INL/MIS-22-67227-Revision-0

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

May 2022

Changing the World's Energy Future

Kelly M McCary, Joshua E Daw

Idaho National Laboratory

INL/MIS-22-67227-Revision-0

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

Kelly M McCary, Joshua E Daw

May 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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

Kelly McCary, Josh Daw

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 (2022)
  - 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
  - National Energy Technology Laboratory
    - Dr. Michael Buric
  - Oak Ridge National Laboratory
    - Dr. Christian Petrie

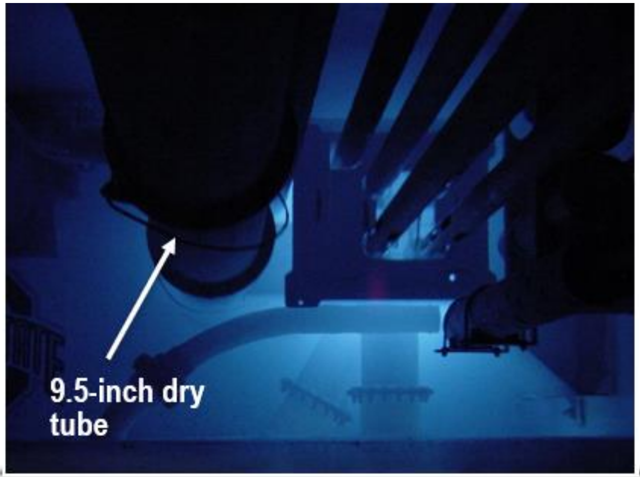
FY2020		Status	Scheduled	Actual	Notes
Task 1	Clad Sapphire Optical fiber	Complete	January 2020	March 2021	Delayed due to procurement of sapphire fibers
Task 2	Characterize Sapphire Fiber	Complete	June 2020	April 2021	Delayed -covid travel restrictions
Task 3	OSURR Irradiation	Complete	October 2020	April 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	On-going	May 2022		
Task 5	MITR Irradiation	Delayed	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	Planned	September 2022		
Task 5	MITR Irradiation	Delayed	July 2022		Pushed by Facility
	Deliverable 1: Journal Paper	Planned	September 2022		
	Deliverable 2: Final Report	Planned	September 2022		

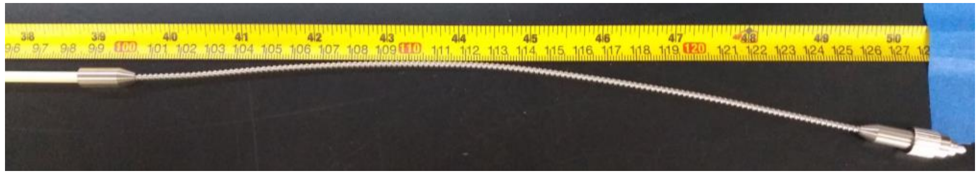
Technology Impact

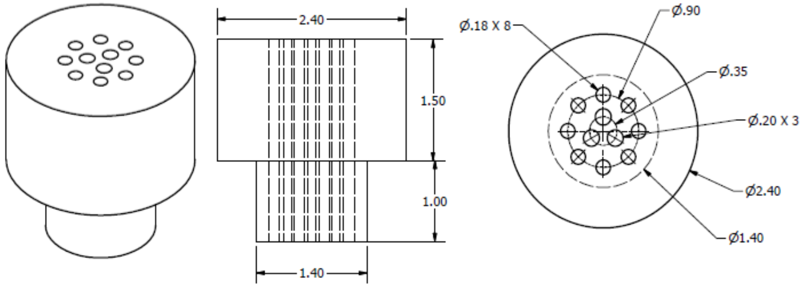
- This work is advancing nuclear technology by characterizing and demonstrating a new sensor technology with the potential to make measurements with high spatial and temperature resolution at higher temperatures than prior optical sensors. This technology can also be applied to measurements other than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

