April 17, 2025

**Dr. Kelly McCary**
Radiation Measurement Scientist

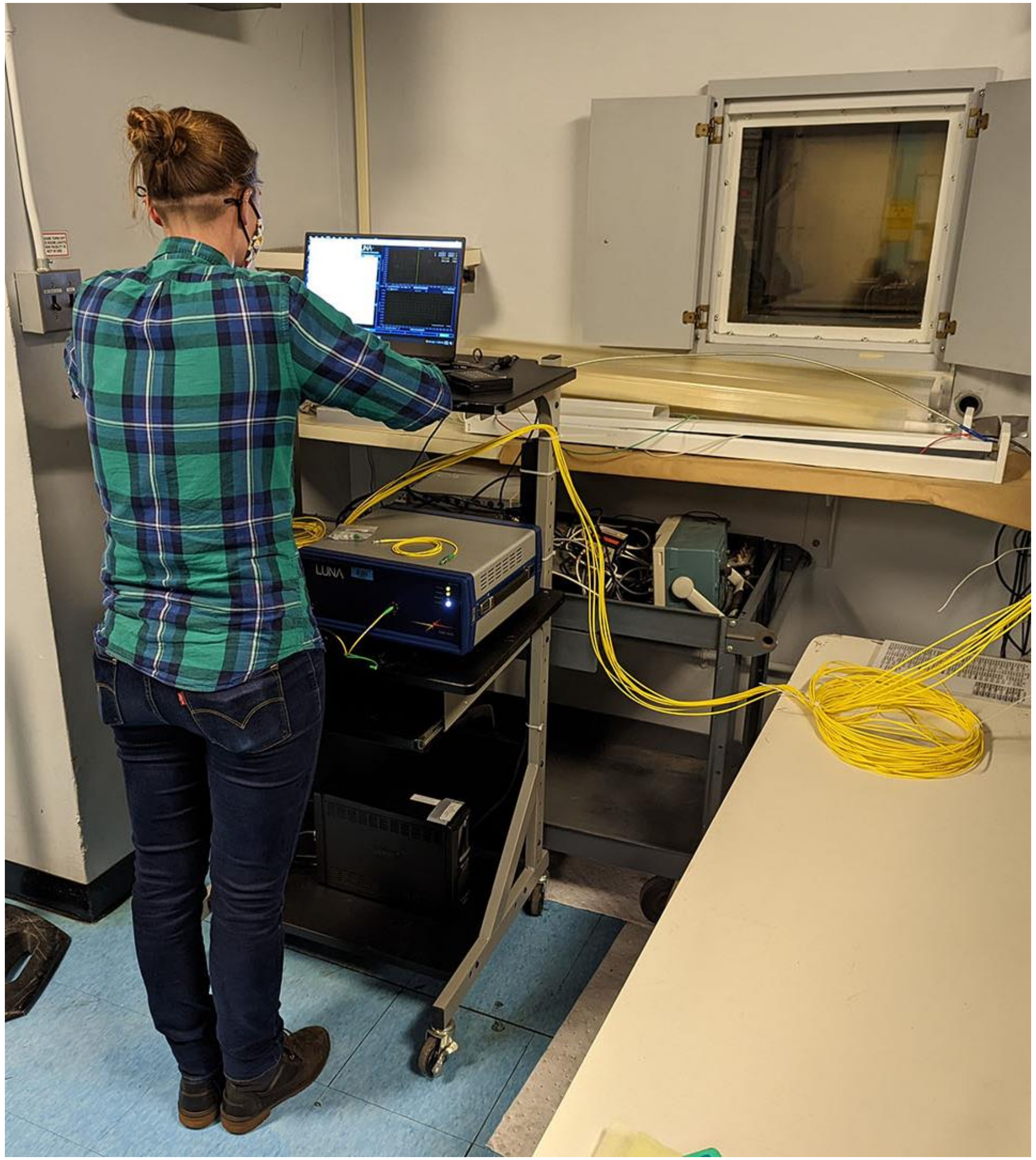
# High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors

Nuclear Science User Facilities Annual Program Review

# Goals and Objectives

Investigate the in-pile performance of sapphire optical fiber temperature sensors and to develop clad sapphire optical fibers for in-pile instrumentation. Evaluate the distributed sensing performance of the sensors through optical backscatter reflectometry under combined radiation and temperature effects, and high fluence.

- Objective 1: Fabricate sapphire optical fiber sensors.
- Objective 2: Evaluate the clad sapphire fiber.
- Objective 3: Characterize in-pile temperature sensing of sapphire optical fiber and combined temperature and irradiation effects.
- Objective 4: Evaluate the lifetime and sensing performance of the sensor under irradiation to high neutron fluence



# Technology Impact

- This work is advancing nuclear technology by characterizing and demonstrating a new sensor technology with the potential to make measurements with high spatial and temperature resolution at higher temperatures than prior optical sensors.  This technology can also be applied to measurements other than temperature.
- This research will deliver modern optical fiber sensing techniques usable in multiple extreme environment applications. In the area of nuclear fuel/material testing, these fibers will enable access to operational data with excellent time and space resolution during irradiation testing.
- Commercialization is underway by Luna Innovations. This research represents the opportunity to close technology gaps and demonstrate the potential of sapphire optical fibers.

# High Temperature Testing: Clad Sapphire

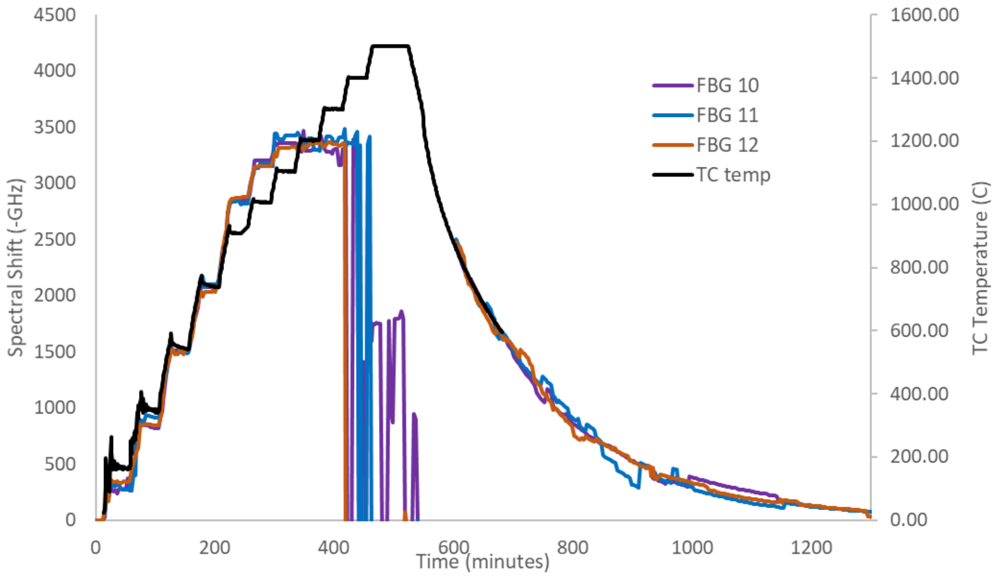
**Two thermal tests were completed with clad sapphire fiber:**

