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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Goal, and Objectives

• Develop new optical fibers for nuclear industry
• Explore and demonstrate distributed multi-functional fiber optical sensors for nuclear industry
  – με, T, vibration, P, level, chemical, and radiation with high spatial resolutions
• Evaluate various distributed sensing schemes and demonstrate unique capability
• Develop manufacturing schemes for sensor-fused smart parts for nuclear industry.
• Evaluate fiber sensors for extreme harsh environments (neutron radiation).

Participants

• 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:

• 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 (but not all environments).
  - High Temperature up to 800°C, high pressure up to 2500 psi, gamma radiation (MGy).
  - High neutron radiation (to be evaluated)
- 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 (but not all environments are extremely radioactive)
- Need perform a wide range 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>
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</thead>
<tbody>
<tr>
<td>Normal Operation</td>
<td>2 mGy/hr</td>
<td>50 µGy/hr</td>
<td>&lt;10 mGy/hr</td>
<td>50 Gy/day</td>
</tr>
<tr>
<td>Radiation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Operation</td>
<td>350 Gy</td>
<td>8.8 Gy</td>
<td>1.75 kGy</td>
<td>200 kGy</td>
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<tr>
<td>20-yr Dosage (Gy)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Post-Accident Radiation</td>
<td>2 Gy/hr</td>
<td>5 Gy/hr</td>
<td>5 Gy/hr</td>
<td>N/A</td>
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<tr>
<td>(Gy/hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Accident</td>
<td>1.44 kGy</td>
<td>3.7 kGy</td>
<td>3.7 kGy</td>
<td>N/A</td>
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<tr>
<td>30-day Dosage (Gy)</td>
<td></td>
<td></td>
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</table>
Research Approach

Fibers
- 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
  - Fiber optical vibration sensing for radiation environments

Implementations and Applications in Nuclear Engineering
- Smart parts manufacturing: Fiber embedding and testing
- New sensor platforms (smart cable, small concrete, and …?)
Experiment Setup

• γ radiation: max. ~5000 Gy/hr on fibers
• Performed in Westinghouse Churchill facility
• Brillouin OTDR schemes and Rayleigh OFDR distributed sensing scheme
• Fiber Bragg gratings and fiber acoustic sensors
Experiment Setup

- LUNA OBR 4600
- Swept wavelength interferometry
- Compares (with cross correlation) backscattering vs. reference to determine loss, temperature, and strain
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)

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
Spatial Mapping of Radiation

(a) Radiation Total Dosage (krad)

(b) Elevation (m) vs. Losses (dB/mm)

4 minutes, 9 minutes, 11 minutes
Electrical Cable as Sensor Platform

- Using electric cables as ubiquitous sensor platforms.
- No need to re-design nuclear power systems for sensor integration.
- Direct monitoring of cable aging with high spatial resolution.
- Fiber inserted as distributed sensors or point sensors with interrogation length 0.1-10 km.
  - Temperature
  - Pressure
  - Strain (cable degradation)
  - Volatile chemical and hydrogen
  - Leak and moisture
  - Radiation
Distributed Pressure Measurements

- OFDR birefringence measurements
- Rayleigh scattering reference between 2 polarization states
- Demonstrate distributed sensing cross 10-meters
Distributed Pressure Measurements for Steam Pipes

- “Appropriate” harsh environments (modest/minimal neutron radiation)
- Radiation-harden microstructural fiber for simultaneous temperature and pressure measurements
- T ~ 650°C, Pressure 200 bars
  - T resolution 1°C
  - P resolution 1%
- Distributed fiber solution 1-cm resolution
- One fiber cable, one fiber feedthrough.
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 >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.
Active Fiber Sensors: Level Measurements in Spent Fuel Rod Pool

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

![Diagram of active fiber level sensor in spent fuel rod pools.]

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

- 50/50 Bi-directional Coupler
- Current Source
- Isolator
- Heated Fiber
- Liquid
- Heating Light Source

**OBR for Rayleigh Backscattering**

**Graphs:**
- Liquid Nitrogen Level Sensing
- Liquid Helium Level Sensing

**Temperature Change (K)** vs **Fiber Length (mm)**
• 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
Sensor-Fused Additive Manufacturing

Establish a reliable way to implement fibers in harsh environments

- Standard optical fibers
- Electroless/sputtering coating of glue layers
- Electroplating of Ni/Fe protective layer
- Embedding process using a 3D printing scheme (LENS) into mixed alloy
- Repeated thermal cycling and annealing at 900°C appears to yield consistent results
- 3D printing provide GREAT protection to fiber sensors
Sensor Package via 3D Printing

TEC of Fe-Ni Alloy

![Graph showing TEC of Fe-Ni Alloy](image)

![3D printed sensor package](image)
Fiber Optic Acoustics Sensor for Fast Sodium Reactor

- Thermal acoustic resonators for in-pile temperature sensing.
- Simulators have five acoustic resonators
- Distributed feedback fiber lasers as acoustic sensors
- 3x3 interferometer for fast signal decoding
- Cut-off frequency of measurements 150 kHz
- Frequency measurement accuracy at 1 Hz
DFB fiber acoustic sensor measurements
In-Pile Neutron Tests: FBG Point Sensors and Distributed Sensors

Thermal Regeneration Process

- Type I Seed FBG
- H₂-loading
- Heating for Hydrogenation (800°C)
- Regeneration (1200°C)
- Stabilization (1200°C)
- High-T Stable FBG

Enhanced Rayleigh Scattering

- Ultrafast laser irradiation
  - Ti:Sapphire 250-kHz, 180-fs, 780-nm
  - 0.2-0.5 μJ, 0.5-10 mm/s
Highly Stable Rayleigh Fibers at High-T

- Rayleigh enhanced fiber stable up to 800°C in 10% hydrogen!
- Temperature measurement 5-mm spatial resolution
- Repeatability better than 4°C at 800°C in H2 environments
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.
- Mature TRL levels of fiber sensors by developing new sensor packaging scheme and sensor-fused smart components
Questions?

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