U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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Fiber-Optic Sensor for Simultaneous Measurement of Temperature and Pressure

FY2018 Progress
for
DOE SBIR Award DE-SC0017826

Advanced Sensors and Instrumentation Annual Webinar

October 31 – November 1, 2018

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Luna Innovations Incorporated

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Luna Overview

We're organized into two main business segments: **Products and Licensing** and **Technology Development**, which work closely together to turn ideas into products

Products and Licensing segment

Fiber optic instruments:

Develop and commercialize breakthrough technologies for targeted industries

- Sensing products for the high growth aerospace, automotive, and energy markets
  - ODiSI™-6000 Series
  - OBR™-4600
  - Hyperion™ si155 and si255
- Test & measurement solutions, primarily for the telecommunications industry
  - OBR™-4600
  - OVA™5000

Terahertz solutions:

Develop and commercialize disruptive sensing technologies for manufacturing applications

- Leading provider of industrial systems for quality control, inspection, and process control

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Technology Development segment

Applied research:

Contract research ultimately focused on commercialization

- Focused areas: **Sensing & instrumentation**, Materials, Health sciences, Optical systems, Terahertz

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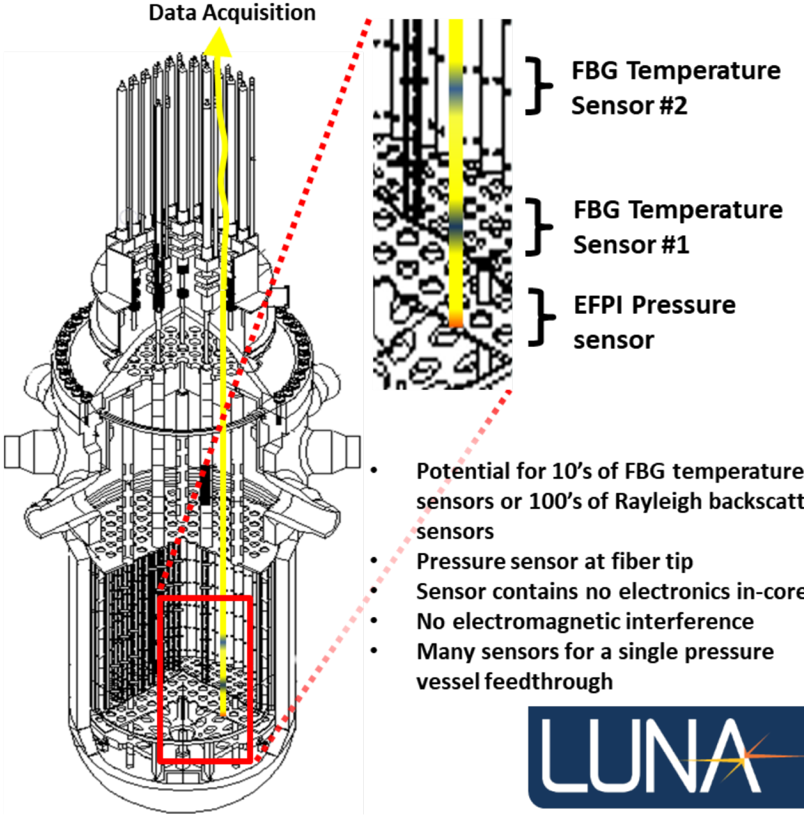
Luna Locations

The Problem

- Desire sensors that reduce containment vessel feedthrough count
- Combine fiber optic sensors to measure multiple properties
  - No in vessel power requirements
  - Signal cable reduced by number serial inline sensors
- Targeting DOE Labs, Gen III & IV Commercial nuclear power, other high temperature harsh environments

Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure



- Potential for 10's of FBG temperature sensors or 100's of Rayleigh backscatter sensors
- Pressure sensor at fiber tip
- Sensor contains no electronics in-core
- No electromagnetic interference
- Many sensors for a single pressure vessel feedthrough

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Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure

Technology Summary

This project demonstrated the feasibility of radiation resistant fiber optic multi point temperature and pressure sensors. During Phase I sensors were successfully evaluated to 1000˚C, combined temperature and pressure of 300˚C and 2500psi, and to neutron fluence of 9E17 n/cm^2. Temperature and pressure measurements are achieved by combining Fiber Bragg Gratings (FBGs) on the same fiber as one of Luna's Extrinsic Fabry-Perot Interferometer (EFFPI) sensors. This design utilizes recent advances in fiber chemistry and FBG manufacturing techniques resulting in radiation hardened sensors.

Technology Impact

Current temperature measurements utilize single point Type-K thermocouples, and to the PI's knowledge, there exist no in-core pressure sensors.

Luna's sensor under development, will provide multipoint temperature readings with single point pressure at the fiber tip. This new class of sensor will provide for advanced monitoring while decreasing cable feedthroughs.

