U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy
Sensors and Instrumentation
Annual Review Meeting

High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle

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NEET Program

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Project Overview

Goal, and Objectives

- Develop new optical fibers for nuclear industry
- Demonstrate distributed multi-functional fiber optical sensors for high spatial resolution measurements
  - με, T, P, level, chemical, **and radiation** with high spatial resolutions
- Evaluate various distributed sensing schemes and demonstrate unique capability

Participants (End-to-End, Rapid Advancing TRLs)

- University of Pittsburgh: Dr. Kevin P. Chen (PI), Zsolt Poole, Aidong Yan, Rongzhang Chen, and Mohamed Zaghloul
- Westinghouse Electrical Company: Dr. Michael Heibel, Dr. Robert Flammang, and Melissa Walter
- Corning Inc.: Dr. Ming-Jun Li and Jeffrey Stone

Schedule:

- 3 Years: One type of new fiber per year
- Year 1: active fiber sensing technique developments, multi-functional fiber fabrications
- Year 2: distributed pressure and temperature measurements in radiation environments
- Year 3: distributed hydrogen sensing in radiation environments

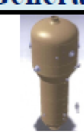
Project Overview

What is unique about fiber optical sensors?

- Resistant to harsh environments
- Fully embeddable into concrete, metal, and existing infrastructures
- Unique capability to perform distributed measurements with high spatial resolution (1-10cm)

What is unique about nuclear applications?

- Radiation (among other harsh conditions)
- Need perform a wide arrange of measurements beyond temperature and strains

	Spent Nuclear Fuel Pool	**Containment Dome**	**Steam Generator**	**Research Facilities (LHC, LMJ, ITER)**
				
Normal Operation Radiation	2 mGy/hr	50 μGy/hr	<10 mGy/hr	50 Gy/day
Normal Operation 20-yr Dosage (Gy)	350 Gy	8.8 Gy	1.75 kGy	200 kGy
Post-Accident Radiation (Gy/hr)	2 mGy/hr	5Gy/hr	5 Gy/hr	N/A
Post-Accident 30-day Dosage (Gy)	1.44 Gy	3.7 kGy	3.7 kGy	N/A

Research Approach

Fibers

- Identify (or invent) fiber structures/compositions that are highly robust or highly sensitive to radiations
- Developing new optical fibers with built-in capability to perform distribution radiation measurements (for measurements and for calibration)
- Developing new multi-functional optical fibers for multiple parameter measurements

Sensing Technology

- Evaluate various distributed sensing schemes (Rayleigh, Brillouin, FBGs) under radiation for short and long terms measurements
- Develop new distributed sensing technology beyond T/strain measurements
  - Liquid levels
  - Pressure and T simultaneously + radiation
  - Chemical (hydrogen) and spatially resolved chemical reaction

Implementations and Applications in Nuclear Engineering

- Fiber embedding and testing
- New applications (smart cable, small concrete, and …?)

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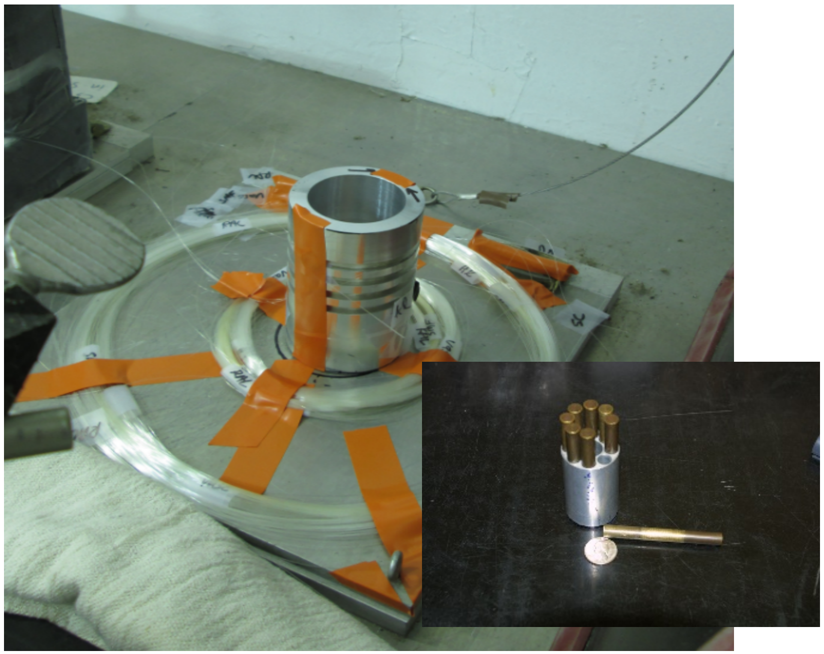
Accomplishments