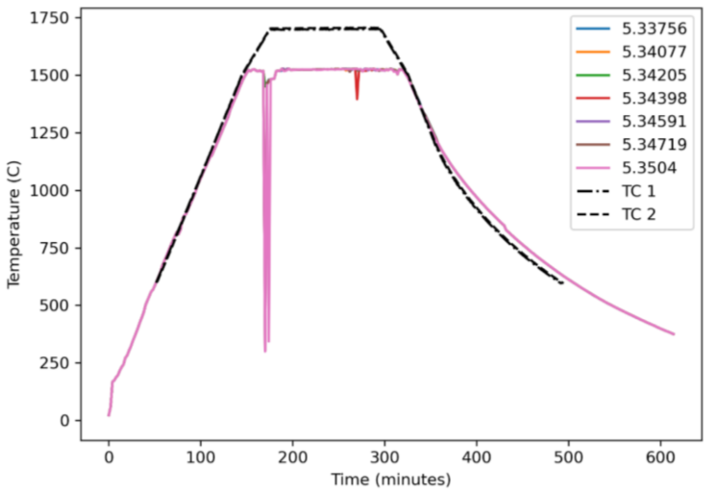
- 8 in. heated region furnace
- Interrogated with a Luna Innovations OBR 4600
- All the fibers were placed in alumina tubes that were closed on the heated end, then spliced to silica lead-out fibers

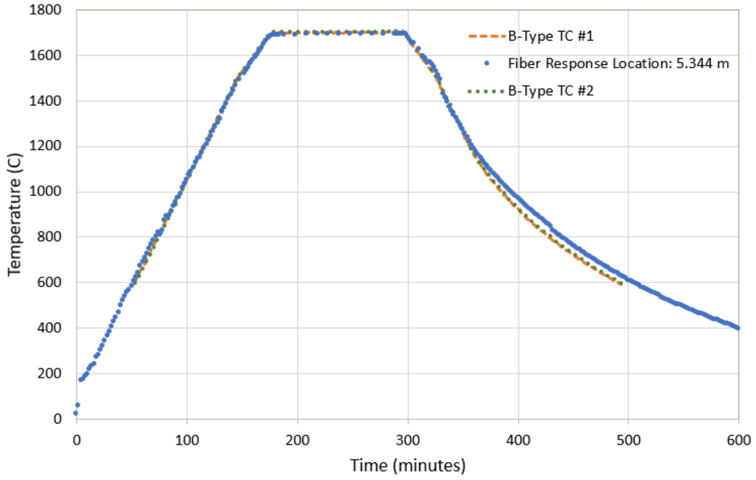
**Test 1: to 1500℃**

- When the furnace was heated past 1100℃, the sensing mechanism failed
    - Attenuation and exceeded range of OBR