Project Summary

Period of Performance: Total Budget: $149,998

Start Date: 6/12/17 End Date:3/11/18

Key Milestones & Deliverables	
2017 Sept.	• Project Kickoff
2017 Oct.	• Complete Sensor Designs
2017 Nov	• Fabricate Sensors
2018 Jan	• Sensor Operation in OSURR
2018 March 24th	• Final report
2018 May 1st	• Phase II proposal

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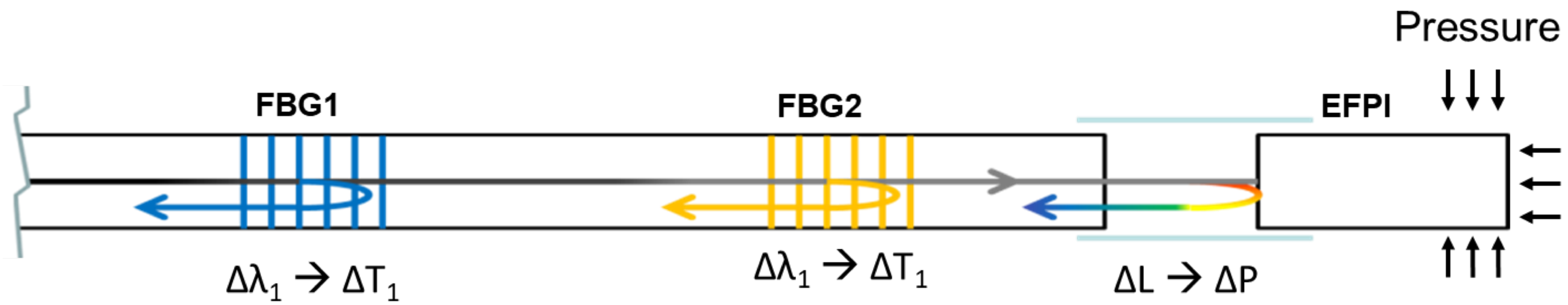
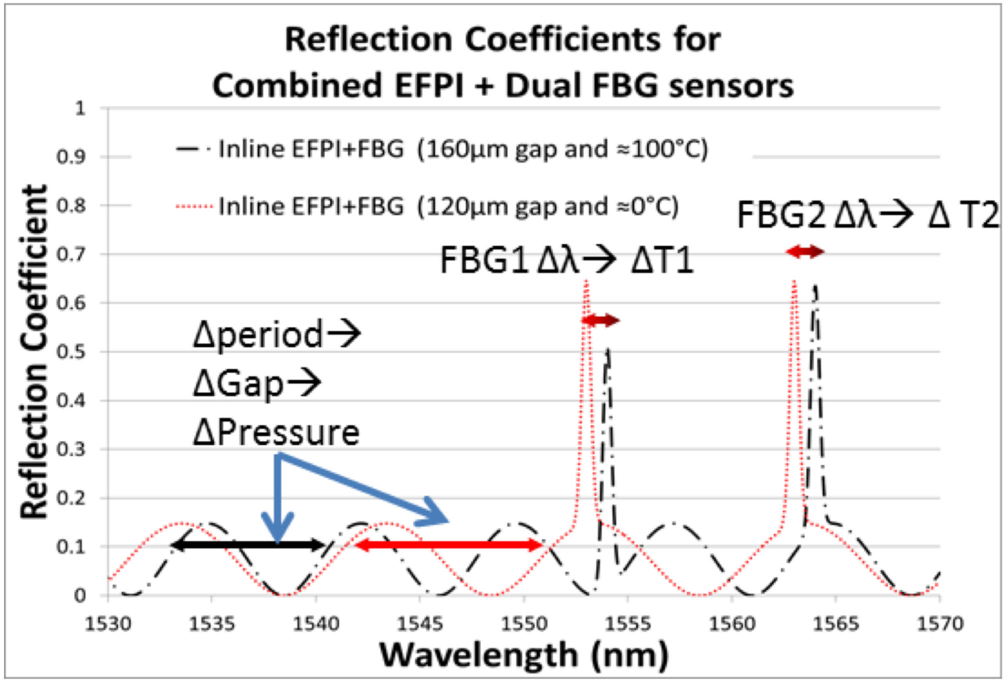
Sensor Response for EFPI with Serial FBGs





- Change in temperature at FBG yields a wavelength shift directly proportional to temperature
- Change in Pressure at the EFPI produces a change in cavity length which is measured by the change in fringe period