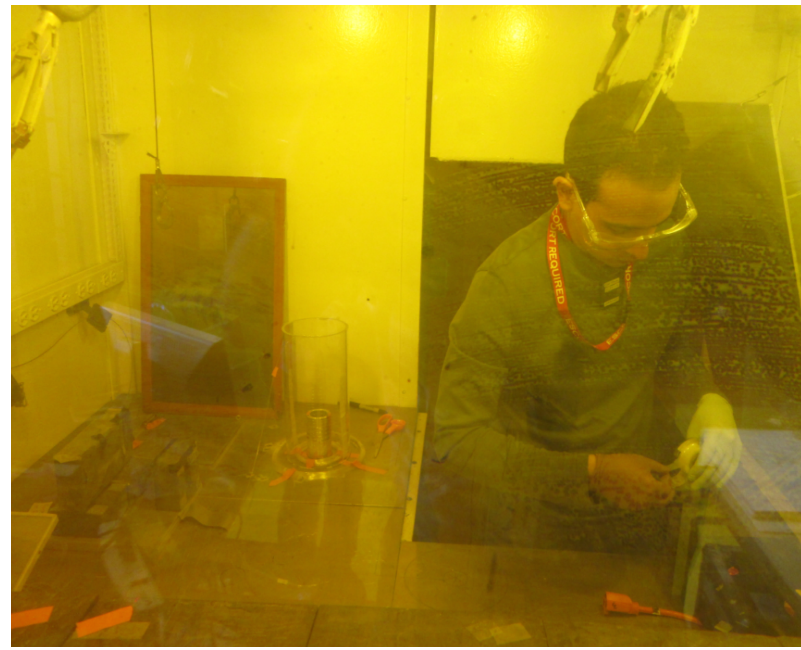
- **(Description of milestones, deliverables, outcomes for FY15)**
  - Deliverable 1: Demonstrated active fiber sensing schemes for multi-functional distributed fiber sensing over a span of 10 meters for both temperature and liquid level sensing.
  - Deliverable 2: Developed multi-core, multi-functional fiber cables with integrated capability to monitor radiation with –cm spatial resolutions.
  - Outcome 1: Developed nano-material enabled distributed fiber chemical sensors
  - Outcome 2: Evaluated various distributed sensing schemes (Rayleigh and Brillouin) and their suitability for distributed measurements in both short and long terms.
  - Outcome 3: Evaluated radiation effects on various optical fibers to identify both radiation sensitive and radiation resistant fiber structures.

Accomplishments: New Fibers

Radiation Tests



Hot Cells



- γ radiation: max. ~5000 Gy/hr on fibers
- Performed in Westinghouse Churchill facility
- Loss and Brillouin OTDR schemes
- Rayleigh, FBG in new fibers, DFB lasers (on-going)

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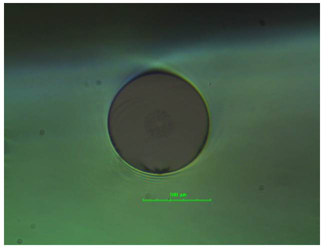
Radiation Tests

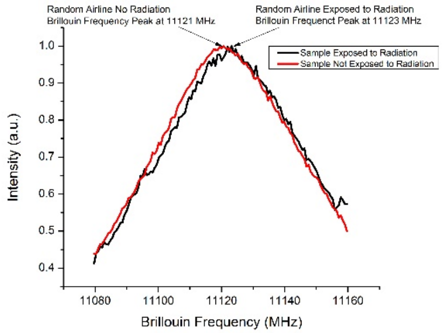
Radiation Tests

Fiber Types	SMF28	Vascade	High Ge-	Alumina	Random air-hole
RIA (dB/km)	96	61	115	35651	51

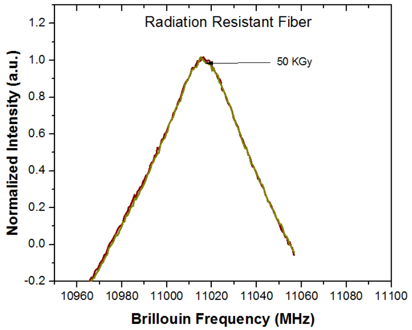
- 1MGy γ dosage (Co-60 source)
- SMF-28 standard optical fiber
- Vascade: Corning ultra-low loss, pure silica core/F-doped cladding
- Random air-hole: new all silica fiber
  - Random air-hole cladding (low cost)
  - All silica structures (sustain >400C more than F-doped fibers)

Random Air Holes Fiber

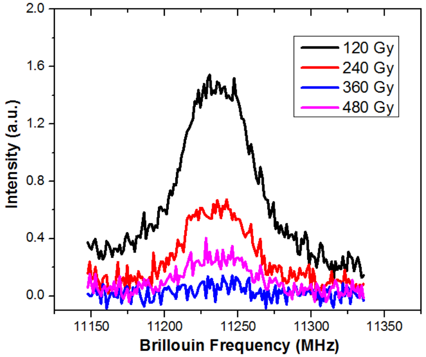




Radiation Resistant Fiber



Radiation Sensitive Fiber

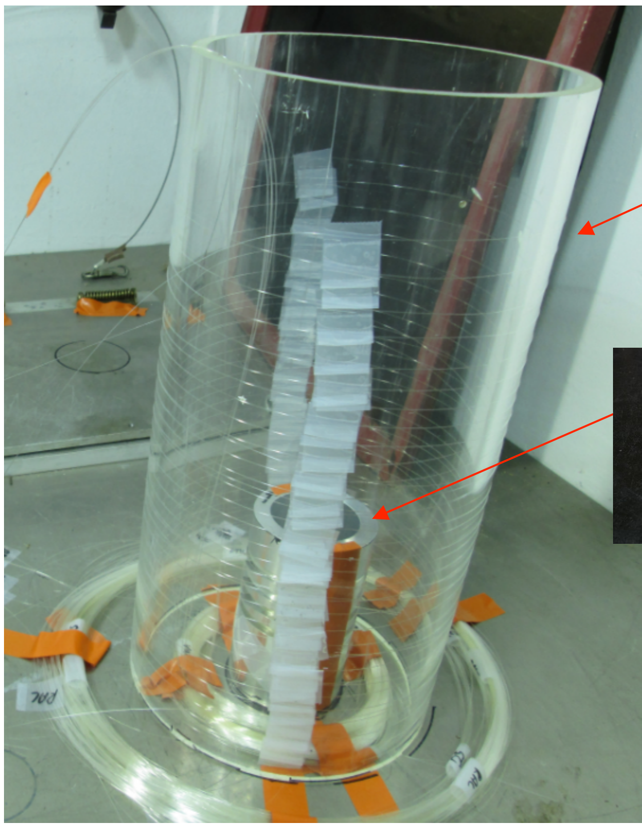


Data/Tests to be done

- Neutron radiation
- Increase dosage to 10 MGy
- Head-to-head comparison with Rayleigh/FBG
- Test strain/T coefficient vs. radiation