**Test 2: to 1700℃ – success with iterative referencing**



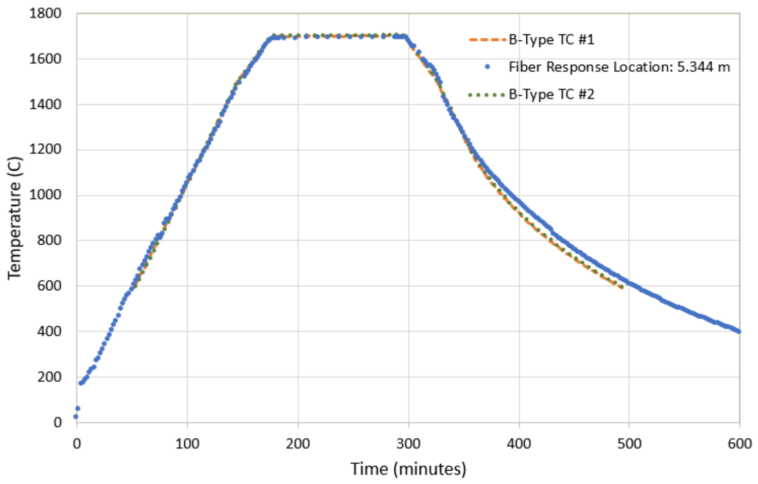



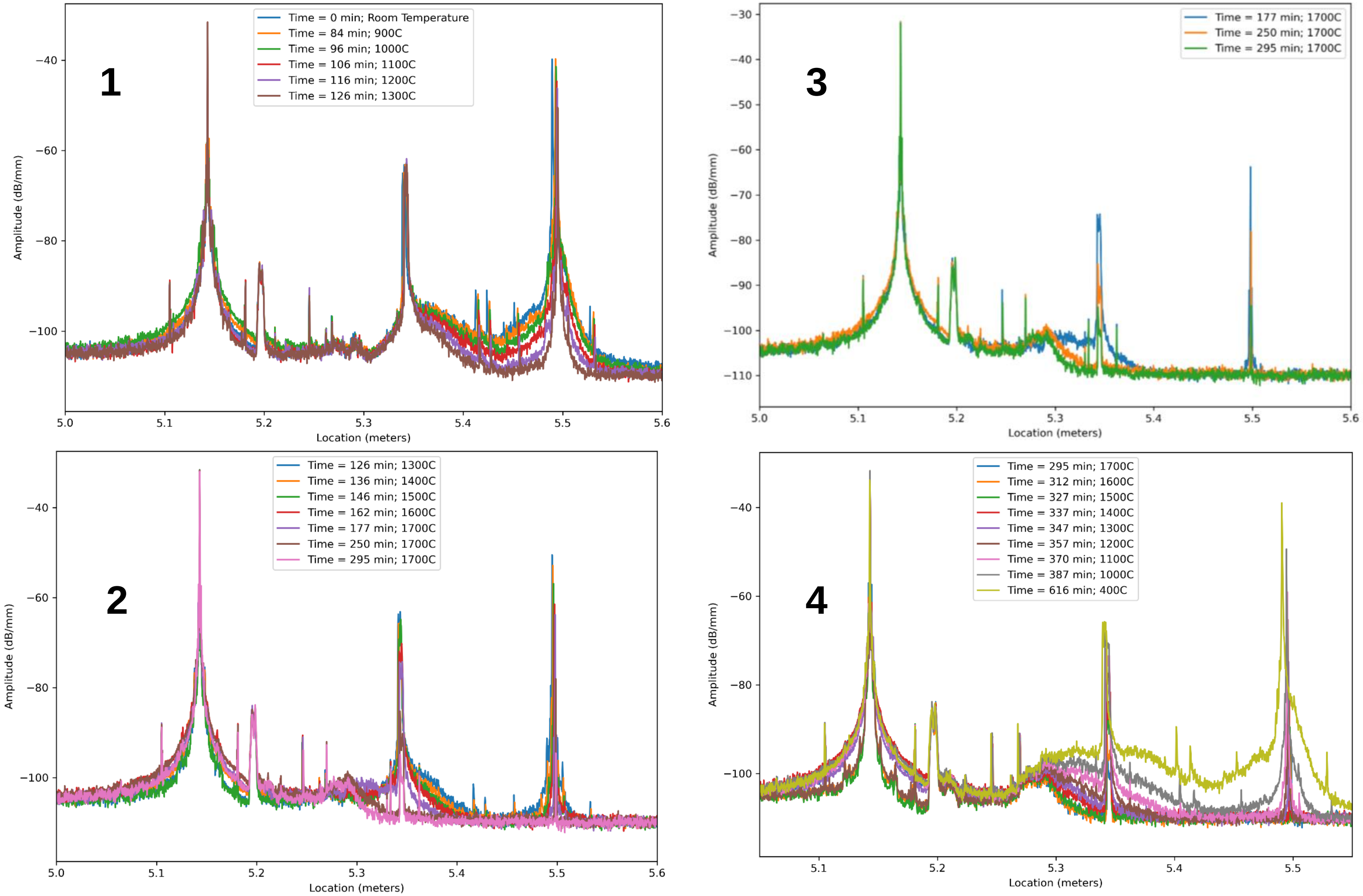



# High Temperature Testing: Clad Sapphire

**A reduction in amplitude was observed with increasing temperature and time in both tests**

- This reduction recovers completely when the fibers cool



# **High Temperature Testing:** Clad Sapphire

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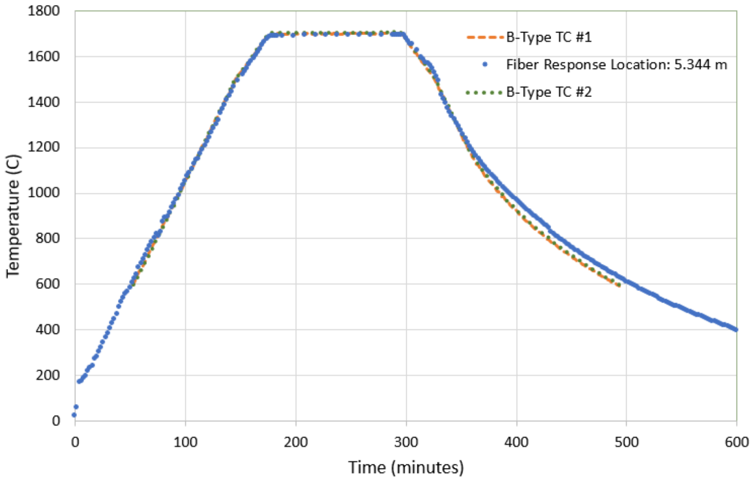
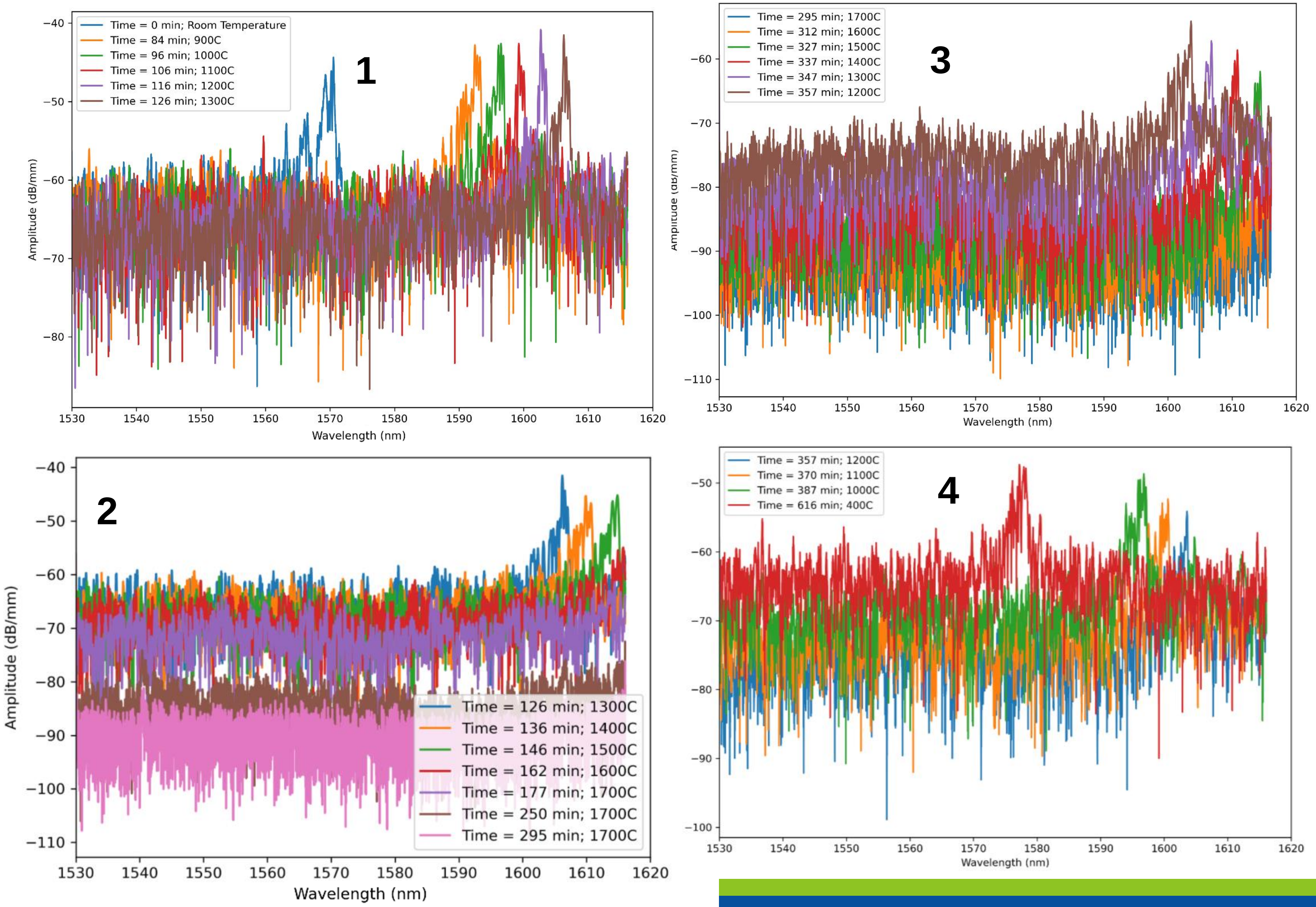


# High Temperature Irradiation

The heated irradiation was designed to test the fibers at various temperatures from ambient to 1600ºC

- Total fluence: 3.2 x $10^{17}$ n/cm$^2$
  - Thermal: 2.3 x $10^{17}$ n/cm$^2$

**Sensor 1:** 75 um diameter – 13 FBGs inscribed by FemtoFiberTec

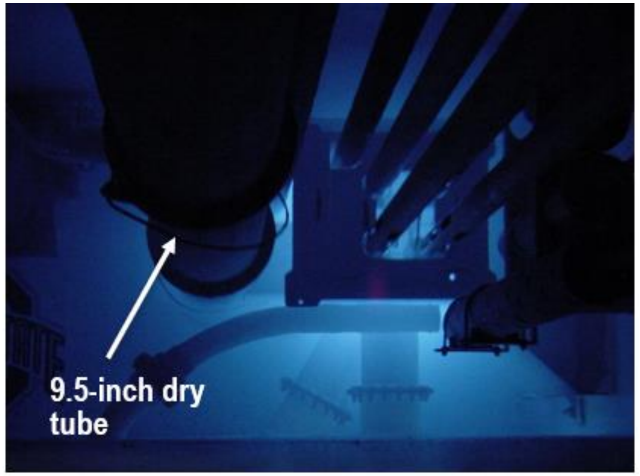
**Sensor 2:** 100 um diameter – 2 FBGs inscribed by UPitt

