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

ASI Advanced Sensors and Instrumentation

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

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NSUF Nuclear Science User Facilities

Project Overview

- 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 to verify single-mode behavior and determine and characterize light modes supported by optical fibers.
- 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.

- Participants (2023)
  - Idaho National Laboratory: Lead organization
    - Dr. Joshua Daw, Kelly McCary
  - The Ohio State University
    - Dr. Thomas Blue, Josh Jones, NRL
  - The Massachusetts Institute of Technology
    - NRL

FY2020		Status	Scheduled	Actual	Notes
Task 1	Clad Sapphire Optical fiber	Complete	January 2020	March 2021	Delayed due to procurement of sapphire fibers
Task 2	Characterize Sapphire Fiber	Complete	June 2020	April 2021	Delayed -covid travel restrictions
Task 3	OSURR Irradiation	Complete	October 2020	April 2021	Delayed -covid travel restrictions
	Deliverable 1: Sapphire Fibers	Complete	September 2020	March 2020	
	Deliverable 2: FY20 Annual Report	Complete	September 2020	September 2020	
FY2021					
Task 2	Characterize Sapphire Fiber	Complete	June 2020	April 2021	Delayed -covid travel restrictions
Task 3	OSURR Irradiation	Complete	October 2020	April 2021	Delayed -covid travel restrictions
Task 4	Data Analysis: OSURR Data	Complete	May 2022		
Task 5	MITR Irradiation	Complete	July 2022	TBD	Pushed by Facility
	Deliverable 1: Experimental Data	Complete	September 2021	April 2021	
	Deliverable 2: FY21 Annual Report	Complete	September 2021	September 2021	
FY2022					
Task 4	Data Analysis: MITR	Complete	September 2022	October 2022	
Task 5	MITR Irradiation	Complete	July 2022	July-December 2023	Pushed by Facility
	Deliverable 1: Journal Paper	Drafted	March 2022	In Progress	
	Deliverable 2: Final Report	Ongoing	March 2022	October 2023	

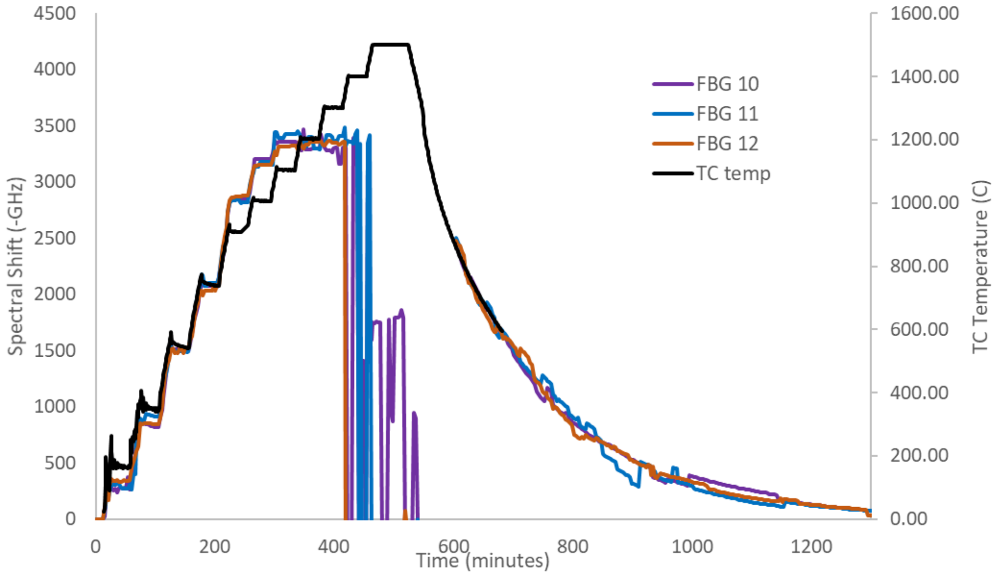
Technology Impact

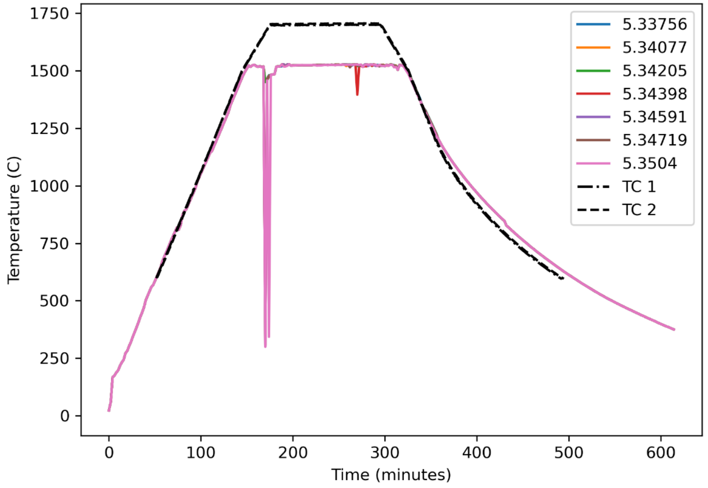
- This work is advancing nuclear technology by characterizing and demonstrating a new sensor technology with the potential to make measurements with high spatial and temperature resolution at higher temperatures than prior optical sensors. This technology can also be applied to measurements other than 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.