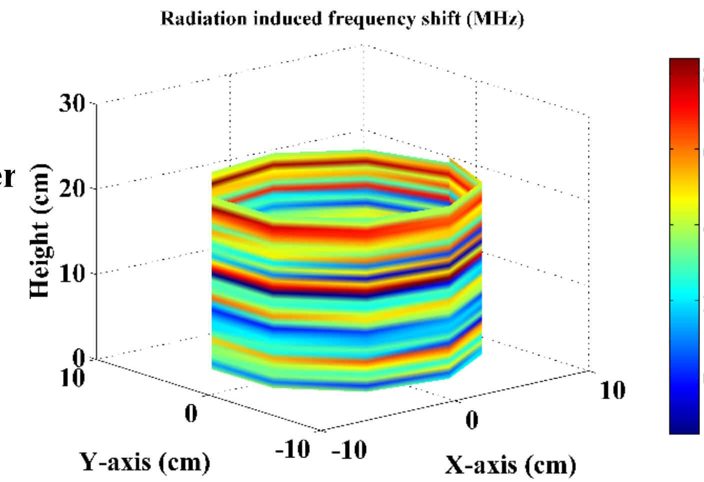
New Capability: 3D Radiation Mapping?

3D Radiation Field Mapping



Radiation Sensitive fiber

Co-60 sources



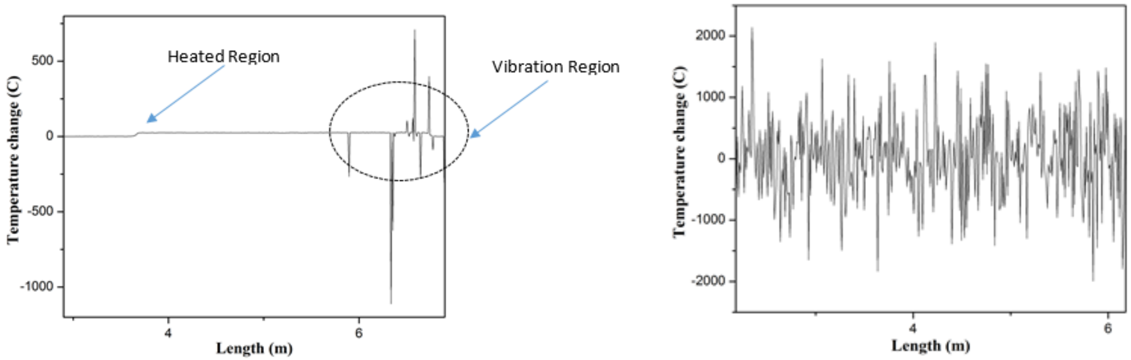
Radiation Field Measurements

- 10-cm spatial resolutions
- Brillouin shift as radiation indicators
- ~100 Gy dosage

Distributed Fiber Sensing Schemes

Rayleigh OFDR

- Good spatial resolution (1-cm) and reasonable interrogation length (1km)
- **Good for distributed loss measurements**
- Unreliable under vibration/radiation, especially for long-term measurements (lost reference, or need **find a good reference**)



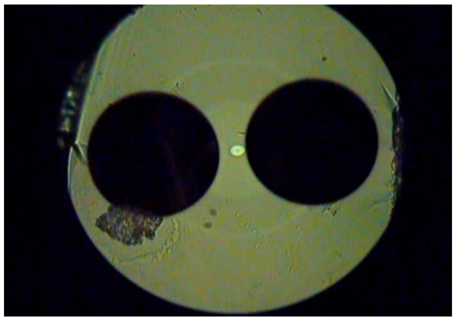
Brillouin OTDR

- Modest spatial resolution (10-50cm), very long interrogation length
- **Reliable under vibration, easy calibration and correction under radiation environments**

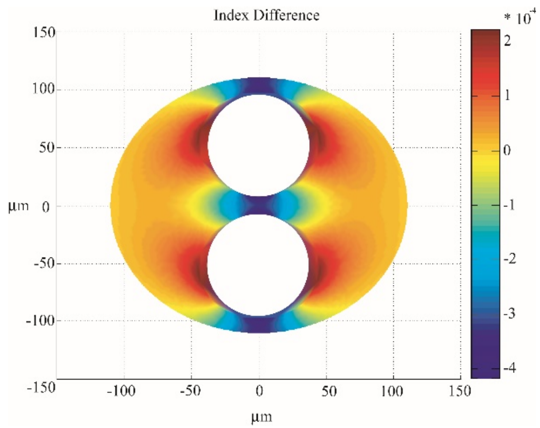
FBG

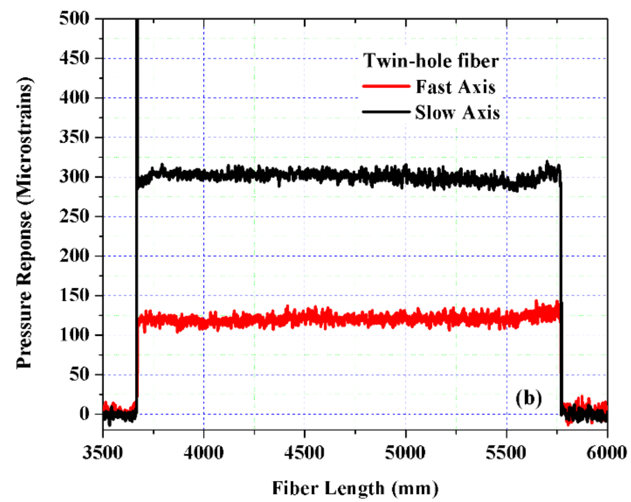
- Low-cost interrogation unit ($2-4k vs. $80-$120k)
- Rapid and reliable measurements (8 kHz sampling)
- Only for multi-point measurements