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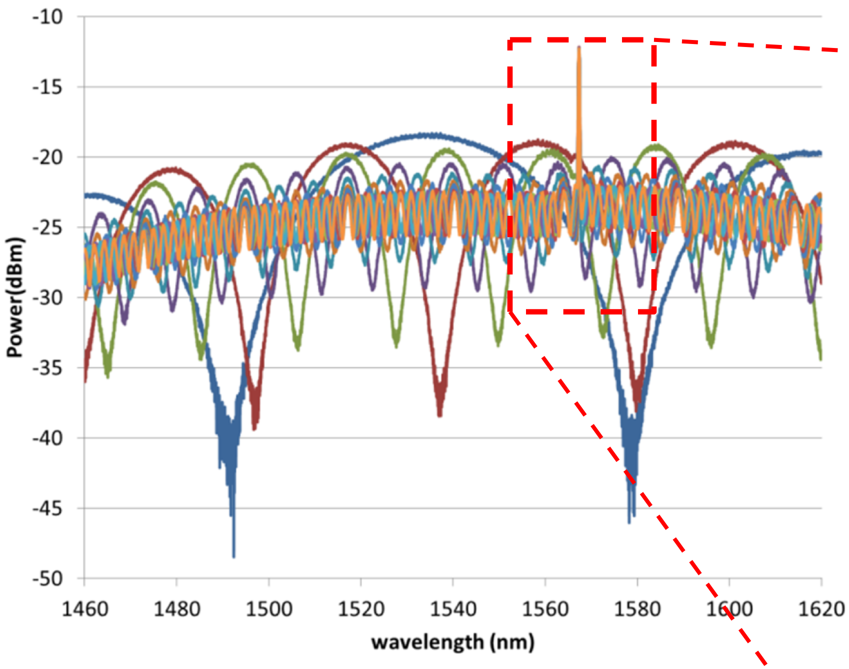
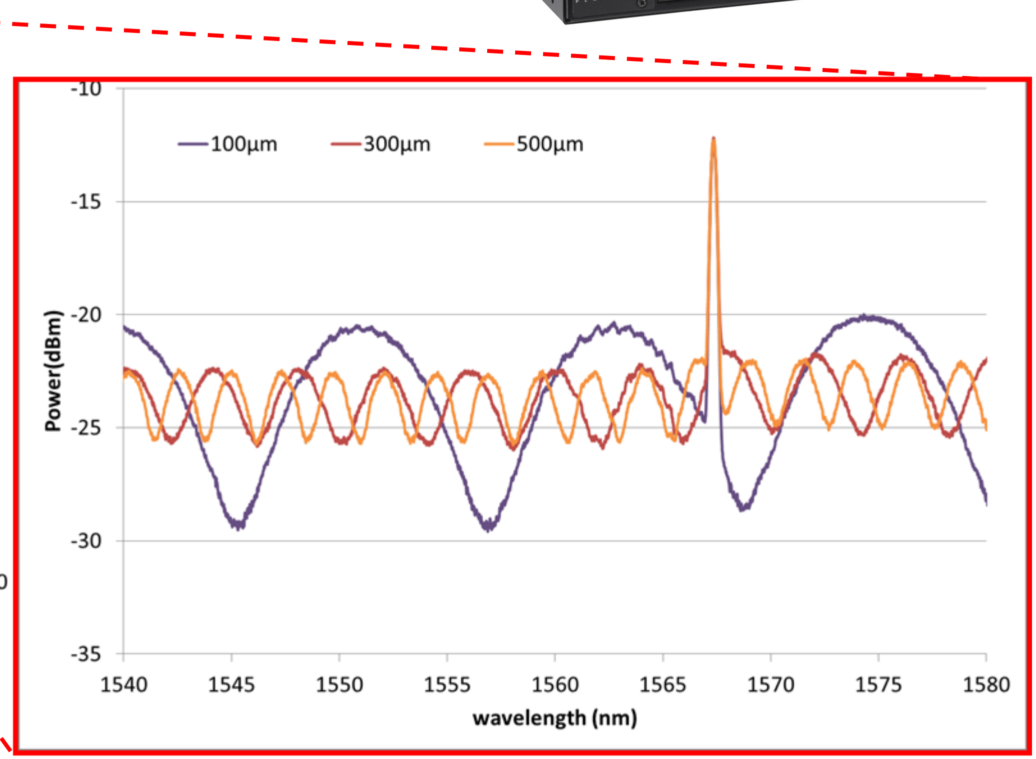
Sample Data from Combined EFPI and fsFBG Sensor Using Luna Hyperion si155

Combined EFPI and fsFBG Sensor
For Multiple EFPI gap distances





Data collected at room temperature using a translational stage to vary EFPI gap

Sample Data from Combined Pressure and Temperature Sensor Using Luna's OBR 4600

Luna constructed fsFBG sensor with EFPI
Data collected with Luna's OBR 4600

- EFPI response is the sinusoidal-like fringe pattern
  - Changes in the period relate inversely to the length of the EFPI cavity which relates directly to pressure
- FBG response is the large Gaussian peak
  - Changes in wavelength of this peak relate directly to temperature and independent of the fringe period
- Tests were run from 0-300°C and 0-2500psi