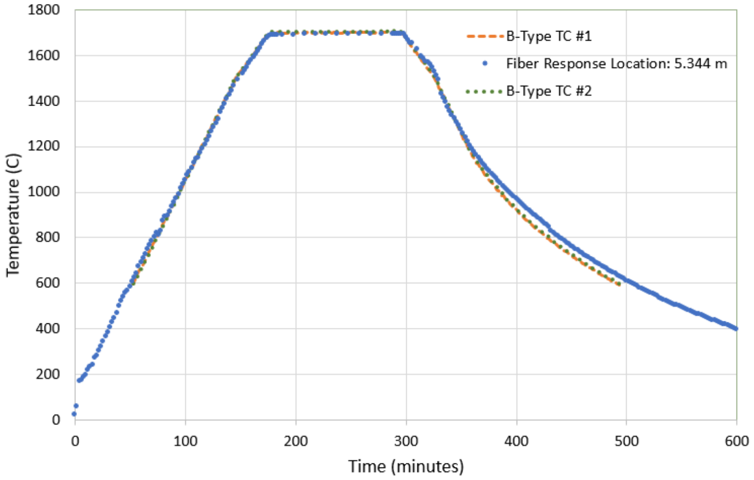
Previous Results: Out of Pile Testing

Two thermal tests were completed with clad sapphire fiber:

- 8 in. heated region
- 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 1500ºC
- When the furnace was heated past 1100ºC, the sensing mechanism failed
  - Attenuation and exceeded range of OBR
- Test 2: to 1700ºC – success with iterative referencing

