Office Of Nuclear Energy
Sensors and Instrumentation
Annual Review Meeting

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

Kevin P. Chen
University of Pittsburgh, Corning Inc, and Westinghouse Electric Company
NEET Program

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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

<table>
<thead>
<tr>
<th></th>
<th>Spent Nuclear Fuel Pool</th>
<th>Containment Dome</th>
<th>Steam Generator</th>
<th>Research Facilities (LHC, LMJ, ITER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Operation</td>
<td></td>
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<tr>
<td>Radiation</td>
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<tr>
<td>2 mGy/hr</td>
<td></td>
<td>50 μGy/hr</td>
<td>&lt;10 mGy/hr</td>
<td>50 Gy/day</td>
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<tr>
<td>Normal Operation</td>
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<td>20-yr Dosage (Gy)</td>
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<tr>
<td>350 Gy</td>
<td></td>
<td>8.8 Gy</td>
<td>1.75 kGy</td>
<td>200 kGy</td>
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<tr>
<td>Post-Accident</td>
<td></td>
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<tr>
<td>Radiation (Gy/hr)</td>
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<td></td>
</tr>
<tr>
<td>2 mGy/hr</td>
<td></td>
<td>5 Gy/hr</td>
<td>5 Gy/hr</td>
<td>N/A</td>
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<tr>
<td>Post-Accident</td>
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<td></td>
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<tr>
<td>30-day Dosage (Gy)</td>
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<tr>
<td>1.44 Gy</td>
<td></td>
<td>3.7 kGy</td>
<td>3.7 kGy</td>
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</table>
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 …?)
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

- $\gamma$ 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)
Radiation Tests

Radiation Tests

<table>
<thead>
<tr>
<th>Fiber Types</th>
<th>SMF28</th>
<th>Vascade</th>
<th>High Ge-Alumina</th>
<th>Alumina</th>
<th>Random air-hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIA (dB/km)</td>
<td>96</td>
<td>61</td>
<td>115</td>
<td>35651</td>
<td>51</td>
</tr>
</tbody>
</table>

- 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)

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

Co-60 sources

Radiation Sensitive fiber

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**)

  ![Rayleigh OFDR Diagram]

- **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

- OFDR birefringence measurements
- Rayleigh scattering reference between 2 polarization states
- Demonstrate distributed sensing cross 10-meters
OFDR Measurement Results 800°C

Pressure Response at 800 degree C
- Slow Axis
- Fast Axis
- Birefringence

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

Yr 2: Fibers for Distributed P Sensing
• 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 >600°C
• No electrical components in target environment
Exposed to various concentrations of hydrogen in nitrogen, recovered with nitrogen. Ideal for hydrogen driven energy conversion systems.
Distributed H2 measurements with 5-mm Spatial Resolution at 700C!

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

Yr 3: Fibers for Distributed H2 Sensing
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.
Uniform Heating Cross 10-m Span

- 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

Brillouin Frequency vs. T

Accomplishments: Active Fiber Sensors

Level Sensing in Waters
Fiber Sensor Implementations

Multiple-functional Sensor Embedded in Concretes

Fiber Embedded in Stainless Steel

Air Hole Silica Fiber

Sapphire Fiber

Single-mode Fiber
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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