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Blue trace:    0psi @  87°C
Red  trace: 2500psi @ 275°C
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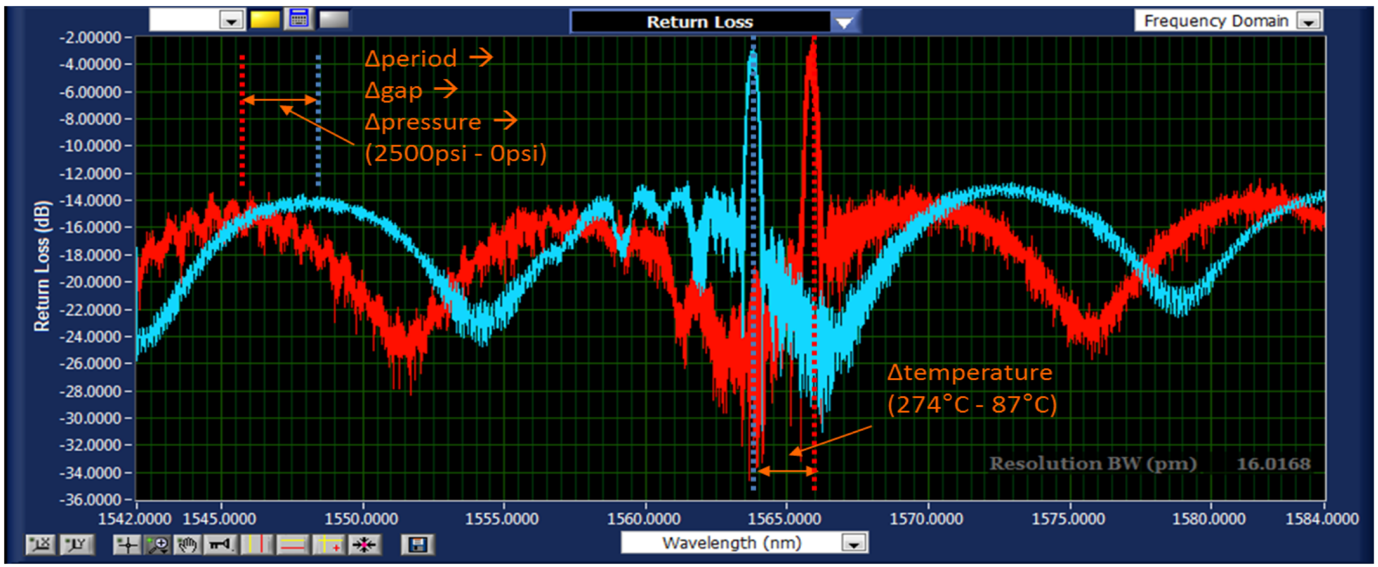
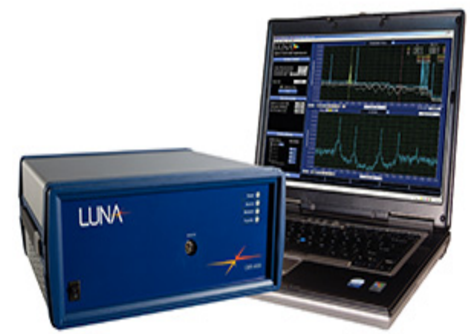
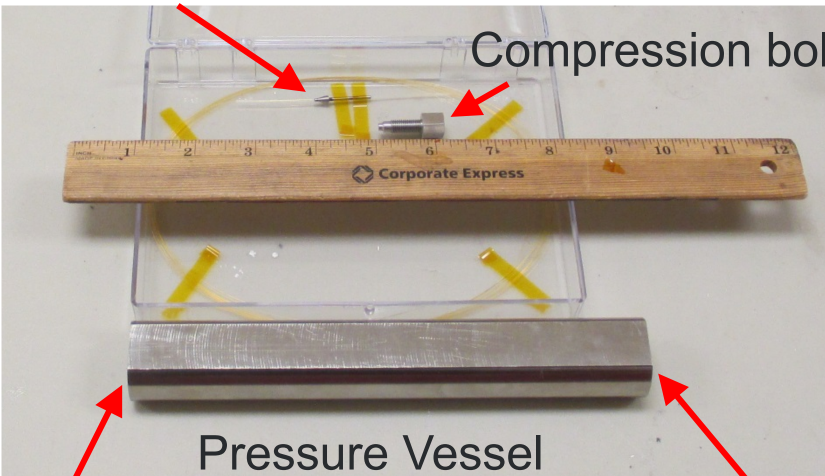




