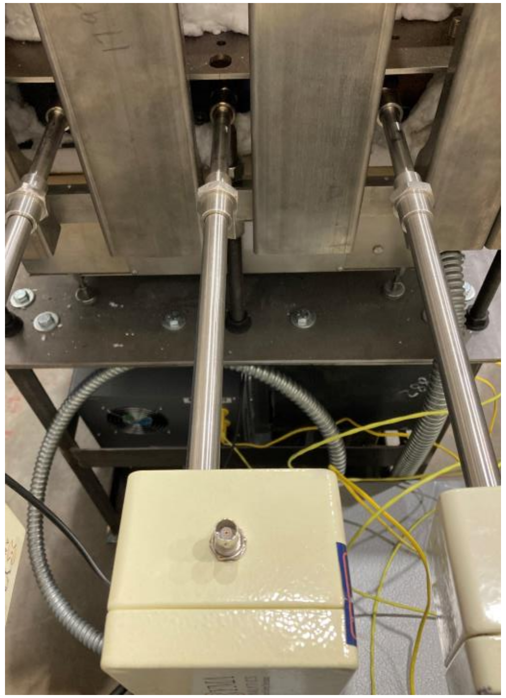
Sensor at 800 C (1472 F)

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



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

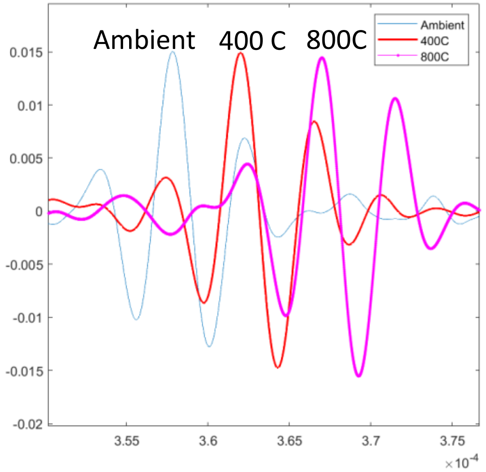




Ultrasonic thermometry probes tested in hot-plate setup.

Data shows peak shifting at various temperatures

Note: High-temperature ready probes (e.g. at left) could eliminate need for standoff for ultrasonic thermometry sensors



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Where can Quantum Contribute?

Is there an intersection of quantum sensors and nuclear applications?

- Cracking
- Creep
- Residual stress
- Wall thickness
- Traditional I&C, Structural integrity sensors

Properties to consider:

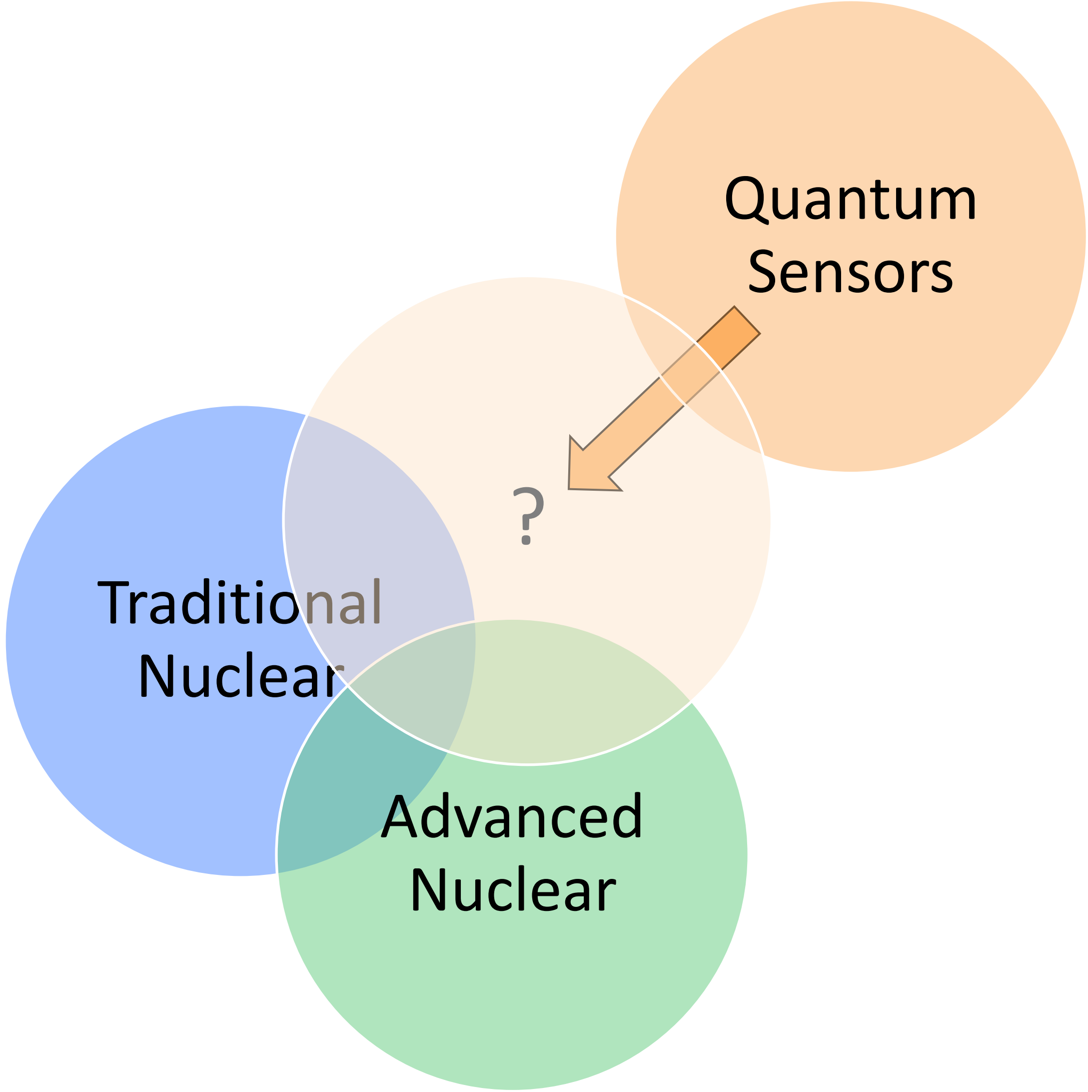
- Electromagnetics:
  - Magnetic, Electric, Radiation
  - Visual/optics
  - Luminosity
  - Scalar, vector Fields
- Mechanical:
  - Force
  - Acceleration
  - Pressure
  - Stress/Strain
- Time
- Temperature
- Chemical

Advanced Ideation

- Inferred insights
- Innovative measurands

Industrial Improvement Possibilities:

- Footprint of Data and sensor package
- Sensor lifetime
- Self calibration / non calibrated
- Reduced cost
- Data processing
- AI
- Digital twins
- Plant integration



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