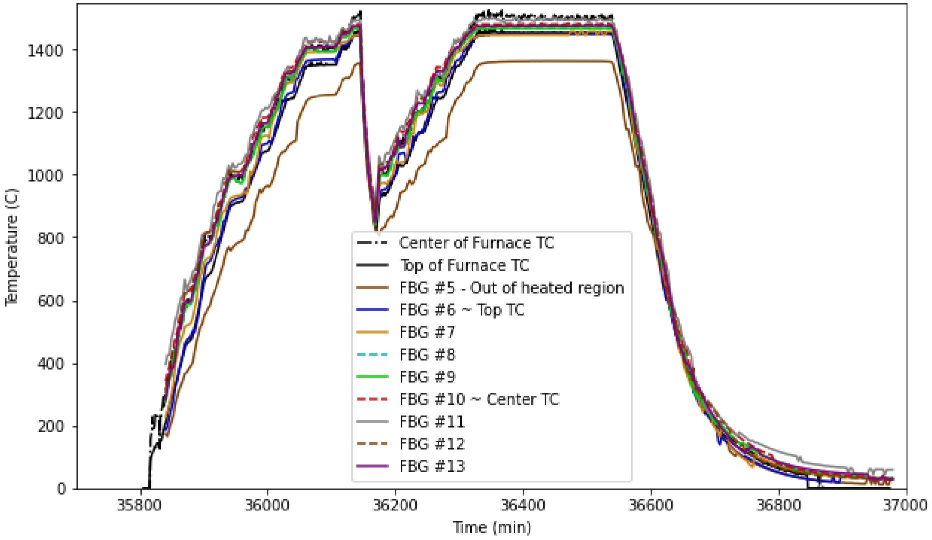
Accomplishments

- Sapphire fiber preparation:
  - Fiber procurement
  - FBG inscription
  - Fiber cladding irradiations
  - Annealing
  - Mode-stripping treatment
- Out of pile furnace testing
- Heated irradiation at OSURR
- MIT Irradiation Ready for insertion









Accomplishments: Sapphire Preparation

Sapphire fiber cladding:

- Four one-day irradiations were completed with the purpose of cladding sapphire fiber
  - Cladding Irradiation #1: Completed January 24, 2019
    - 2 fibers, 100 um OD, with 2 FBGs inscribed by UPitt
    - 1 fiber, 100 um OD, without FBGs
    - 1 fiber, 75 um OD, with 13 FBGs inscribed by FemtoFiberTec
  - Cladding Irradiation #2: Completed March 13, 2020
    - 4 fibers, 100 um OD, each with 1 FBG inscribed by UPitt
  - Cladding Irradiation #3: Completed March 12, 2021
    - 2 fibers, 125 um OD, each with 4 FBGs inscribed by FemtoFiberTec
  - Clad Irradiation #4: Completed March 19, 2021
    - 4 fibers, 125 um OD, each with 4 FBGs inscribed by FemtoFiberTec

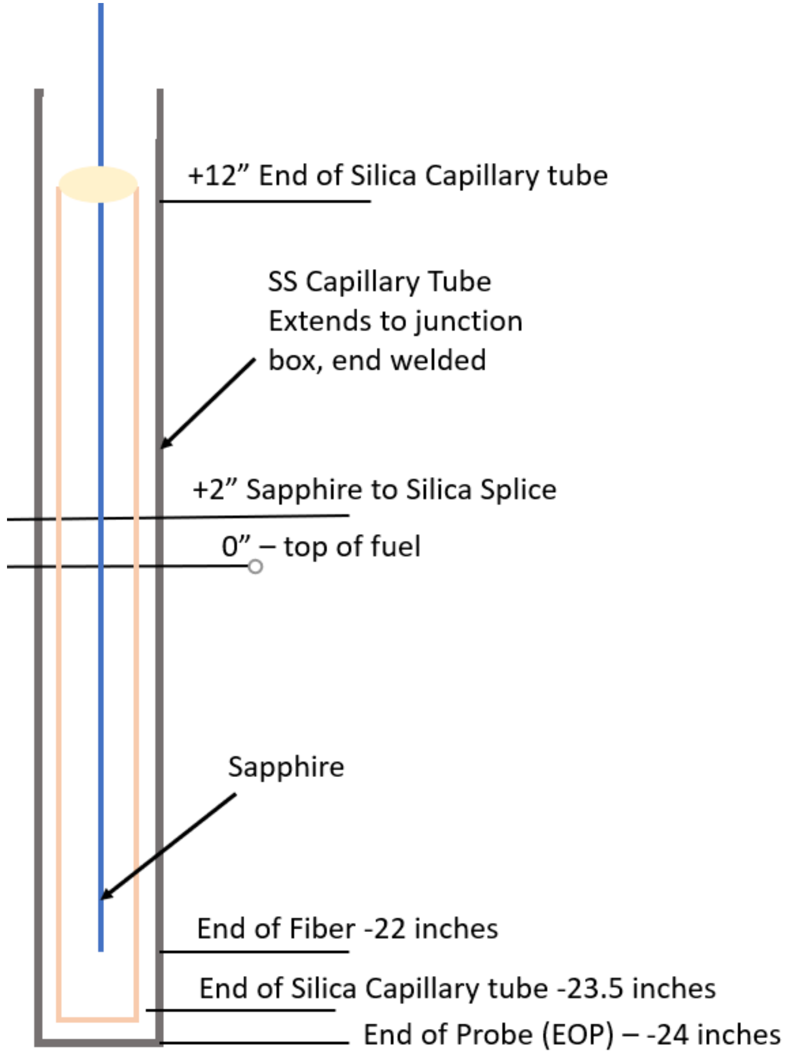
Post-Processing:

- Thermal annealing, polishing and splicing

Challenges: Annealing, Splicing

Accomplishments: MITR Ready for Insertion

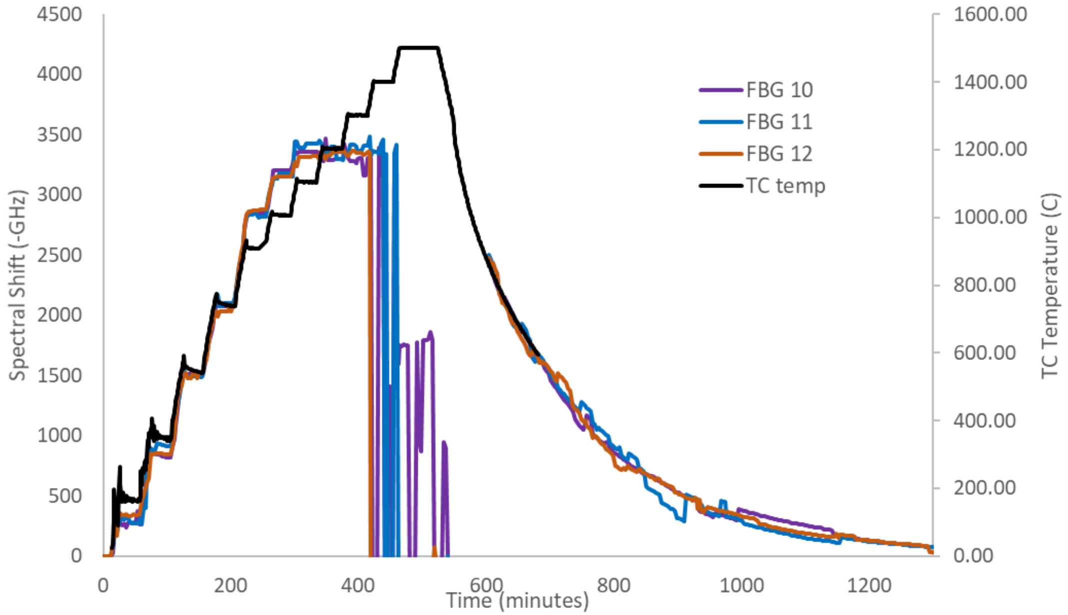
- 8 Sensors prepared and provided to MITR in preparation for irradiation
  - 5 Sapphire sensors
    - 125, 100, and 75 um diameter fibers with inscribed FBGS
    - Clad, and annealed
    - Placed in silica microcapillary tubes to prevent any material interaction
  - 3 Silica Sensors
    - Pure silica core single mode fiber – baseline
    - iXblue and Technica type-II FBGs
    - Active Compensation sensor



Results: Out of Pile Testing

Sapphire optical fiber sensors were tested in a box furnace at up to 1500ºC prior to deployment in OSURR

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



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

Results: Heated Irradiation

Sensor 1: 75 um diameter – 13 FBGs inscribed by FemtoFiberTec
- Annealed to 1500˚C in air, 23.5 in. long