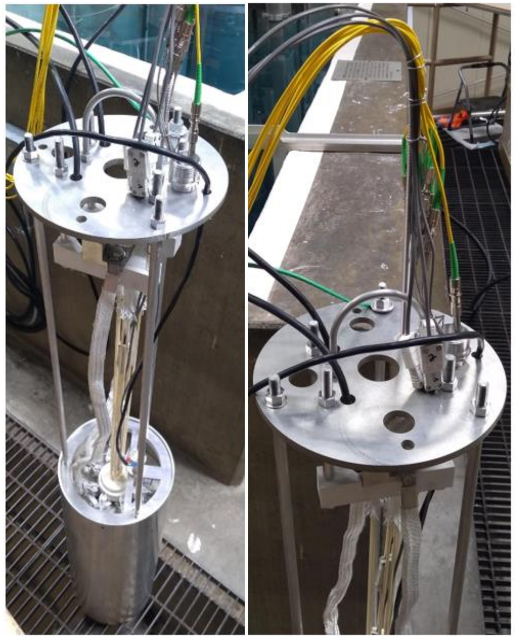
**Sensor 3:** 100 um diameter – 1 FBG inscribed by Upitt

**Sensor 4:** 100 um diameter – No FBGs

**Sensor 5:** 100 um diameter – 1 FBG inscribed by Upitt

| Day | Hours | Power (kW) | Furnace Temp. (Celsius) | Notes |
|---|---|---|---|---|
| 1 | 7 | 450 | off/200 | |
| 2 | 7 | 450 | 400/600 | |
| 3 | 7 | 450 | 800 | |
| 4 | 4 | 450 | 900 | 4 hours, some hours for another customer at 5 kw |
| 5-1 | 0 | | 1000 | Fuse blow |
| 5-2 | 7 | 450 | 1000 | |
| 6 | 7 | 450 | 1100 | |
| 7 | 7 | 450 | 1200 | |
| 8 | 7 | 450 | 1300 | |
| 9 | 7 | 450 | 1400 | |
| 10 | 7 | 450 | 1.5 hrs at 800, 2 hrs at 1000, 2 hrs at 1200 | |
| 11 | 7 | 450 | 1400 1 hr at 1500 | Fuse blow during heating |
| 12 | 6 | 450 | 1500 1 hr at 1600 | |

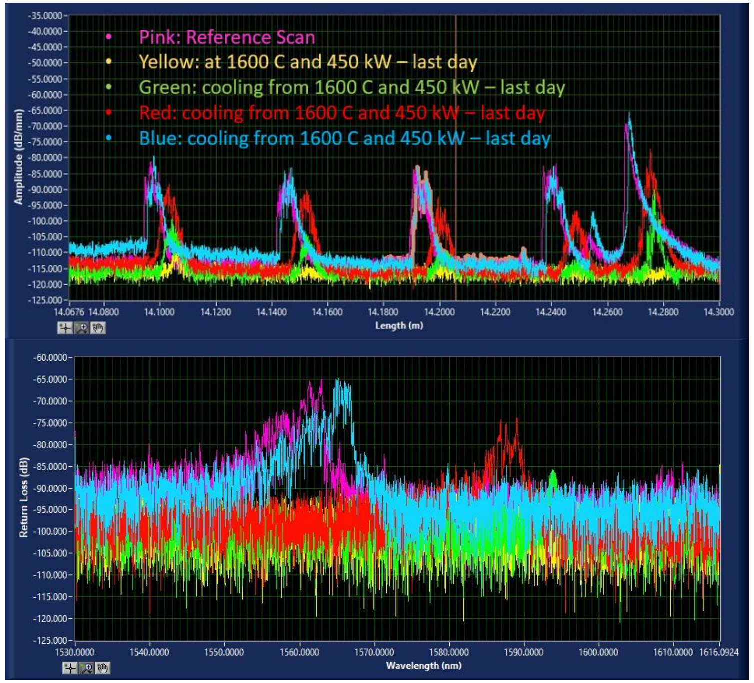


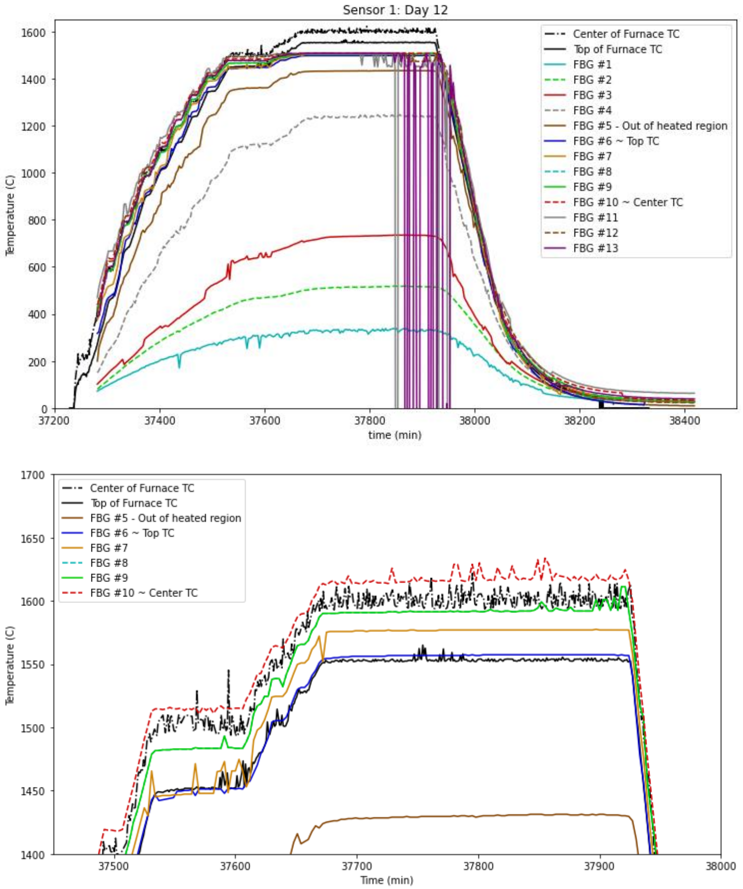
# High Temperature Irradiation

- Similar failure mechanism was observed at 1600ºC in-pile as was observed in out of pile testing.
- After signal loss and amplitude reduction, the FBGs recover as the fiber cools to room temperature
- Like the furnace test, iterative referencing helped maintain the measurement


Backscatter profile and wavelength response of FBG #12 for sensor #1 for the last day of **irradiation heating**.




Backscatter profile and wavelength response of FBG #12 for sensor #1 for the last day of **irradiation cooling**.