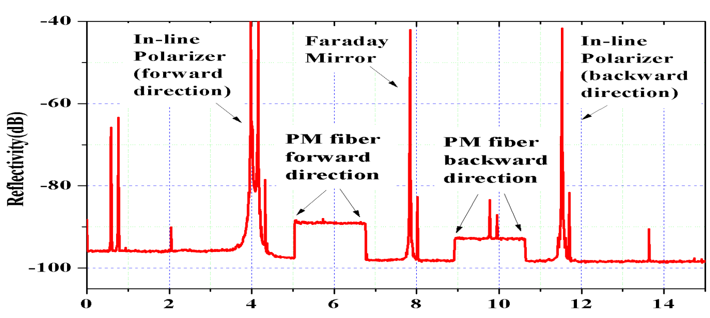
Distributed Pressure Measurements



Large Diameter Elliptical-Core-Off-Centre Twin-Hole Fiber

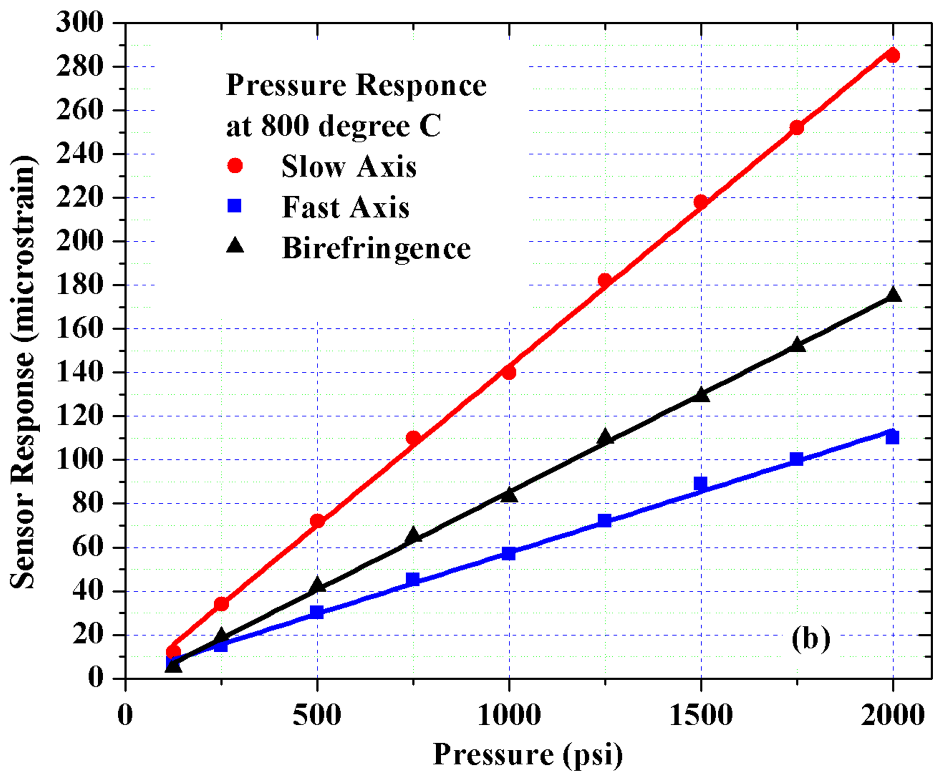


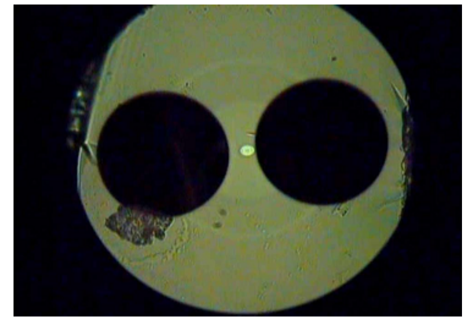




- OFDR birefringence measurements
- Rayleigh scattering reference between 2 polarization states
- Demonstrate distributed sensing cross 10-meters