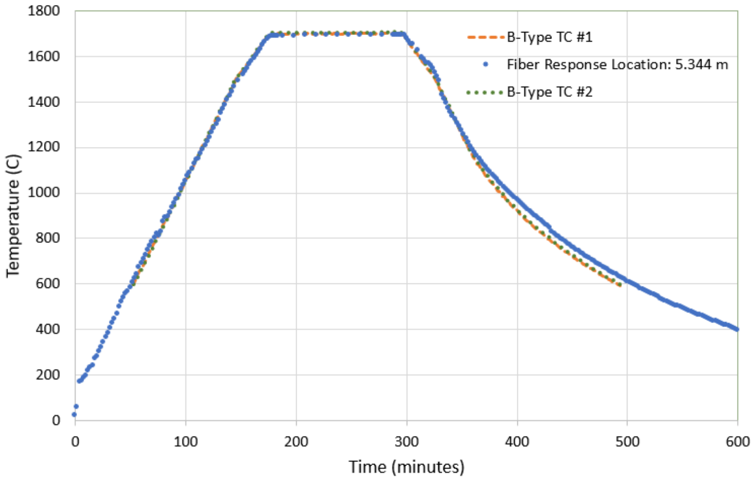


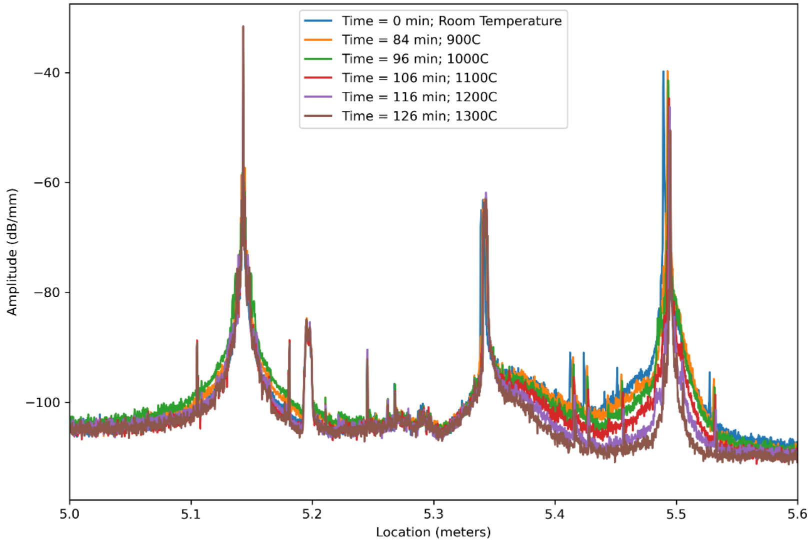


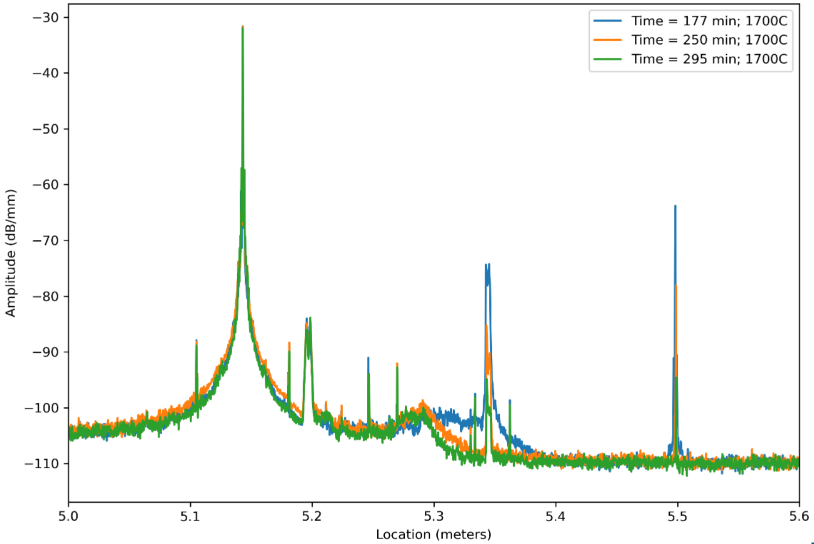


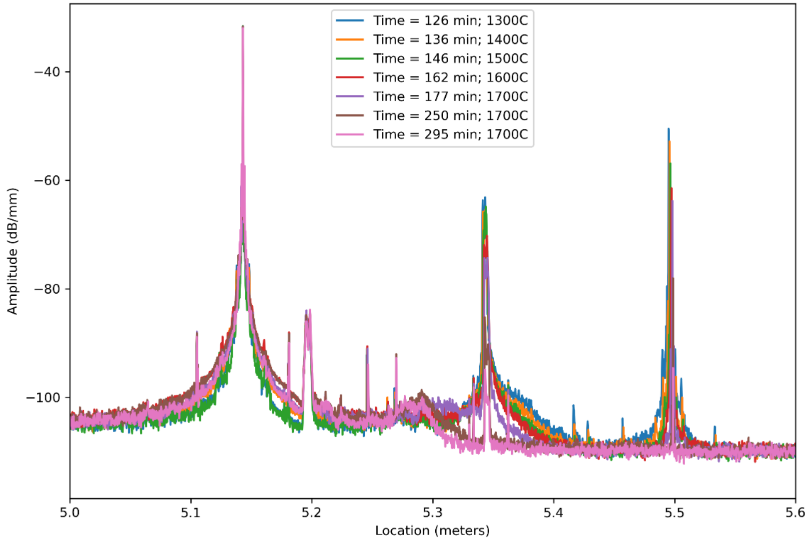
Previous Results: Out of Pile Testing

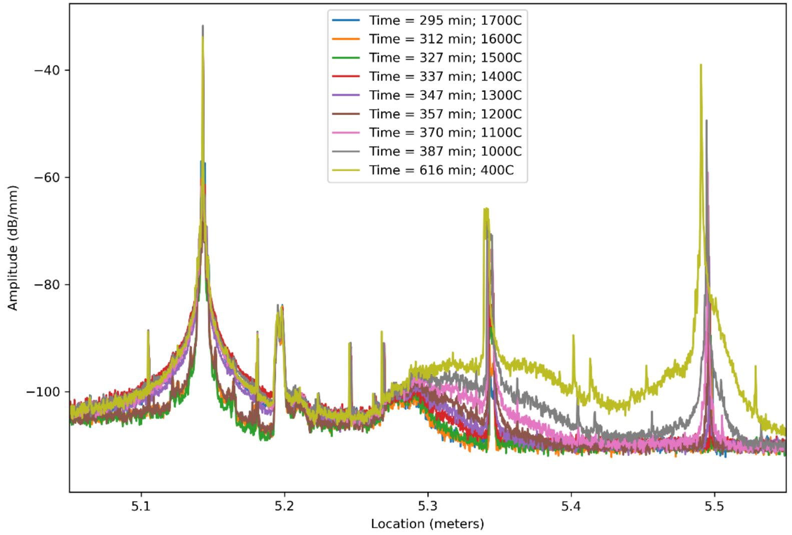
- A reduction in amplitude was observed with increasing temperature and time in both tests
- This reduction recovers completely when the fibers cool





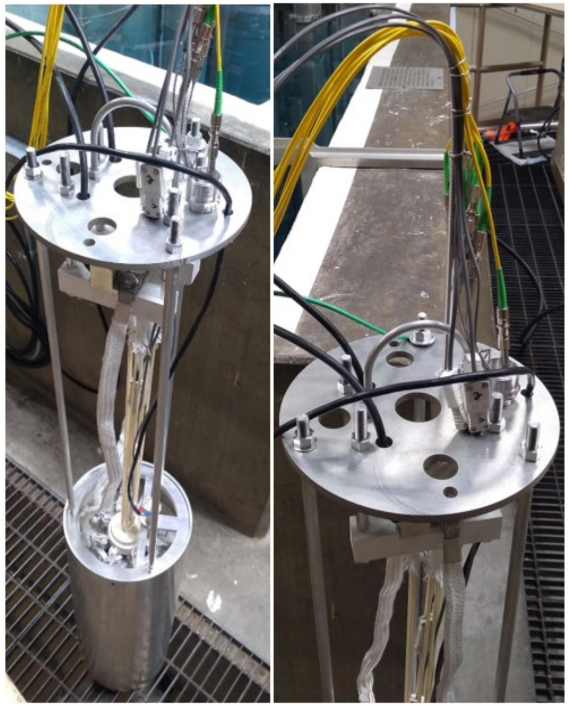






Results: Heated Irradiation

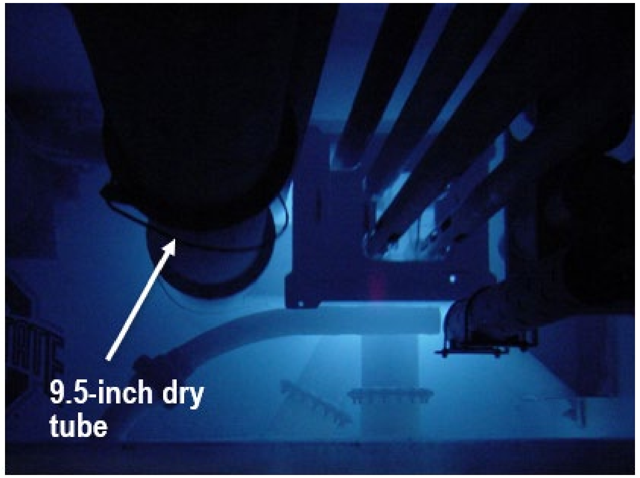
Sensor 1: 75 um diameter – 13 FBGs inscribed by FemtoFiberTec
Sensor 2: 100 um diameter – 2 FBGs inscribed by UPitt
Sensor 3: 100 um diameter – 1 FBG inscribed by Upitt
Sensor 4: 100 um diameter – No FBGs
Sensor 5: 100 um diameter – 1 FBG inscribed by Upitt