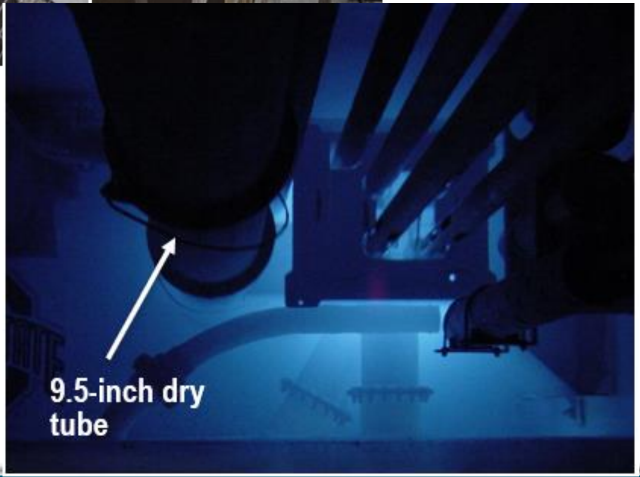
Sensor 2: 100 um diameter – 2 FBGs inscribed by UPitt
- Annealed to 1500˚C in air, 13 in. long

Sensor 3: 100 um diameter – 1 FBG inscribed by Upitt
- Annealed to 1200˚C in air, 15.25 in. long

Sensor 4: 100 um diameter – No FBGs
- Annealed to 1500˚C in air, 9.25 in. long

Sensor 5: 100 um diameter – 1 FBG inscribed by Upitt
- Annealed to 1500˚C in air, 16.25 in. long