Combined Pressure and Temperature Tests

Fiber optic pressure vessel feedthrough
Rated for 300°C and 5000psi

Compression bolt



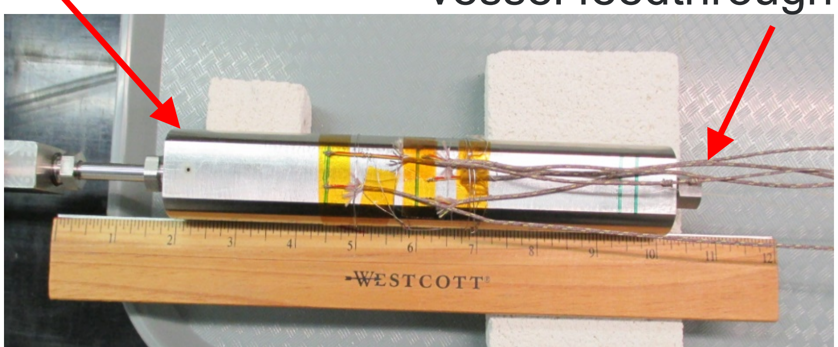
Pressure Vessel

Thermocouple and fiber optic sensor leads

5kpsi max
Argon line

Pressure line port

Fiber optic pressure vessel feedthrough port



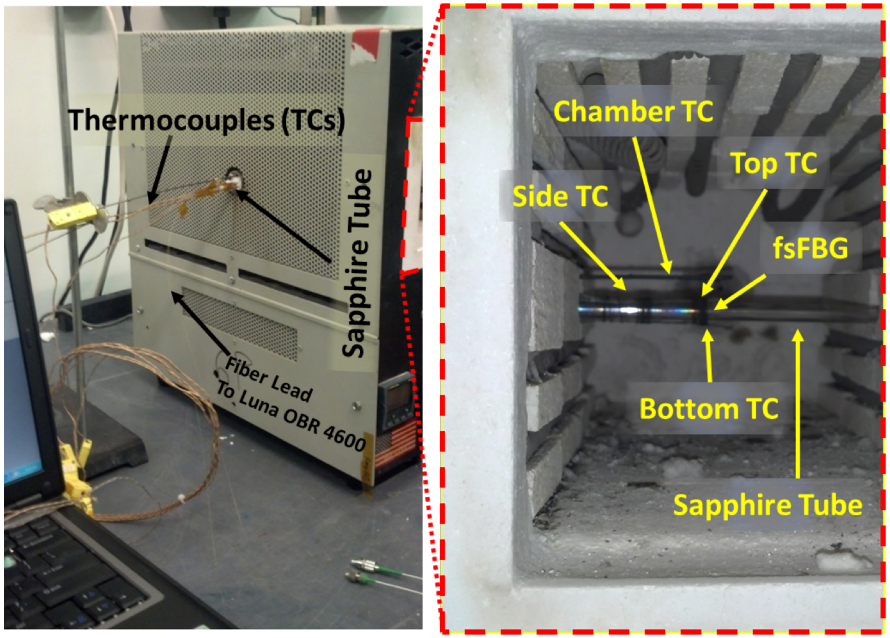
Pressure and temperature test rig

- Thick wall pressure vessel
- Glass to Inconel fiber optic pressure feedthrough
- 5kpsi max argon line
- Furnace

fsFBG High Temperature Tests

High Temperature testing to 1000˚C

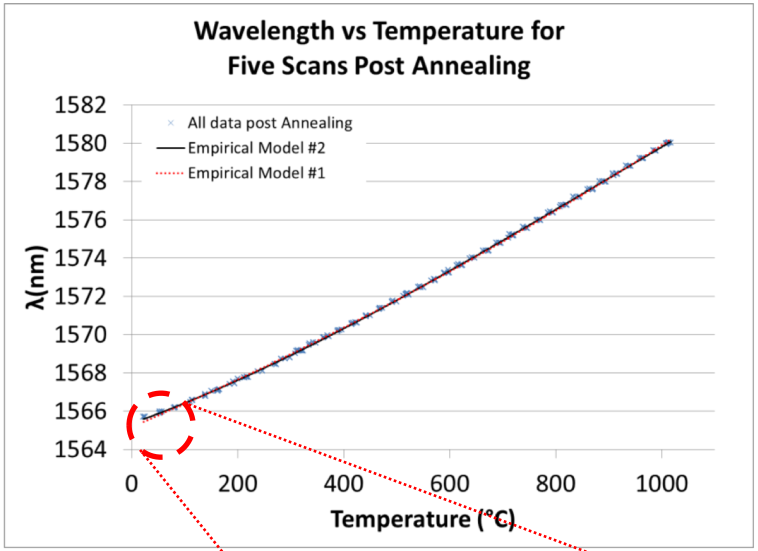
- fsFBG deployed in sapphire tube
- Thermocouples (TC) deployed outside of tube, above and below fsFBG location
- 2 hour annealing at 1000˚C
- 3 post annealing ramps to 1000˚C
- Data interrogation using Luna’s OBR 4600