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	

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

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

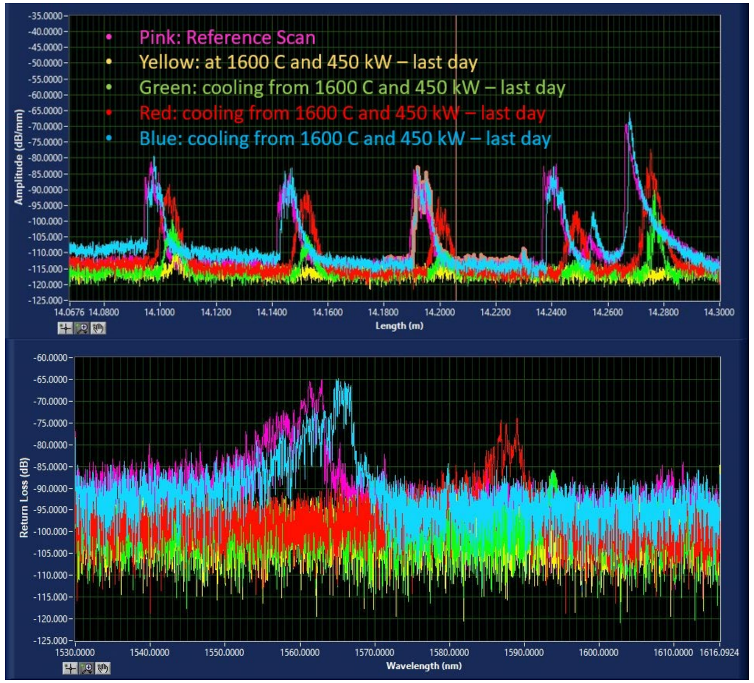


Results: Heated Irradiation

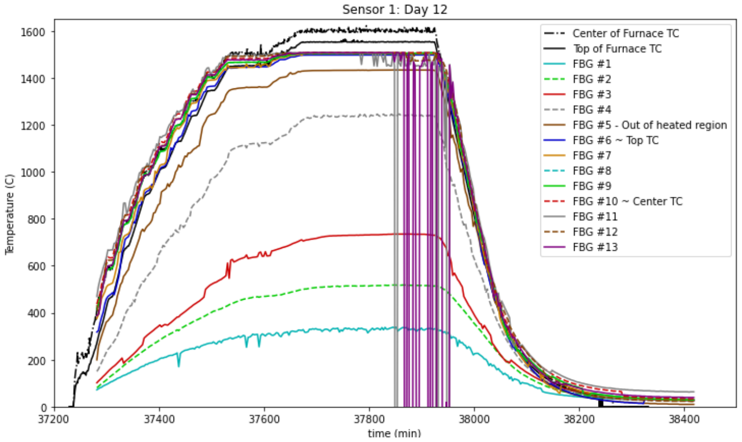
- Similar failure mechanism was observed at 1600ºC in-pile as was observed in out of pile testing. After signal loss and amplitude reduction the FBGs recover as the fiber cools to room temperature
- Like the furnace test, iterative referencing helped maintain the measurement

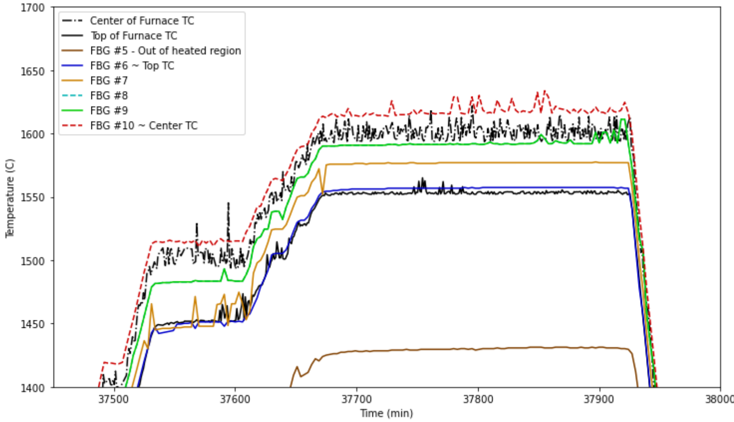
Backscatter profile and wavelength response of FBG #12 for sensor #1 for the last day of irradiation heating.

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



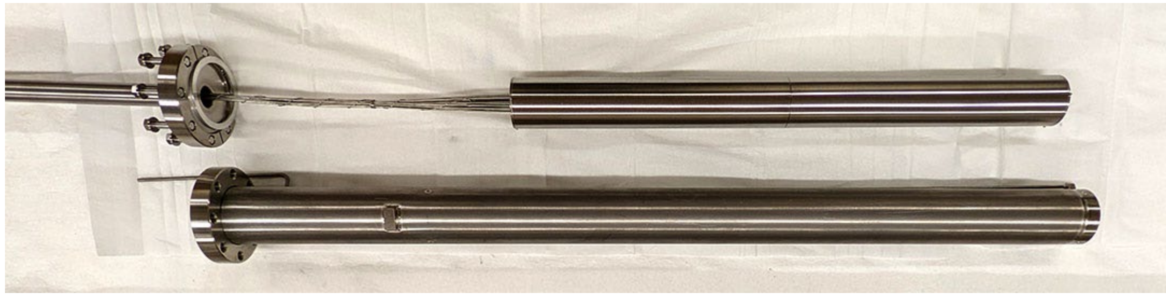
Top: No iterative referencing
Bottom: With iterative referencing

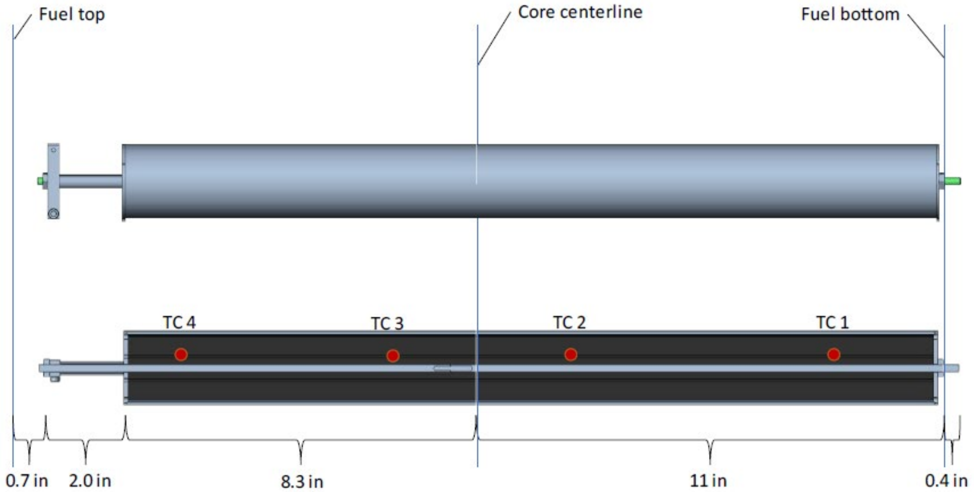




Accomplishments

- MIT Irradiation Complete
  - 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