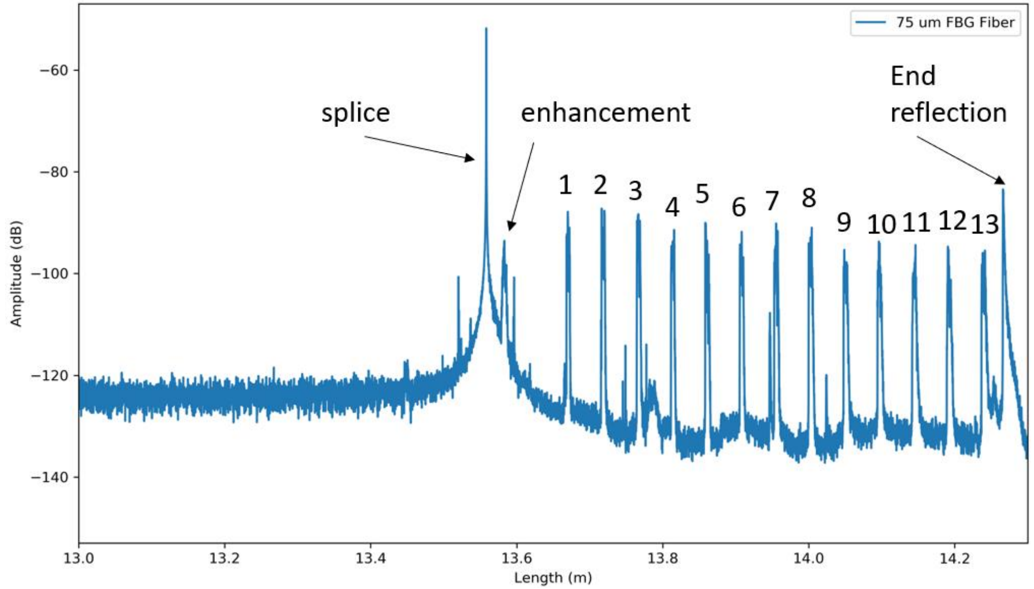


Results: Heated Irradiation

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

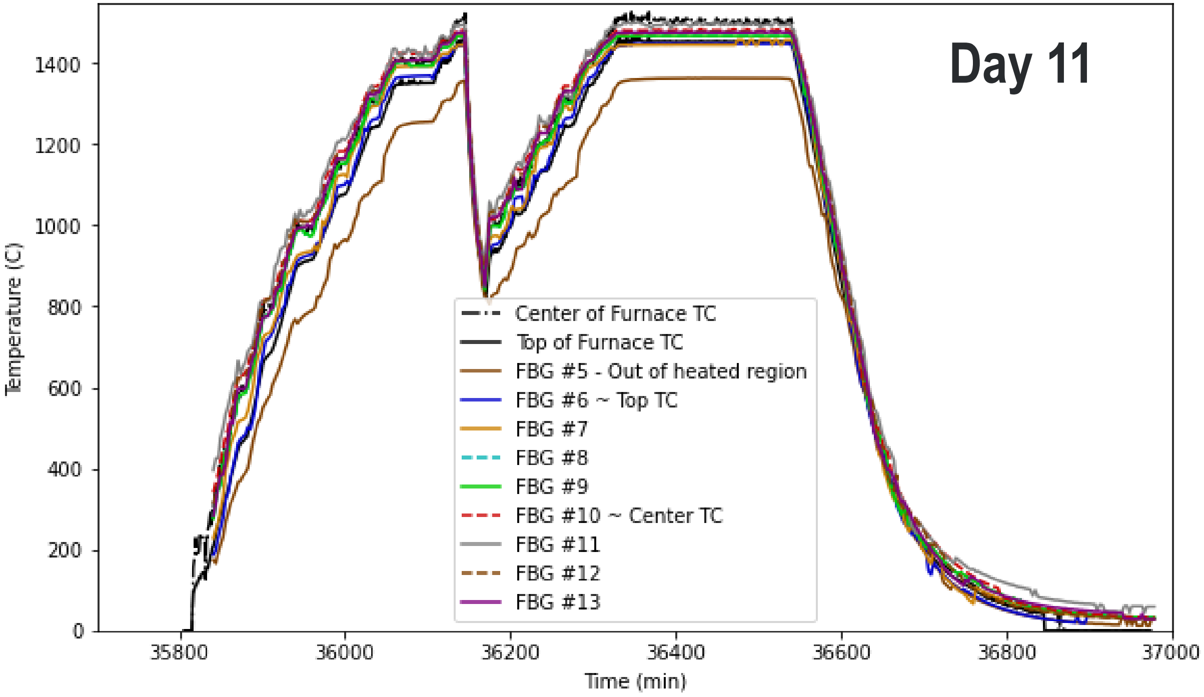


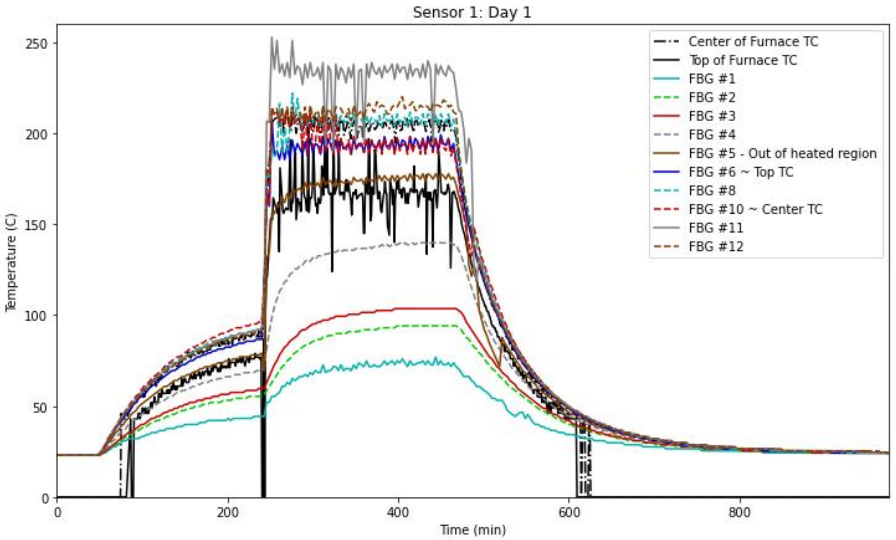
Backscatter profile of sensor #1, 75 um OD sapphire fiber featuring FBGs inscribed by FemtoFiberTec.