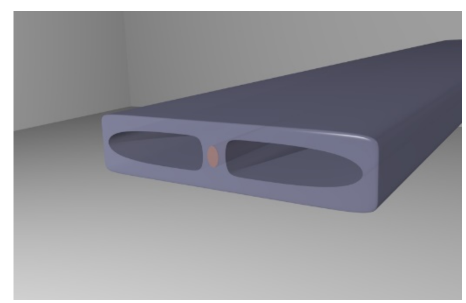
OFDR Measurement Results 800°C





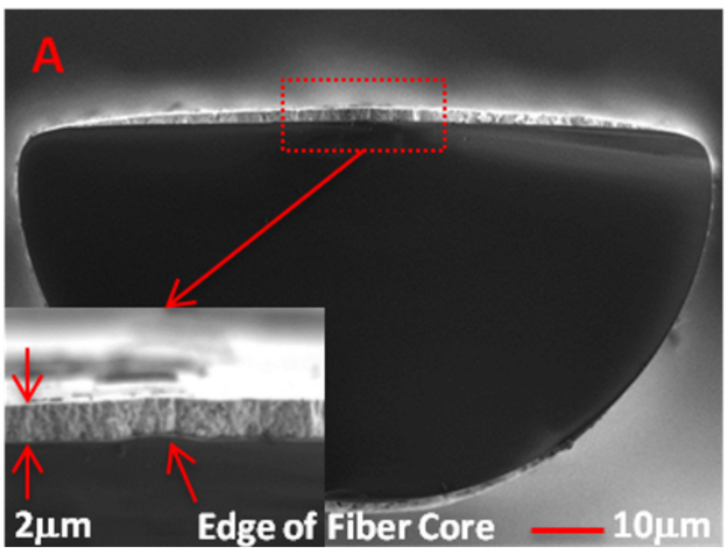
Large Diameter Elliptical-Core-Off-Centre Twin-Hole Fiber

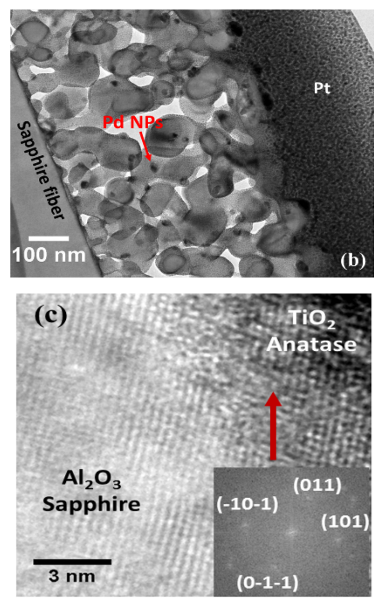
Yr 2: Fibers for Distributed P Sensing

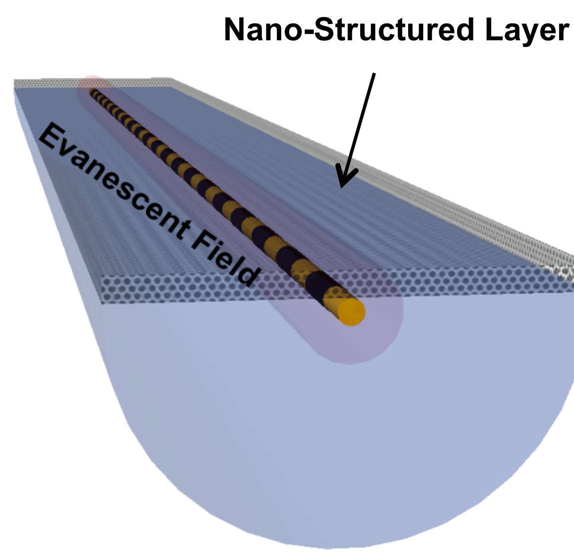


High-T Chemical Sensors

- Nano-Engineered metal oxide sensory film
  - Porosity control for refractive index matching
  - Rare-earth or noble metal dopants for specificity
  - Pd-TiO2
- Sensor must operate >600C
- No electrical components in target environment







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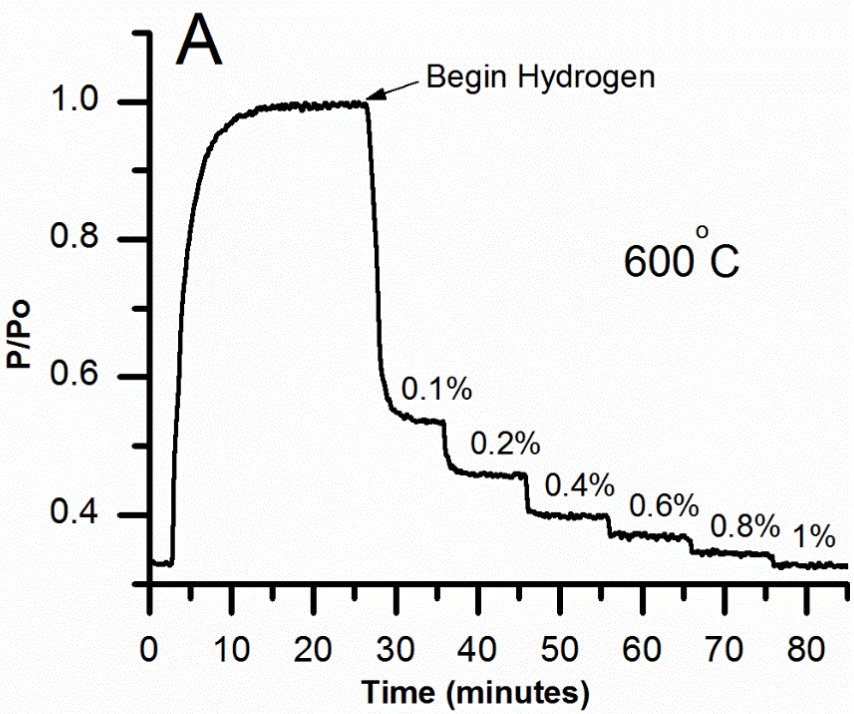
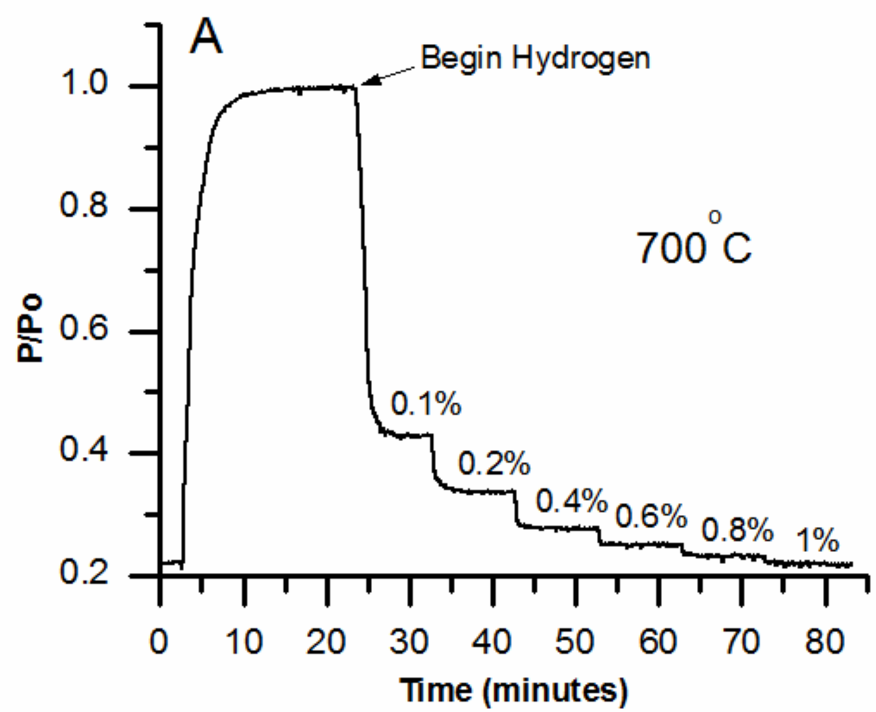
Fiber Optic Hydrogen Sensor at 700C