**Top:** No iterative referencing
**Bottom:** With iterative referencing



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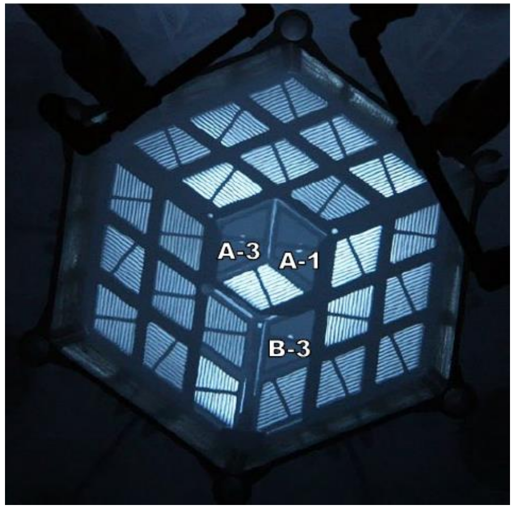
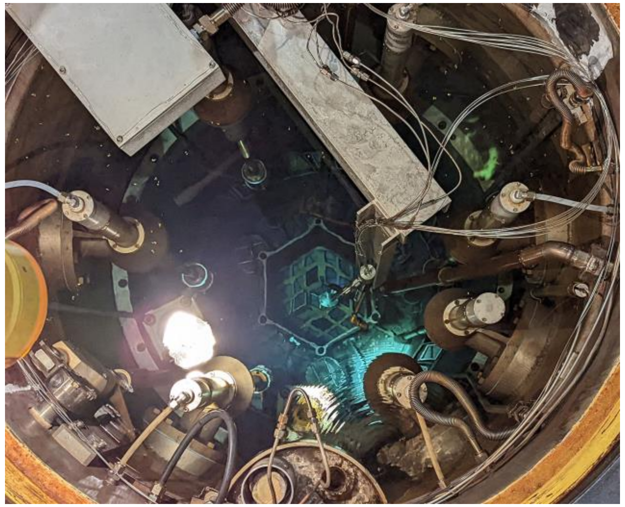
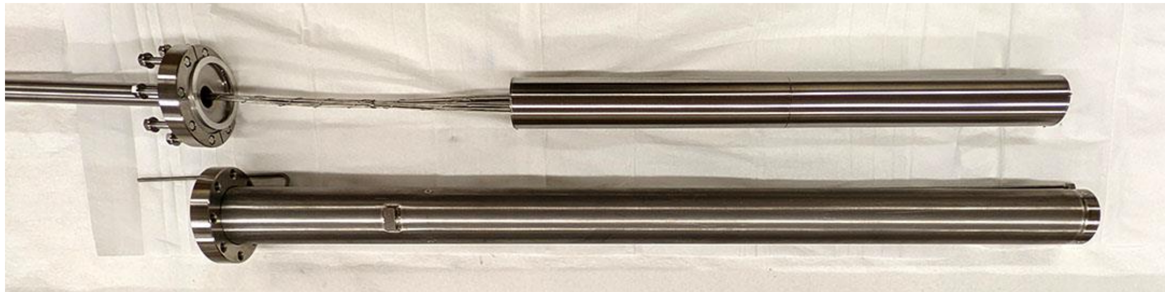
# High Fluence Irradiation

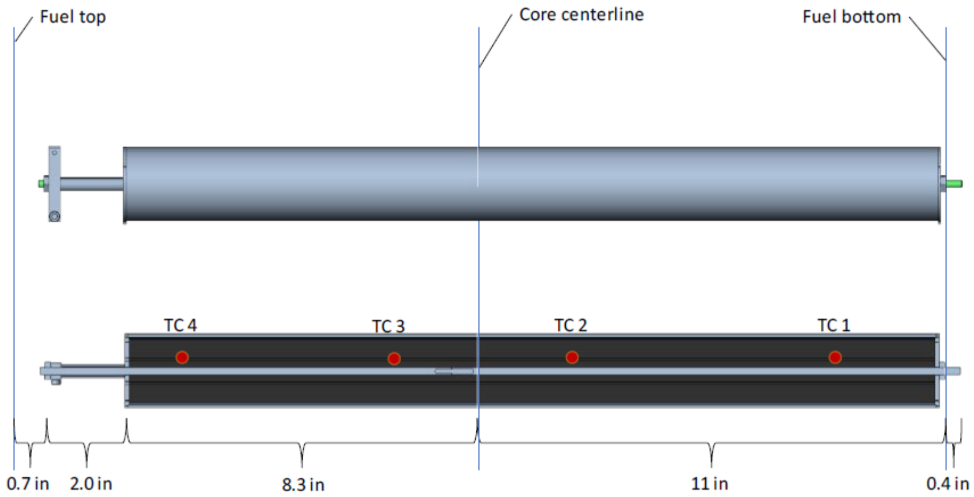
**MITR Irradiation**

- 2 Cycles
- 5 Sapphire Sensors
  - (1) 75 um diameter fibers
  - (2) 100 um diameter fibers
  - (2) 125 um diameter fibers
- In-Core Sample Assembly in Position A-1





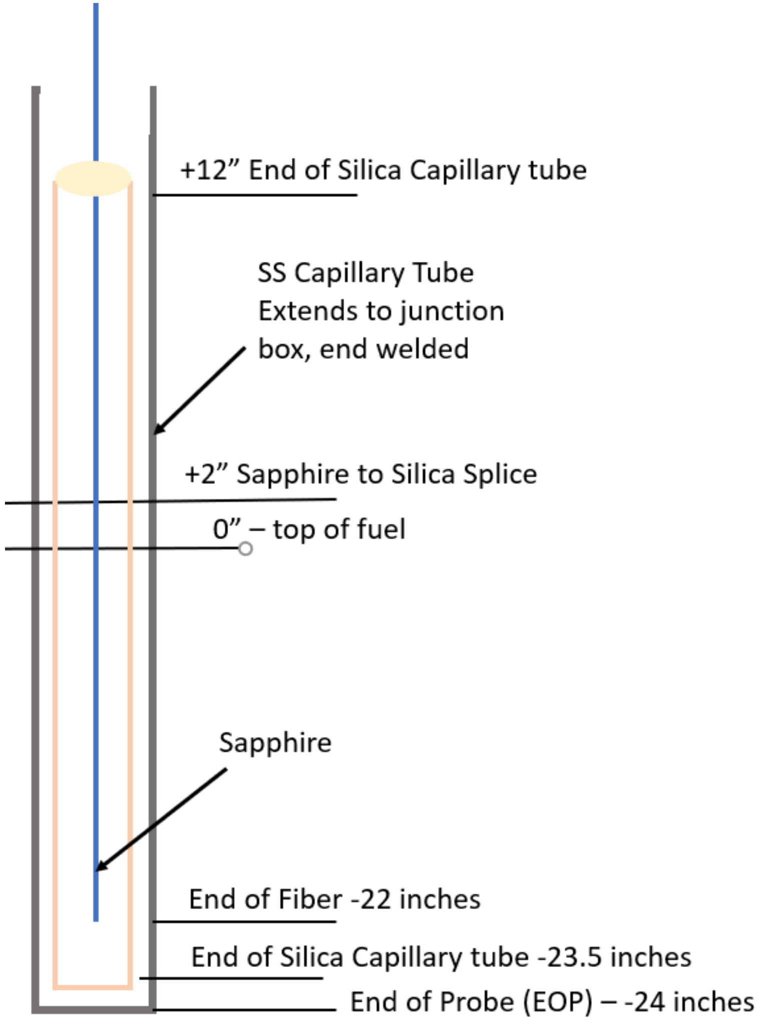



| | Fluence (1/cm$^2$) | Exposure (MGy) |
|---|---|---|
| Total Neutron | 1.6E+21 | |
| Thermal Neutron (< 1 eV) | 2.3E+20 | |
| Fast Neutron (>0.1 MeV) | 7.6E+20 | |
| Fast Neutron (>1 MeV) | 3.5E+20 | |
| Gamma | 1.6E+21 | 1.9E+04 |

# High Fluence Irradiation

Sensors prepared and provided to MITR in preparation for irradiation

- **5 Sapphire sensors**
  - 125, 100, and 75 um diameter fibers with inscribed FBGS
  - Clad, and annealed
  - Placed in silica microcapillary tubes to prevent any material interaction
  - All treated with a mode-stripping spot treatment