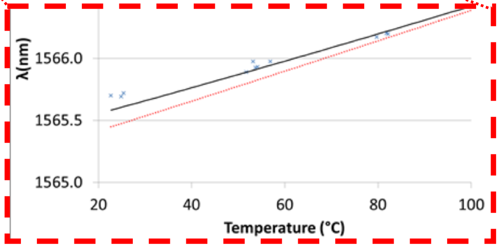


fsFBG High Temperature Tests

fsFBG temperature sensor performance

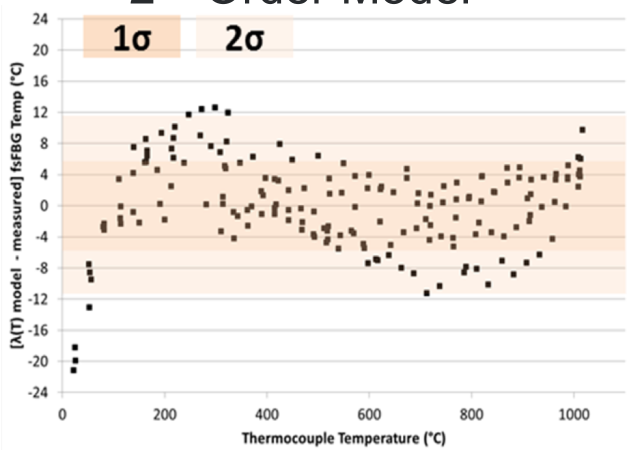
- Two empirically determined models explored
- 1σ deviation from Model #1 ≈ 5.7˚C
- 1σ deviation from Model #2 ≈ 4.4˚C
- With Model #2, the error appears to have little dependence on temperature
- Additional studies and model validation are required