Optical Transmission vs. Hydrogen Concentrations

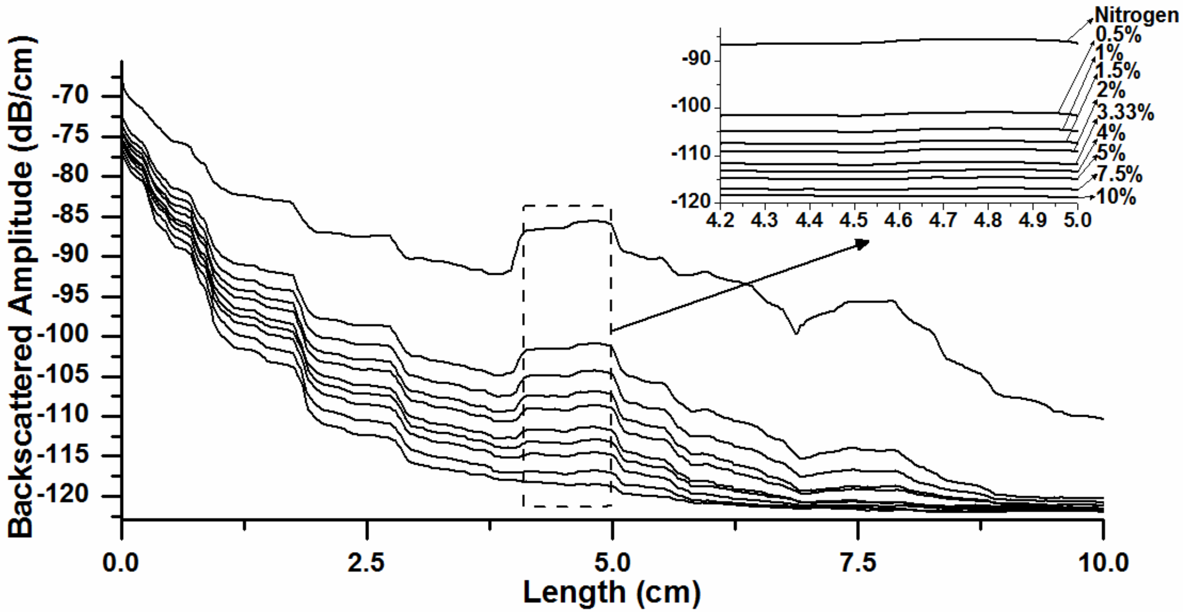




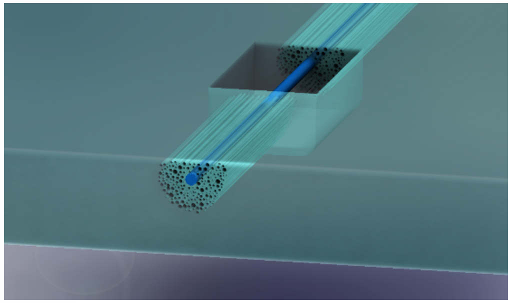
Exposed to various concentrations of hydrogen in nitrogen, recovered with nitrogen
Ideal for hydrogen driven energy conversion systems

Distributed H2 measurement at 700C

Distributed H2 measurements with 5-mm Spatial Resolution at 700C!