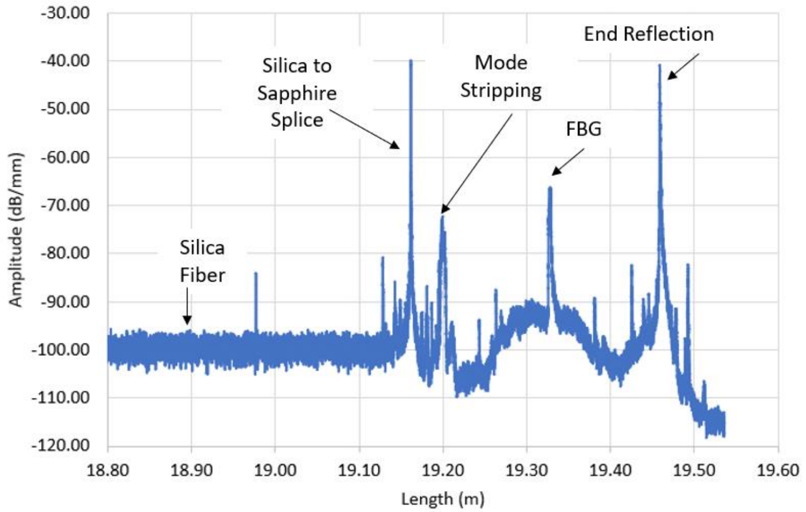
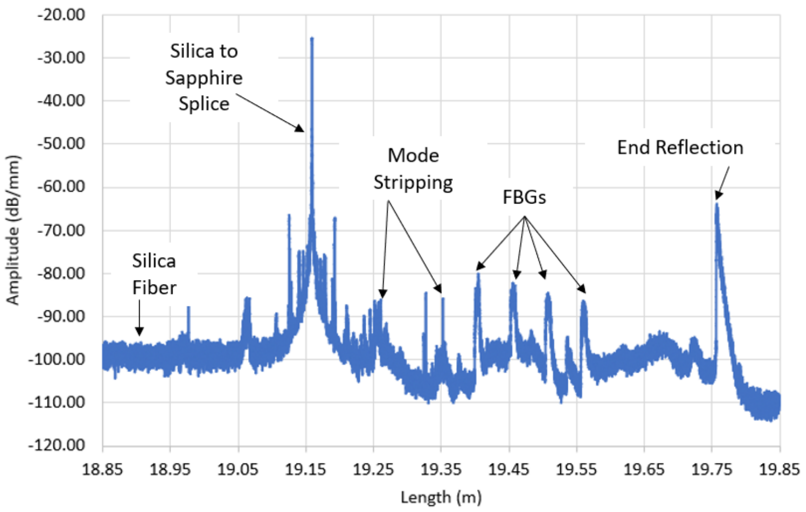




Figure 193: Sensor 3, 100 um diameter with 1 FBG inscribed by U. Pitt, 14 inches long, before installation in the experiment capsule.

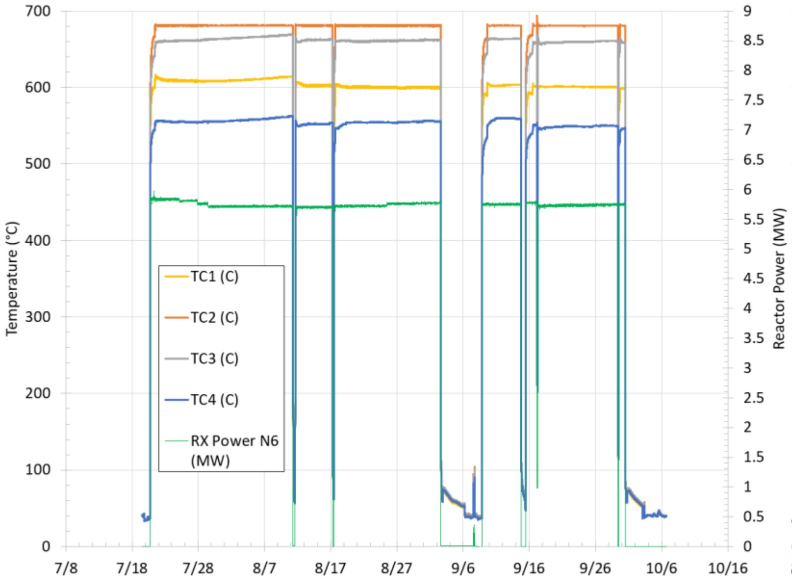



Sensor 4, 125 um with 4 FBGs inscribed by FemtoFiber Tec, 22 inches long, before installation in the experiment capsule.

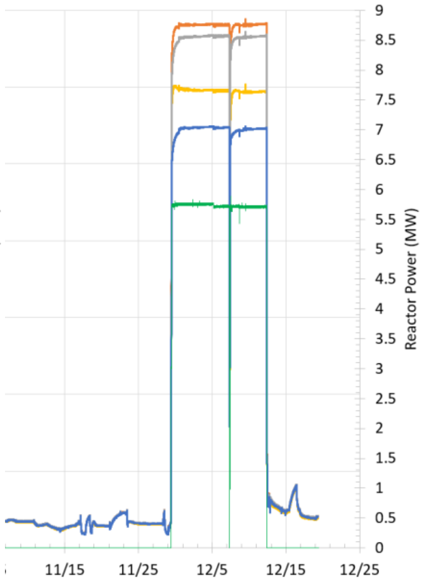
# High Fluence Irradiation

- 2 Cycles in-core
- Temperatures in capsule ranging from approximately 550ºC-680ºC
- Sensors 1 and 2 were broken upon installation

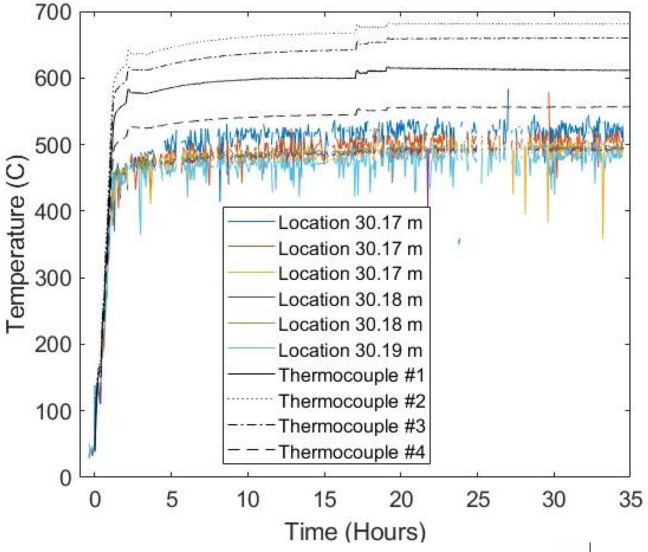
**Cycle 1**




**Cycle 2**

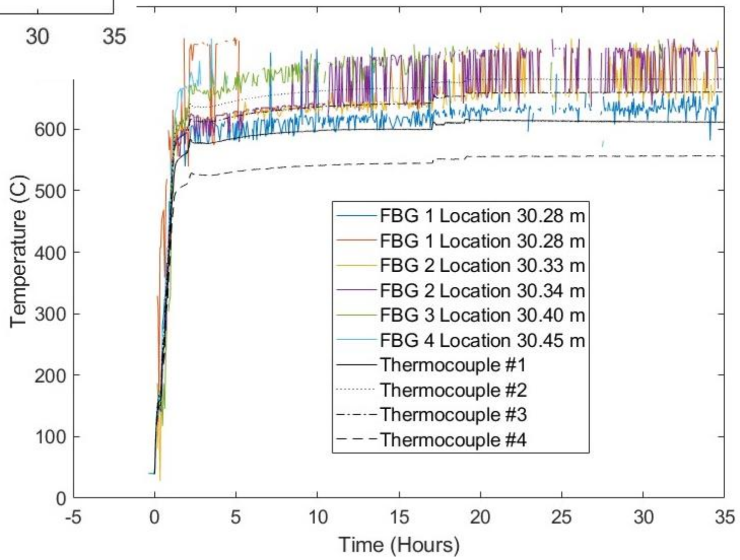



**Sensor 4, no re-referencing**




- OFDR referencing was noisy
- This consistent with previous observations of larger diameter sapphire fibers