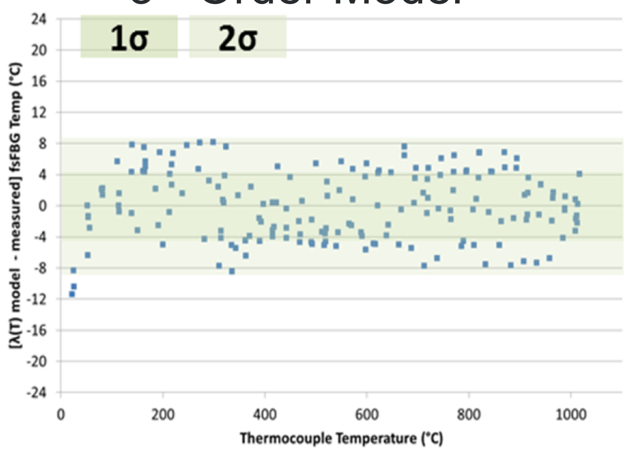


fsFBG Temp (°C) Variance from model

2nd Order Model



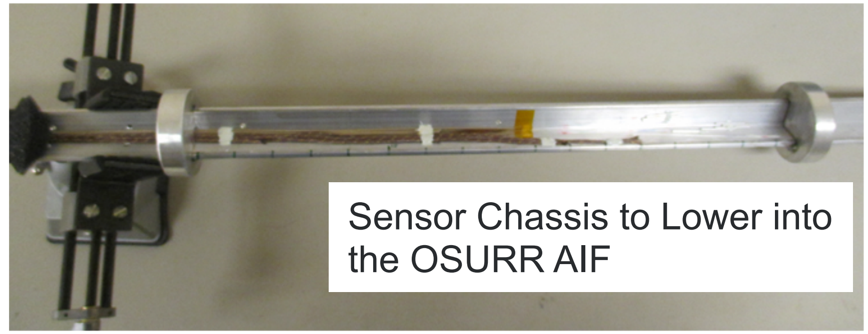
3rd Order Model

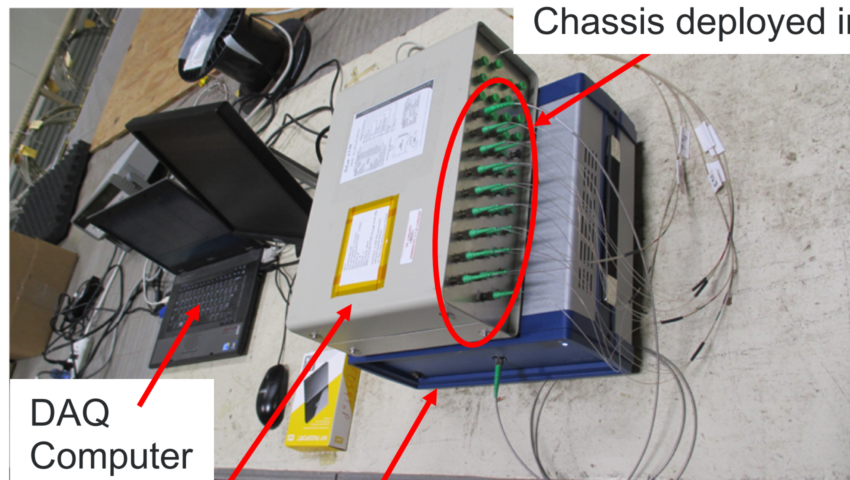


The Ohio State University Research Reactor Sensor Tests In-Core

Sensors were tested at The Ohio State University Research Reactor OSURR

- Aluminum Chassis to hold 17 fiber optic sensors and 6 thermocouples
- Sensor types
  - Dual fsFBG + EFPI
  - Dual fsFBG
  - EFPI
  - Rayleigh scatter
- Sensors interrogated using Luna's OBR 4600
- Four irradiation cycles to a total of 9.18E17 n/cm^2
- Reactor temperatures
  - Reactor off ~20˚C
  - Reactor on ~90˚C





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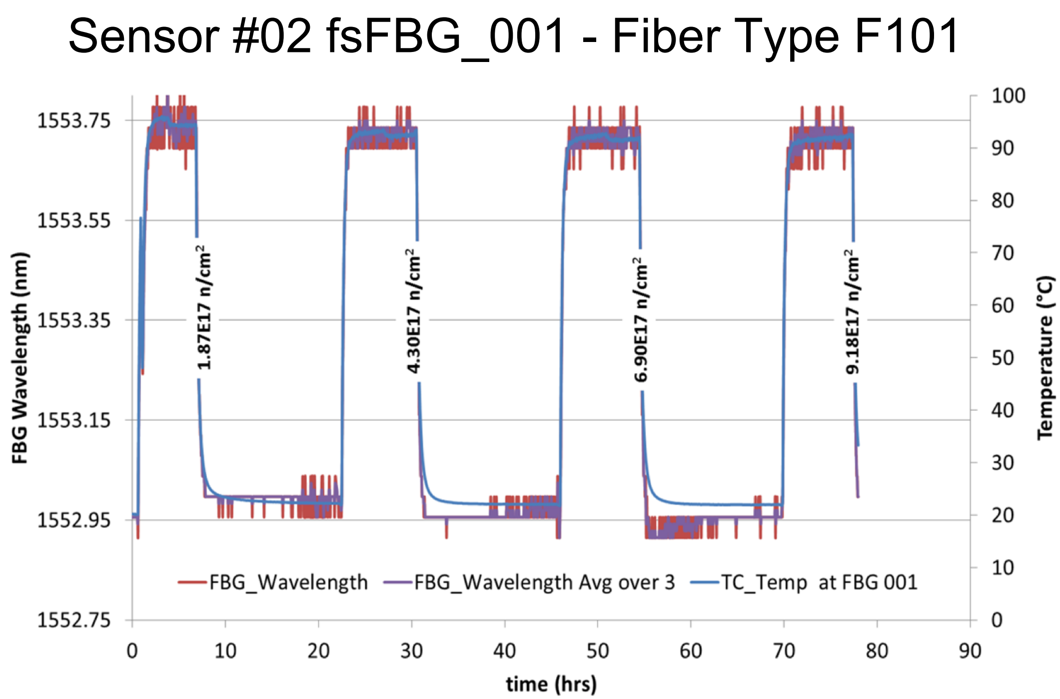
The Ohio State University Research Reactor Sensor Tests In-Core: fsFBG Evaluation

The fsFBG temperature measurement characteristics for both fiber type F101 and F102 performed well in the reactor, with ~±5˚C response compared to the nearby thermocouples, similar to early thermal tests.

fsFBG irradiation effects on peak amplitude:

- F101
  - Initial value ~0.25/mm
  - Peak reduction of:
    6E-21 (1/mm * 1/(neutron/cm²))
- F102
  - Initial value ~0.17/mm
  - Peak reduction of:
    5E-20 (1/mm * 1/(neutron/cm²))