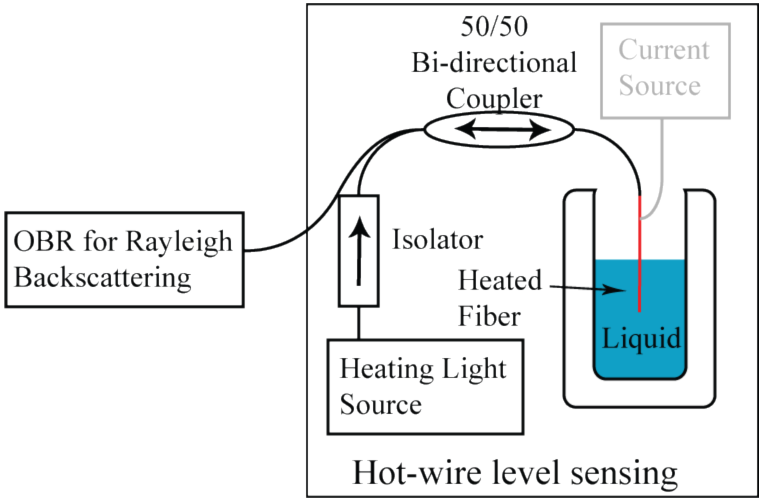
Yr 3: Fibers for Distributed H2 Sensing



- **Goal: chemical sensing as part of fiber functionality**
- **Explore other species measurements**
- **Demonstrate distributed sensing cross 10-meters**

Accomplishments: Active Fiber Sensors

All-temperature Continuous Level Sensing using self-heated fiber and Rayleigh backscattering:



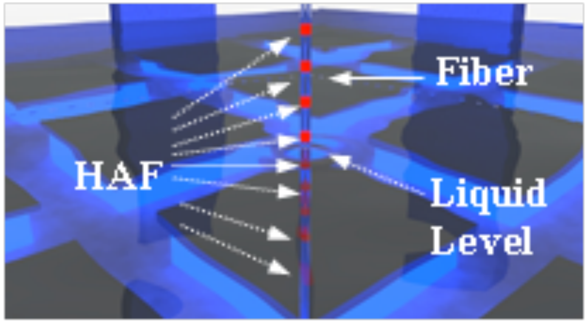
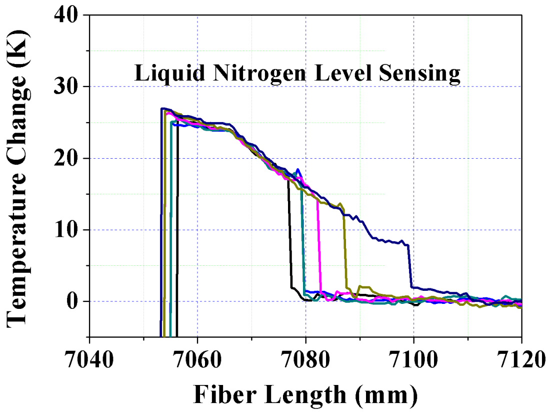
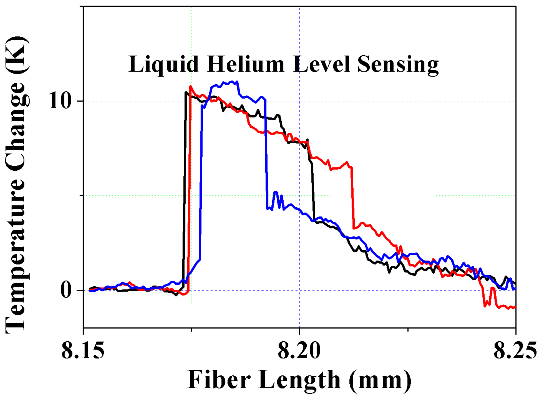


Fig. 10: schematic of active fiber level sensor in spent fuel rod pools.

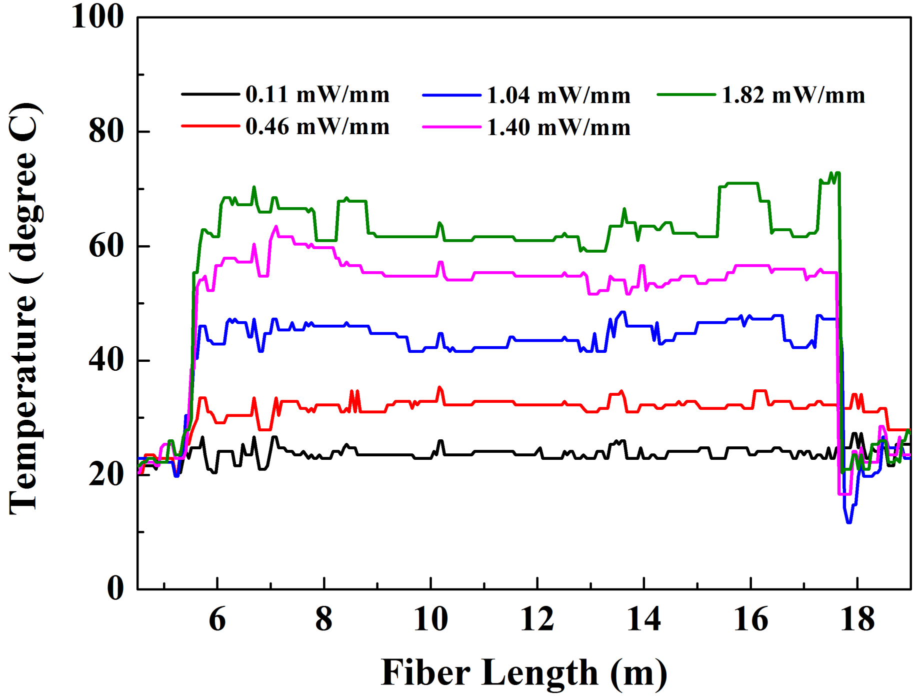




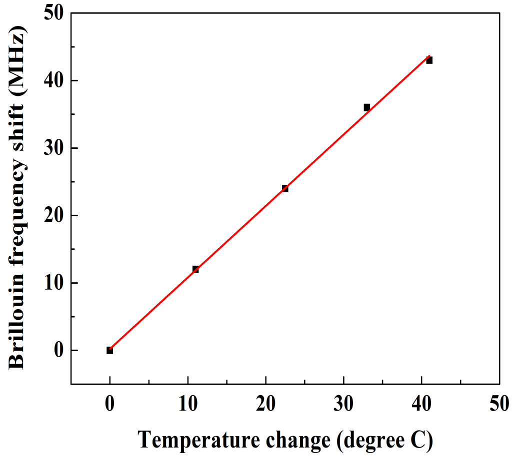
Accomplishments: Active Fiber Sensors

- Heating span 10-m.
- Temperature fluctuation might caused by air flow or coating
- 1-10W electricity for heating
- Power off: temperature measurements
- Power on: water level measurement.
- High sensitivity to surrounding medium validated