Accomplishments

- 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

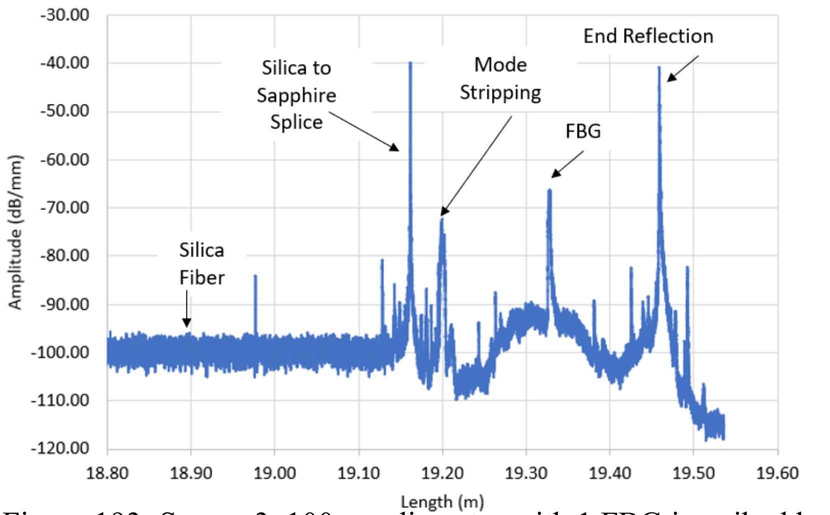
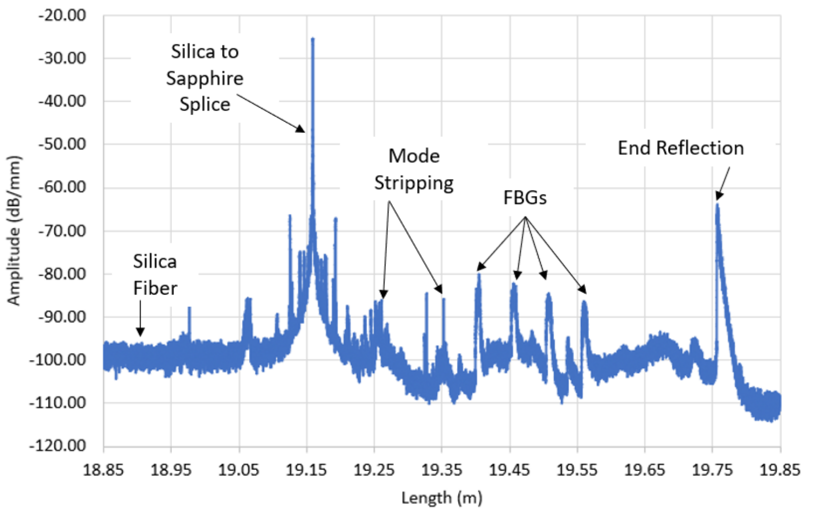
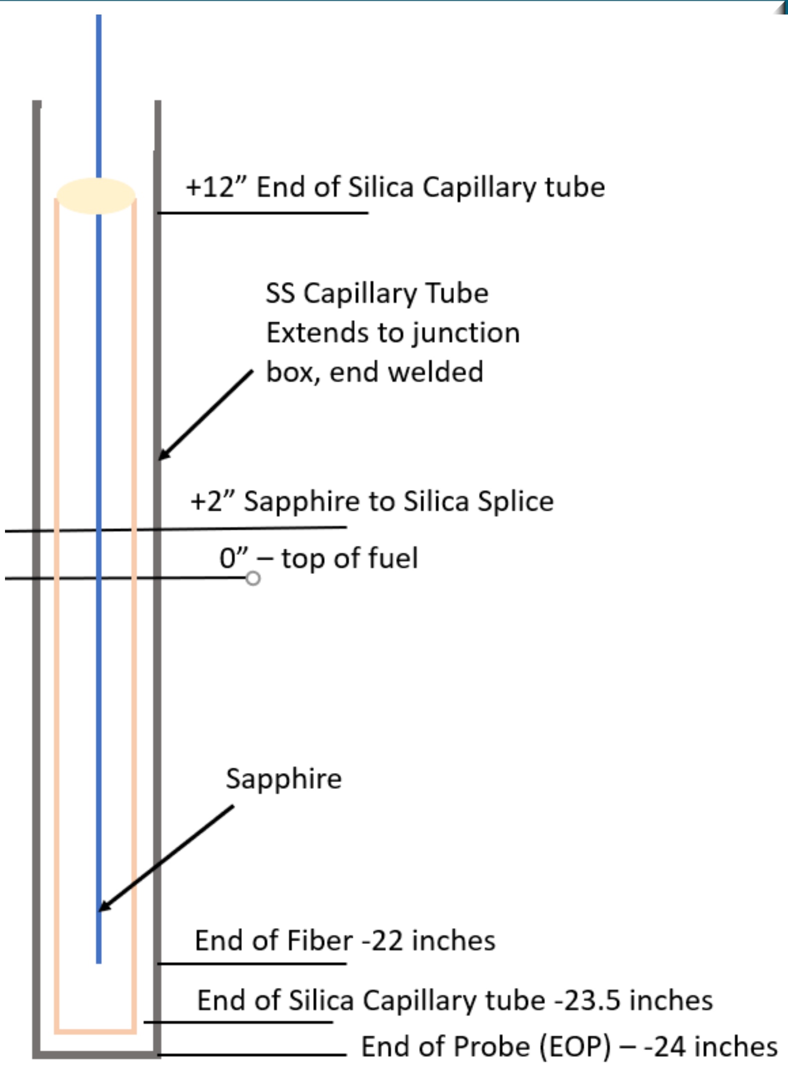


Figure 193: Sensor 3, 100 um diameter with 1 FBG inscribed by U. Pitt, 14 inches long, before installation in the experiment capsule.