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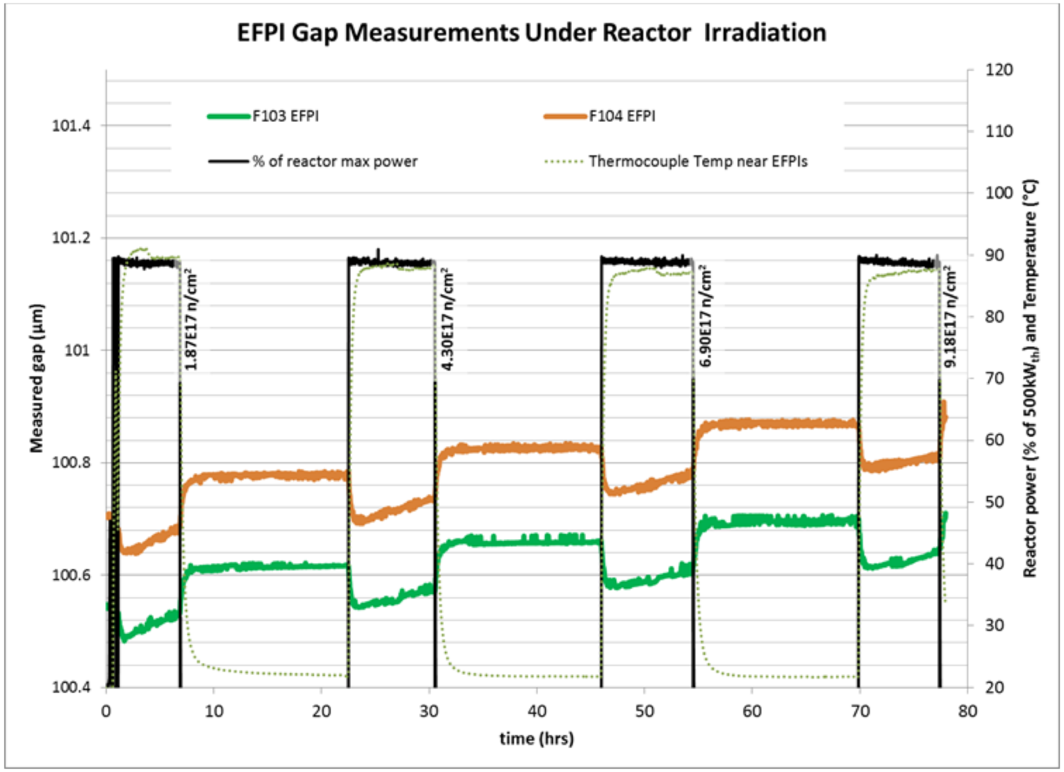
The Ohio State University Research Reactor Sensor Tests In-Core: EFPI Evaluation

The EFPI sensors performed well in the reactor; though, some were noisy. This noise may be due to unanticipated strain coupling. In the case of "F101 Dual FBG with EFPI" additional noise is expected due to not yet having optimized the combination FBG and EFPI sensor analysis algorithms.

F103 EFPI, F104 EFPI, and F105 EFPI show very flat response while the reactor is static with ~0.1µm (corresponds to ~50psi) variation from reactor on to reactor off.



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Phase II Plan (Awarded 9\26\18 – DE-SC0017826)

1. Continue analysis of phase I data
    - 0-1000 ˚C at ambient pressure
    - 300˚C @ 2500psi
    - 0 - 9.18E17 n/cm^2 with varying temperature 0-90˚C
2. Publish Phase I results
3. Advance sensor development for 350˚C @ 3500psi
    - Test sensors to 350˚C @ 3500psi in noble gas
    - Test sensors to 350˚C @ 3500psi water loop
4. Advance sensor development for 525˚C+ @ 100psi
    - Test sensors to 537˚C @ 100psi in noble gas
    - Test sensors to 537˚C @ 100psi in molten salt loop
5. Advance sensor development for 750˚C+ @ 100psi
    - This will require ~$150k additional investment towards development of a very high temperature feedthrough (currently outside the scope of this two year project)
6. Develop advanced analysis algorithms
7. Determine standard operating procedure for sensor calibration
8. Perform high temperature and pressure tests in irradiation environment
9. Perform high irradiation tests

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VIRGINIA TECH
University of Pittsburgh

Technology Impact

The sensor development of the "Fiber-Optic Sensor for Simultaneous Measurement of Temperature and Pressure" project will:

- *Provide never before available:*
  - *In-core single feedthrough multipoint temperature sensing*
  - *In-core pressure sensing*
  - *Multipoint temperature with endpoint pressure sensing*
- *Provide enhanced sensing capabilities for:*
  - *Reactor monitoring*
  - *GenIV fuel and fuel assembly studies*
  - *Solar salt loop monitoring*
- *Enable advanced instrumentation and controls*
- *Be Commercialized via Luna's extensive network of commercial partners in the nuclear industry.*

Conclusion

Phase I Accomplishments:

- Temperature sensing to 1000˚C
- Temperature and EFPI gap sensing in radiation environment of:
  - 9.18E17 n/cm2
  - 2.6E7 rad-Si neutron dose
  - 1.3E9 rad-Si gamma dose
- Temperature and pressure sensing to 300˚C and 2500 psi

Phase II Goals:

- Sensor packaging for existing PWR fleet
- Sensor packaging for GenIV molten salt reactor environment
- Sensor packaging for GenIV molten metal reactor environment
- Sensor testing in combined temperature, radiation, and pressure environment

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