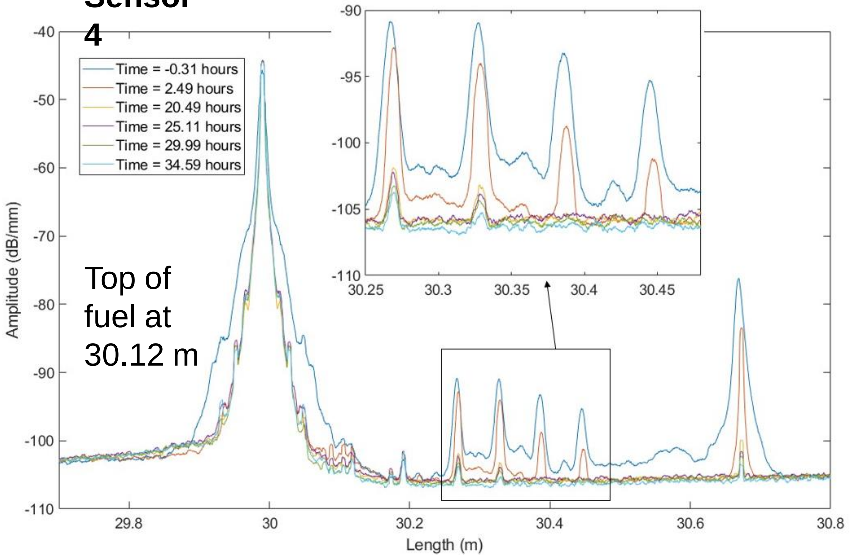
**Sensor 3, with re-referencing**



# High Fluence Irradiation

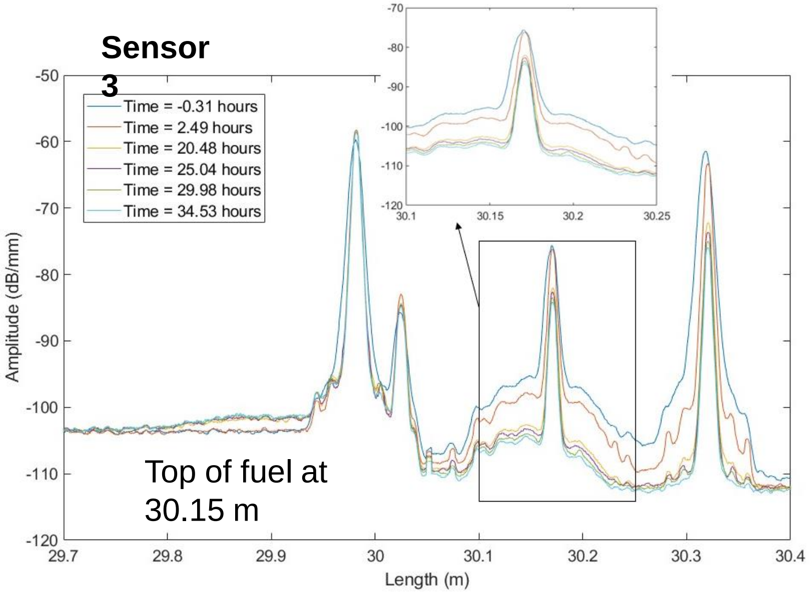
- Significant amplitude reduction during the initial reactor start-up
- Reduction in amplitude was larger in the 125 um fibers than 100 um fibers
- Normalized amplitude shows a faster reduction in amplitude the further away from the silica splice
  - Expected due to increase temperature and flux