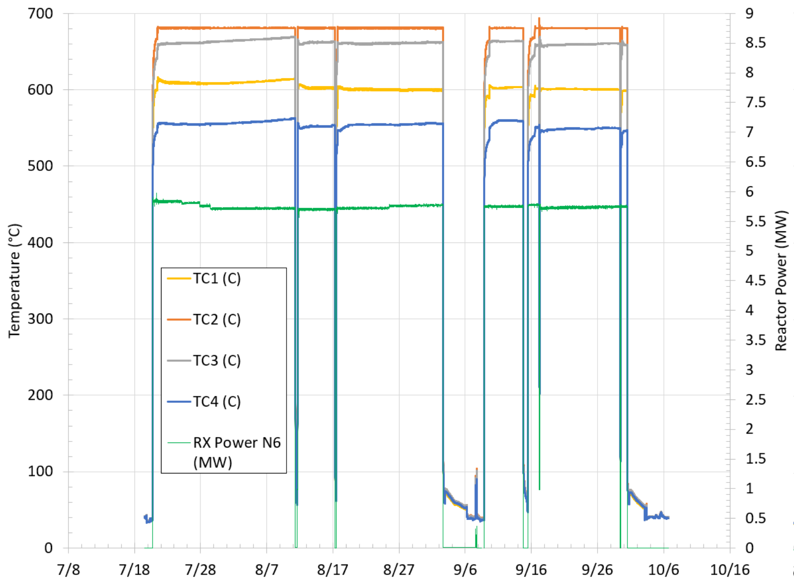
Sensor 4, 125 um with 4 FBGs inscribed by FemtoFiber Tec, 22 inches long, before installation in the experiment capsule.



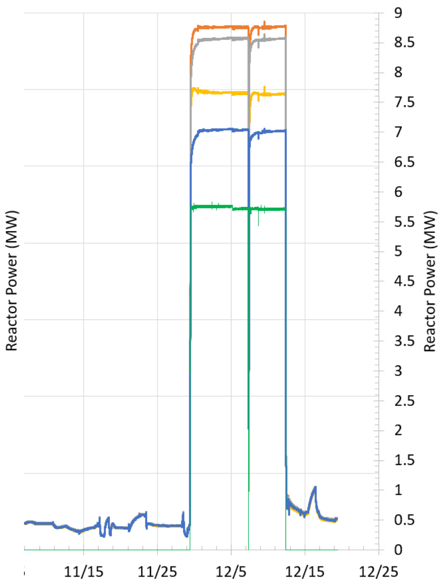
Results: MITR Irradiation

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

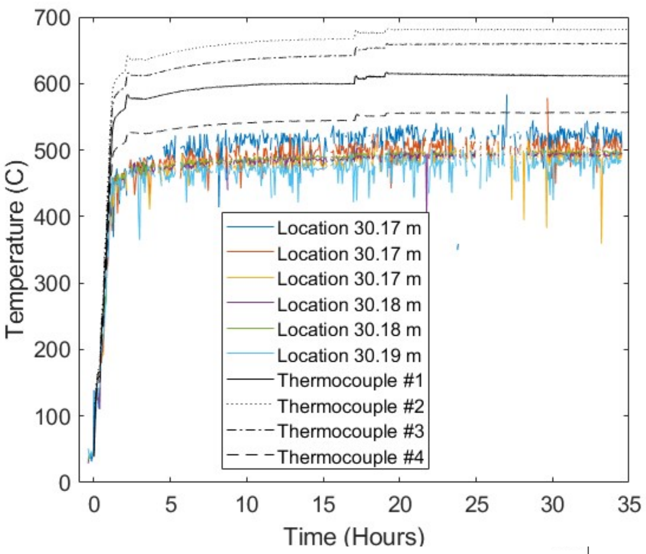
Cycle 1



Cycle 2

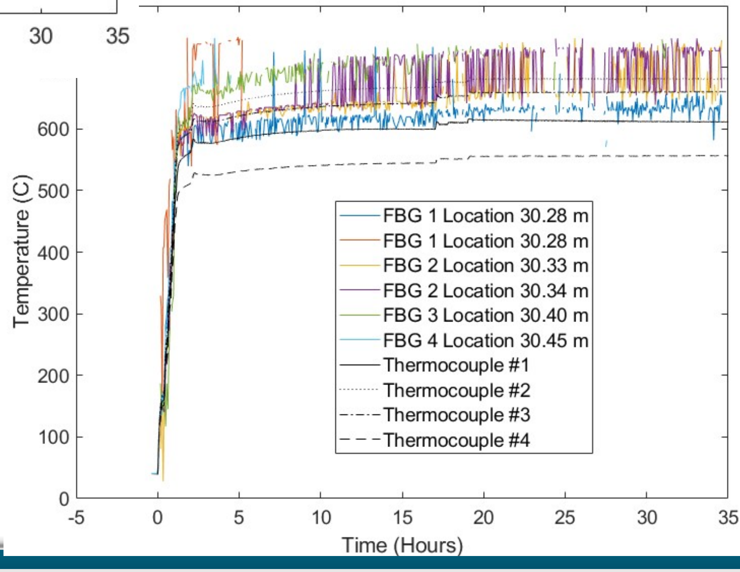


Sensor 4, no re-referencing



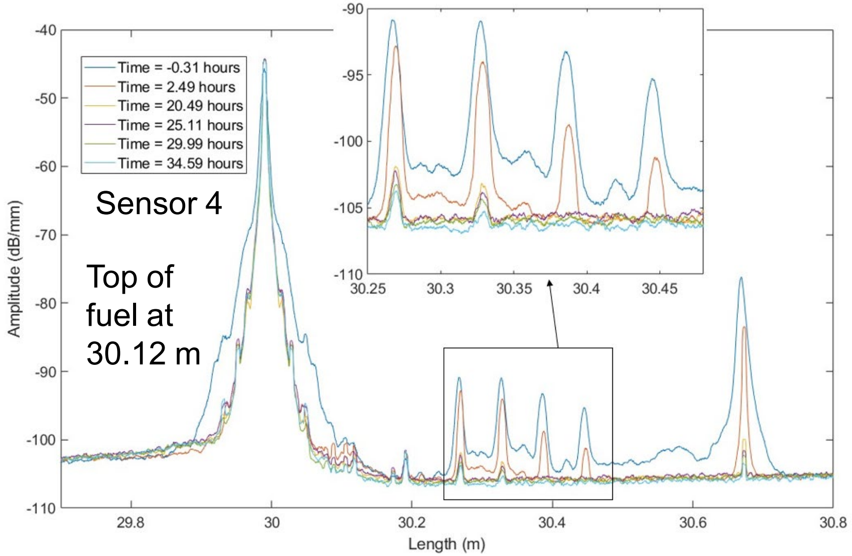
- OFDR referencing was noisy
- This consistent with previous observations of larger diameter sapphire fibers