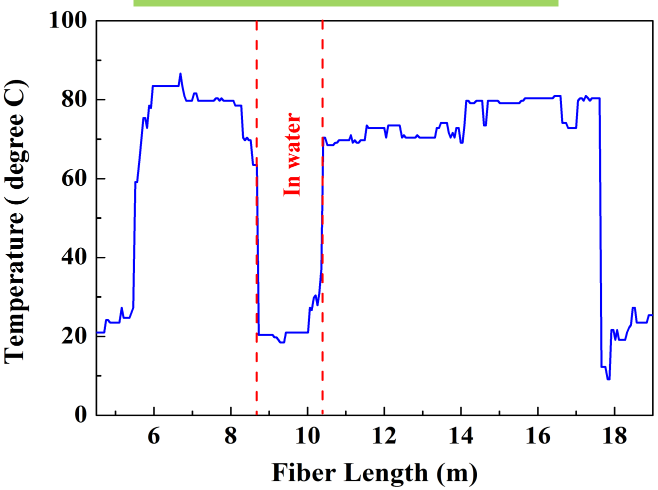
Uniform Heating Cross 10-m Span



Brillouin Frequency vs. T

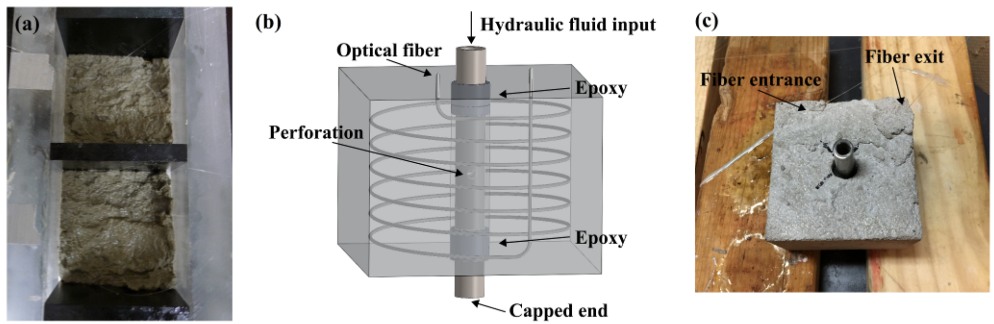


Level Sensing in Waters

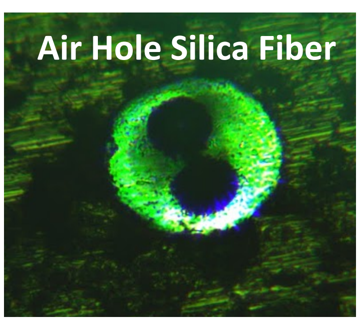


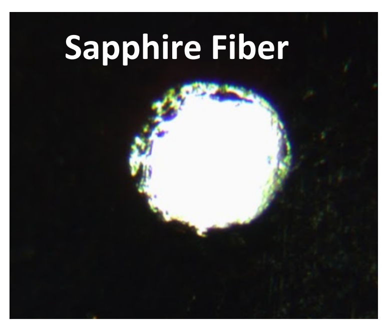
Fiber Sensor Implementations

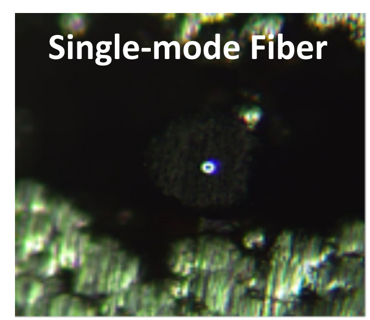
Multiple-functional Sensor Embedded in Concretes



Fiber Embedded in Stainless Steel







Technology Impacts

- ***Advances the state of the art and support NE and nuclear industry***
  - *Develop distributed fiber sensing solutions to perform robust and multi-functional measurements beyond T and $\mu\varepsilon$.*
  - *Develop new optical fibers with an integrated function for distributed radiation measurements.*
  - *Provide unique sensing capability unattainable by other measurement schemes*
- ***Explain how this technology impacts nuclear stakeholders***
  - *Improve safety of nuclear power systems: distributed fiber chemical sensors for gas measurements (e.g. Hydrogen), distributed fiber sensors to monitor spent nuclear fuel pools, and etc.*
  - *Provide new tools to monitor radiation effects to critical components, systems, and infrastructures.*

Conclusion

- ***Invention and Developments of new optical fibers for sensing for nuclear energy.***
- ***Study of optical fiber responses to radiations using distributed fiber interrogation techniques.***
- ***Evaluate various distributed fiber sensing schemes for short and long terms measurements***
- ***Development of new multi-functional fiber sensing schemes with high spatial resolutions.***
- ***Working with nuclear industry to implement new fiber sensors to improve safety and efficiency.***

Questions?

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