**Sensor 4**

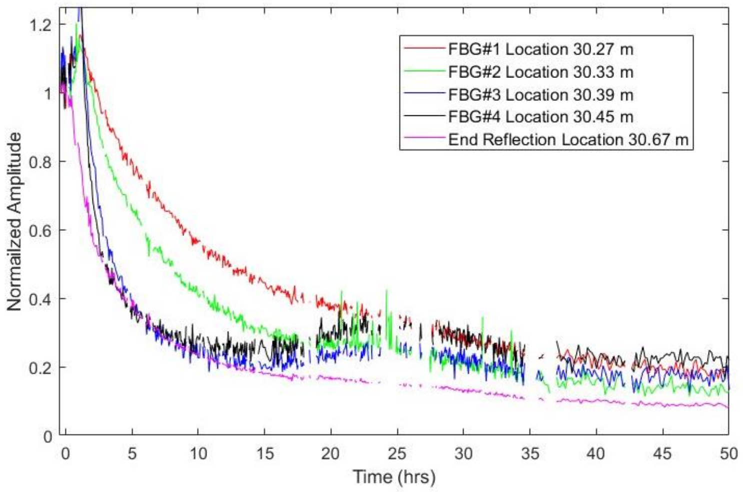


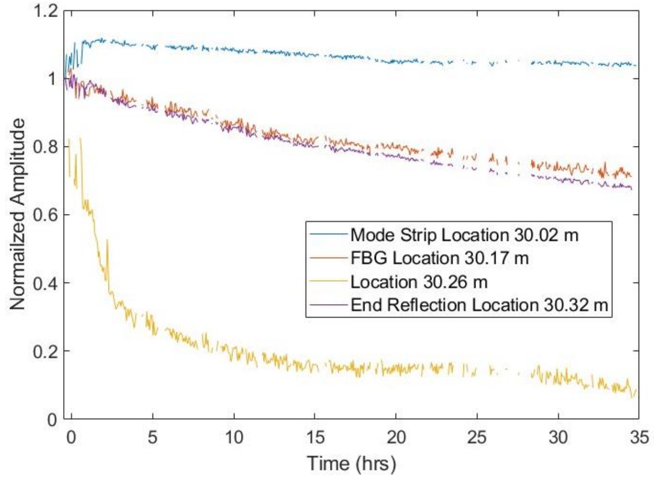

Top of fuel at 30.12 m

**Sensor 3**



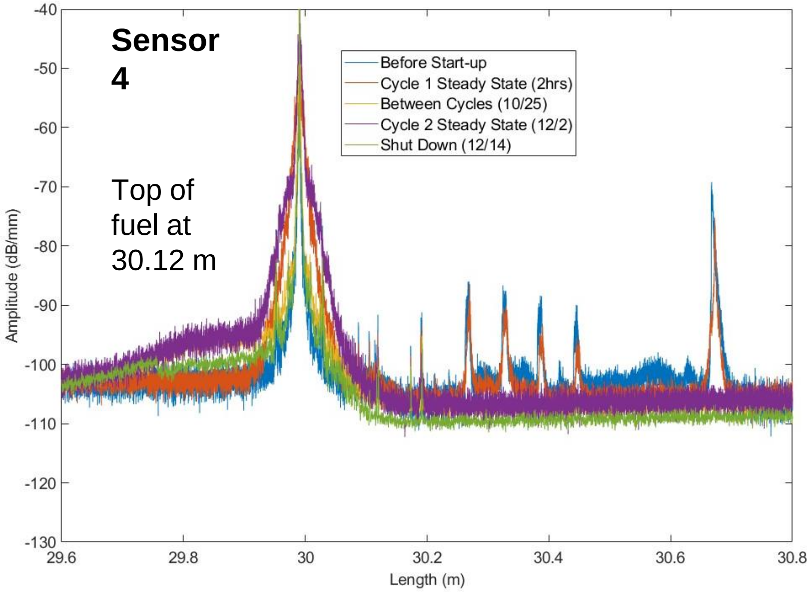

Top of fuel at 30.15 m

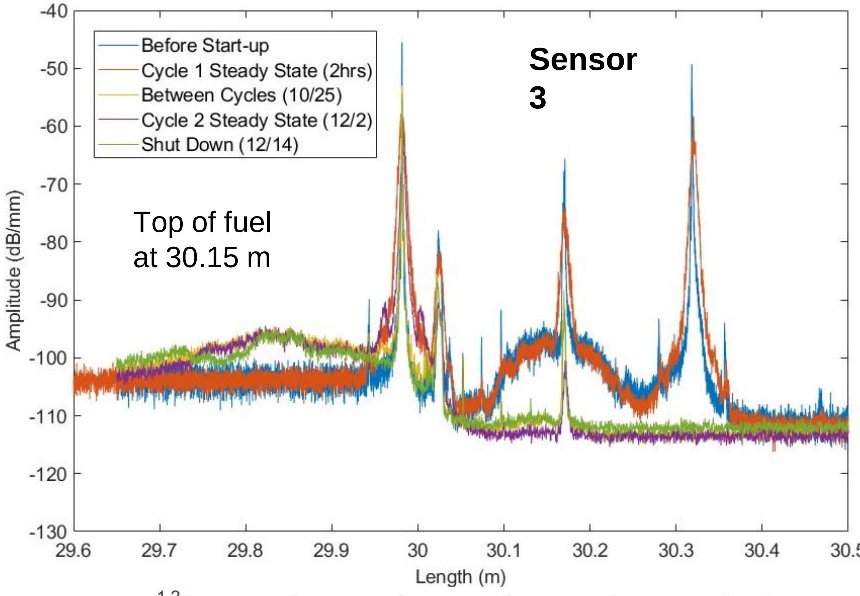


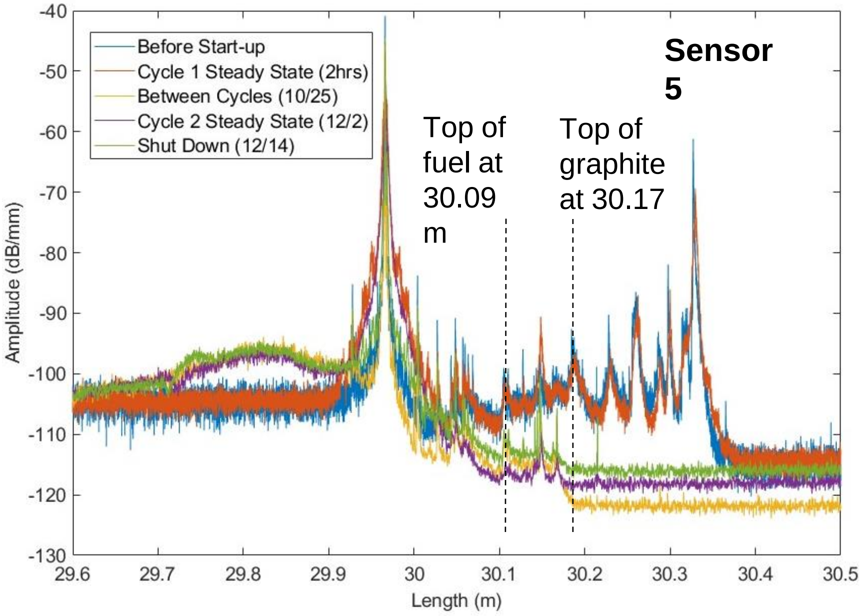



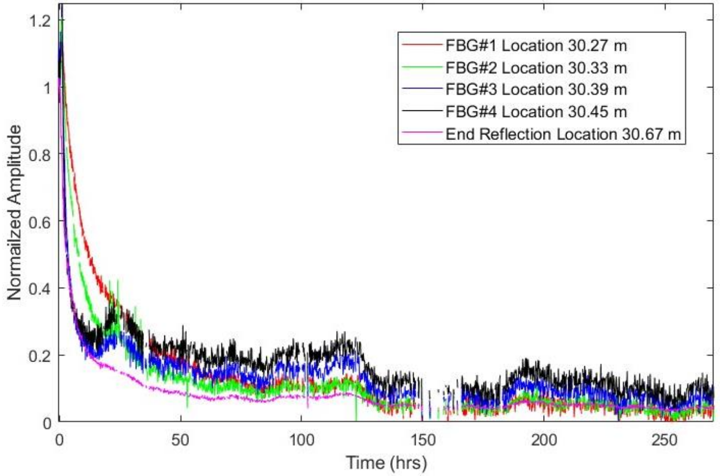
# High Fluence Irradiation

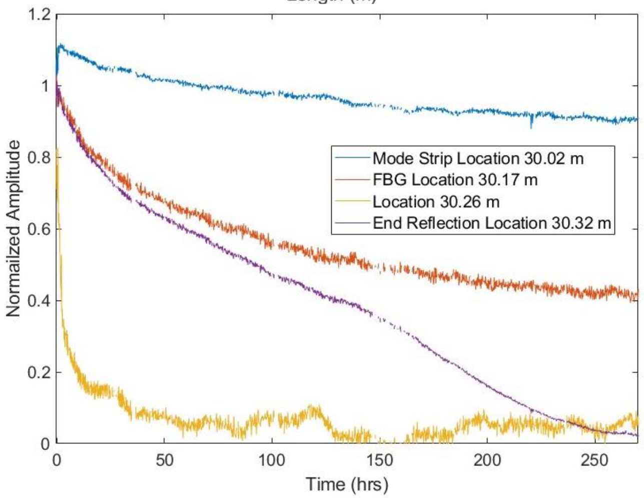
- Signal loss did not recover with reduced temperature
- Temperature appears to have a significant impact on attenuation



# Conclusions

**This work provides a path to deployment for optical fiber-based sensors, including:**

- The technology of clad sapphire optical fiber sensors was advanced through thermal testing up to 1700℃, where previous work had tested up to 1300℃.

- The sensing performance of sapphire optical fibers at high temperatures under irradiation was evaluated up to 1600℃
  - The results of this work indicate that distributed OFDR sensing in sapphire optical fiber is possible with some conditions.
  - The sapphire fibers must be pre-treated appropriately and have well-written defects inscribed to create a stable Rayleigh backscatter signal.
  - This work indicates that sapphire optical fiber sensors may be a solution for ultra-high temperature applications where traditional silica optical fibers fail.
  - Sapphire sensors are a solution for experiment applications with temperatures above 700℃ for long periods of time, or for experiment applications with any duration above 1000℃. Experiment applications with a low total fluence, such as irradiation in TREAT, would also be a good application of sapphire optical sensors.

Kelly McCary
Research Scientist, Radiation Measurements
Idaho National Laboratory
Kelly.Mccary@inl.gov
W (208) 533-4885

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