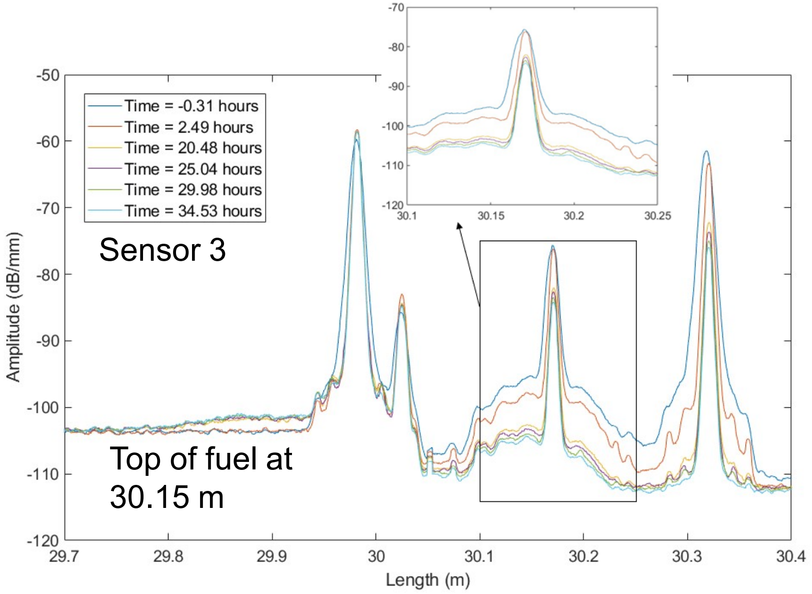
Sensor 3, with re-referencing

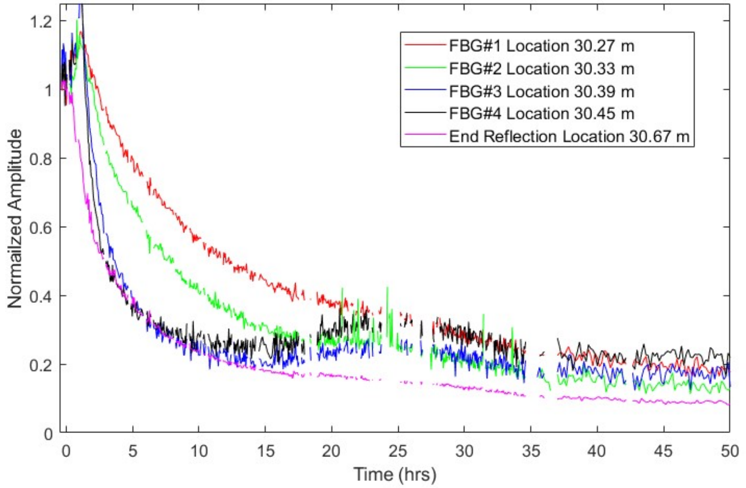


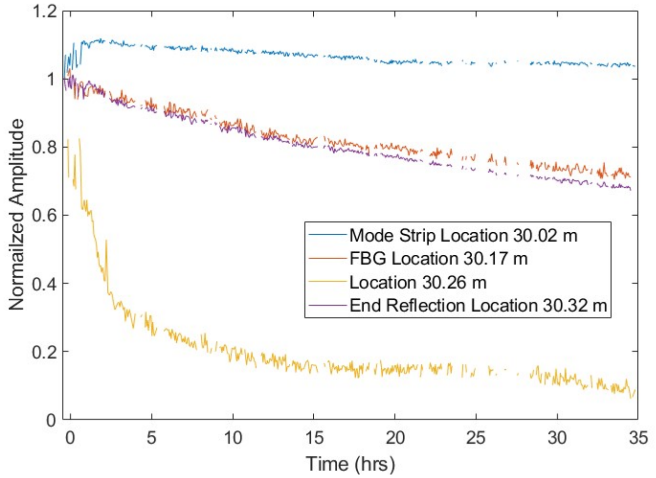
Results: MITR Irradiation

- 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



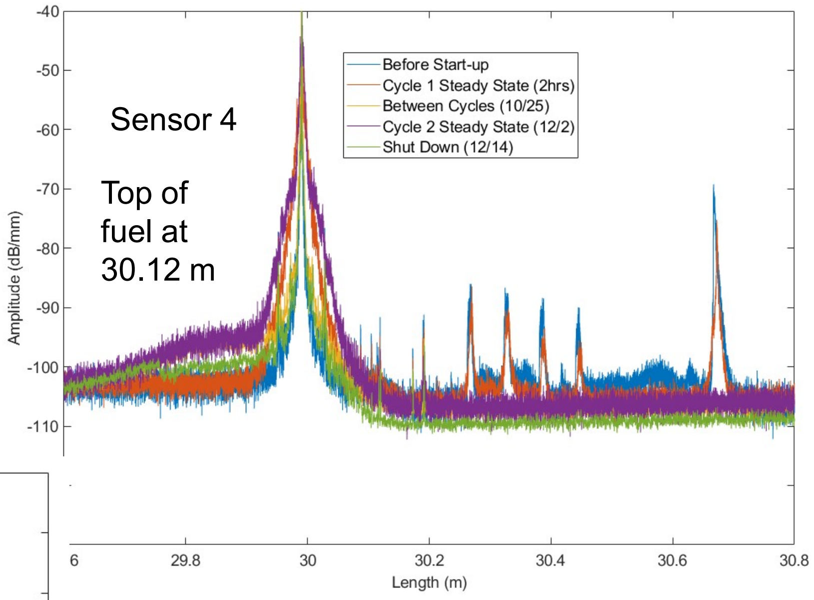


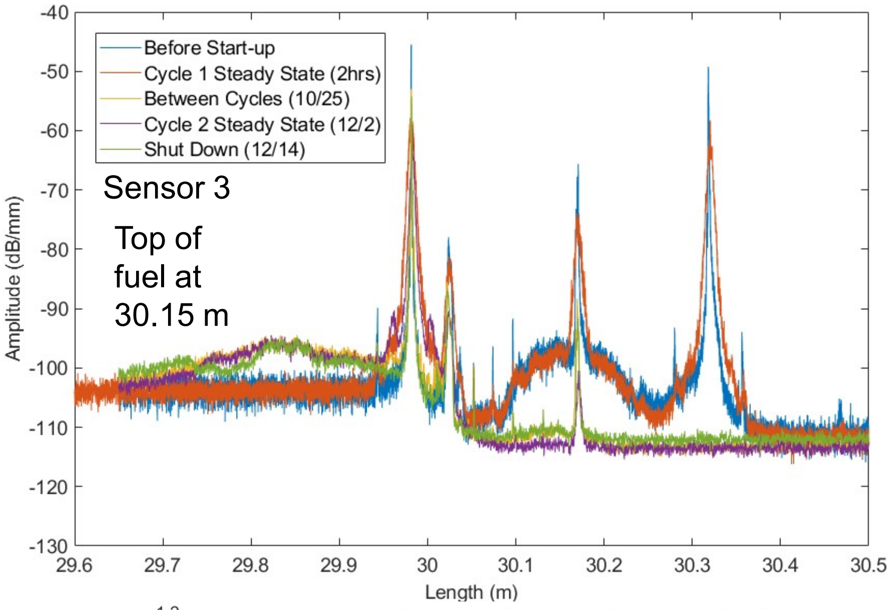


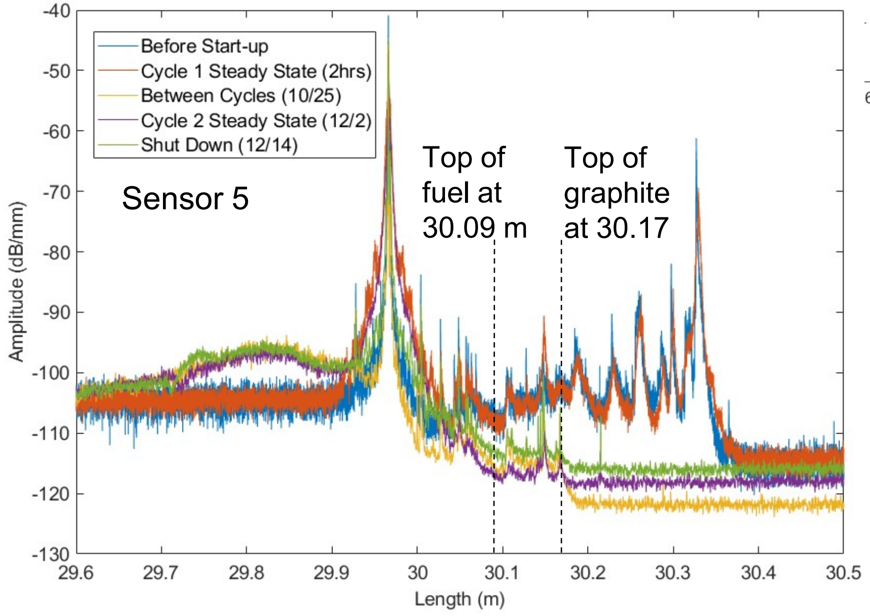


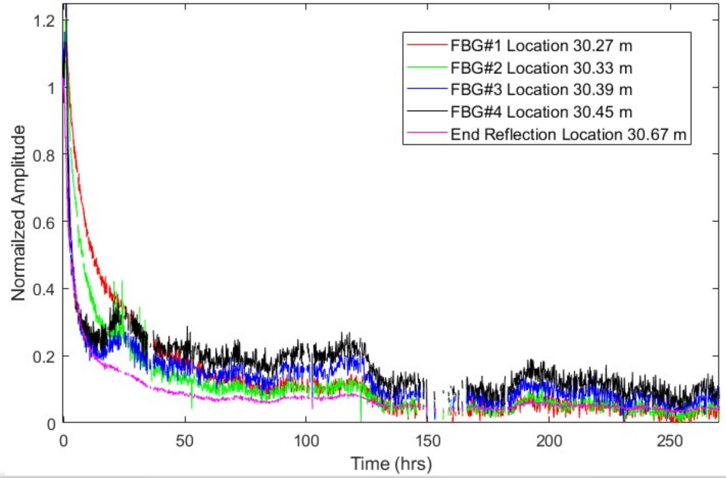
Results: MITR Irradiation

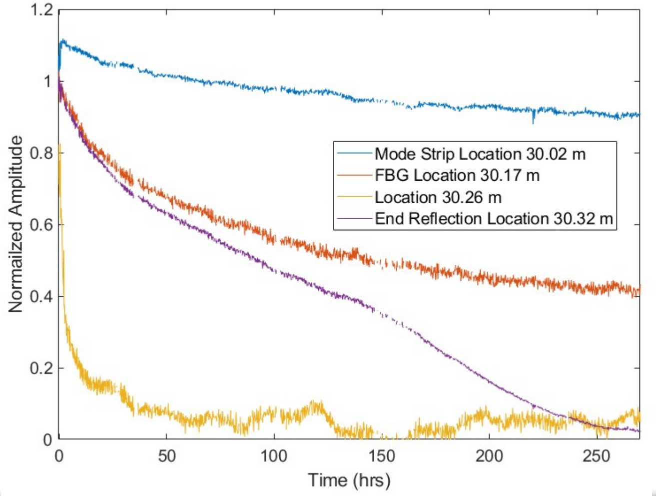
- Signal loss did not recover with reduced temperature
- Temperature appears to have a significant impact on attenuation











Conclusion

Conclusions:

- All objectives have been completed
- Heated irradiation indicates potential for sapphire fiber-based sensors to be used in extreme environments beyond silica fiber temperature limits
- Sapphire optical fiber may not be appropriate for high fluence applications
- Clad sapphire optical fibers have a temperature-dependent attenuation that has not been observed in unclad sapphire
- With the appropriate pre-treatments and data post-processing, sapphire optical fiber has the potential to serve as a distributed sensor up to 1700ºC

Recommended Future Work:

- Further evaluation of clad sapphire fibers to determine source of temperature-dependent attenuation
- Comprehensive evaluation of sapphire optical fiber under irradiation and how the temperature of the irradiation effects the radiation induced attenuation

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