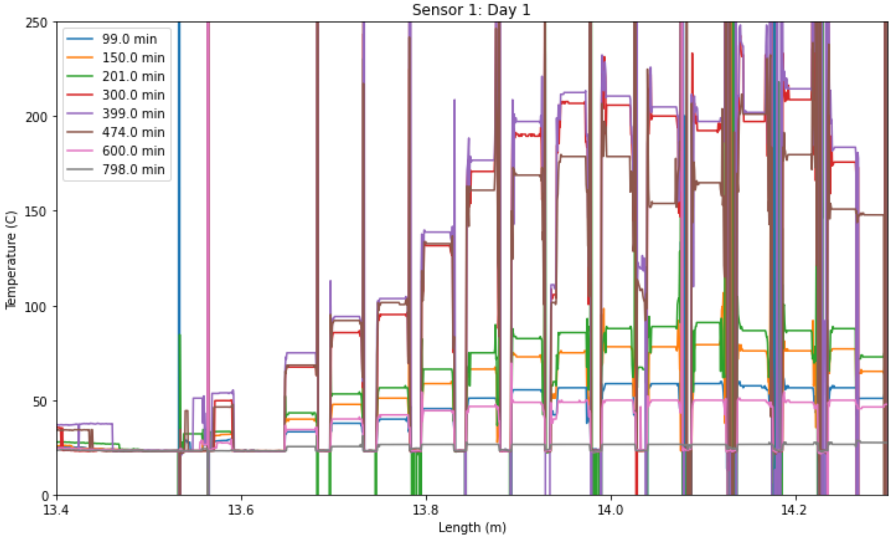
Day	Hours	Power (kW)	Furnace Temp. (Celsius)	Notes
1	7	450	off/200	
2	7	450	400/600	
3	7	450	800	
4	4	450	900	4 hours, some hours for another customer at 5 kw
5-1	0		1000	Fuse blow
5-2	7	450	1000	
6	7	450	1100	
7	7	450	1200	
8	7	450	1300	
9	7	450	1400	
10	7	450	1.5 hrs at 800, 2 hrs at 1000, 2 hrs at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

Results: Heated Irradiation

- The measurement was resolved at the locations of the FBGS
- Sensor 1 – 75 um OD – performed the best
- Sensor gets less noisy with higher temperatures

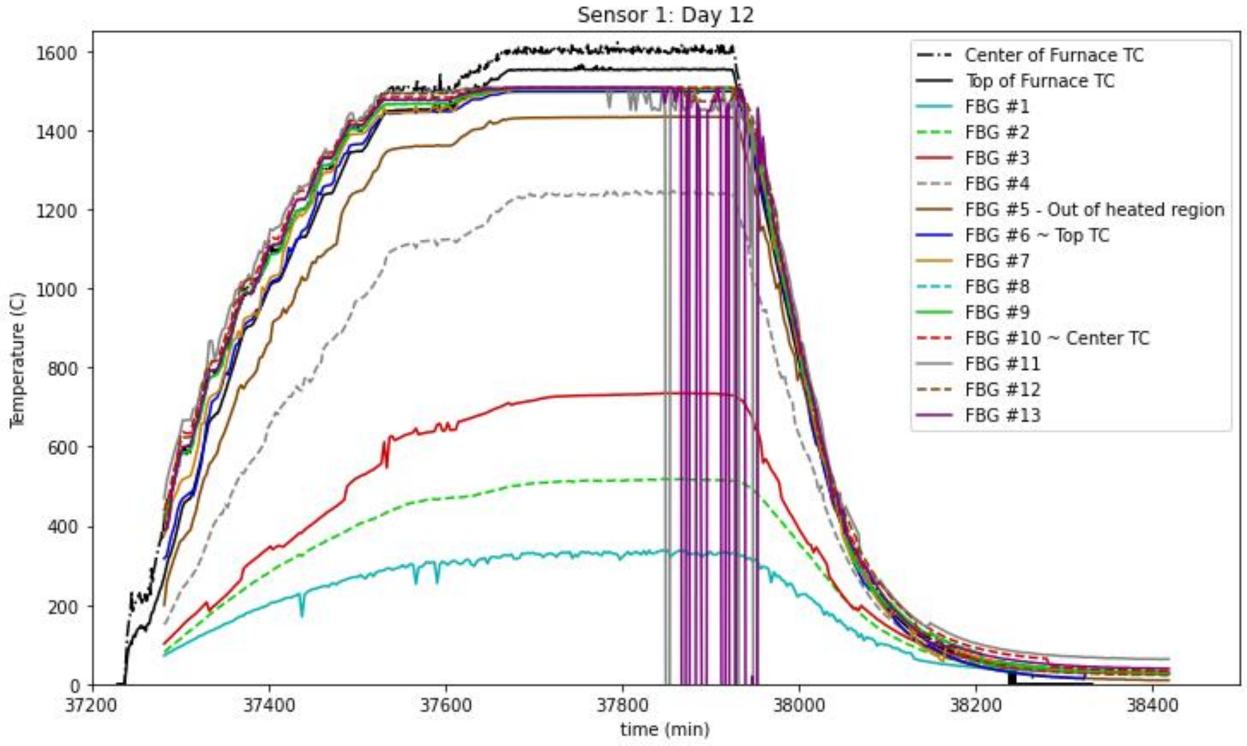


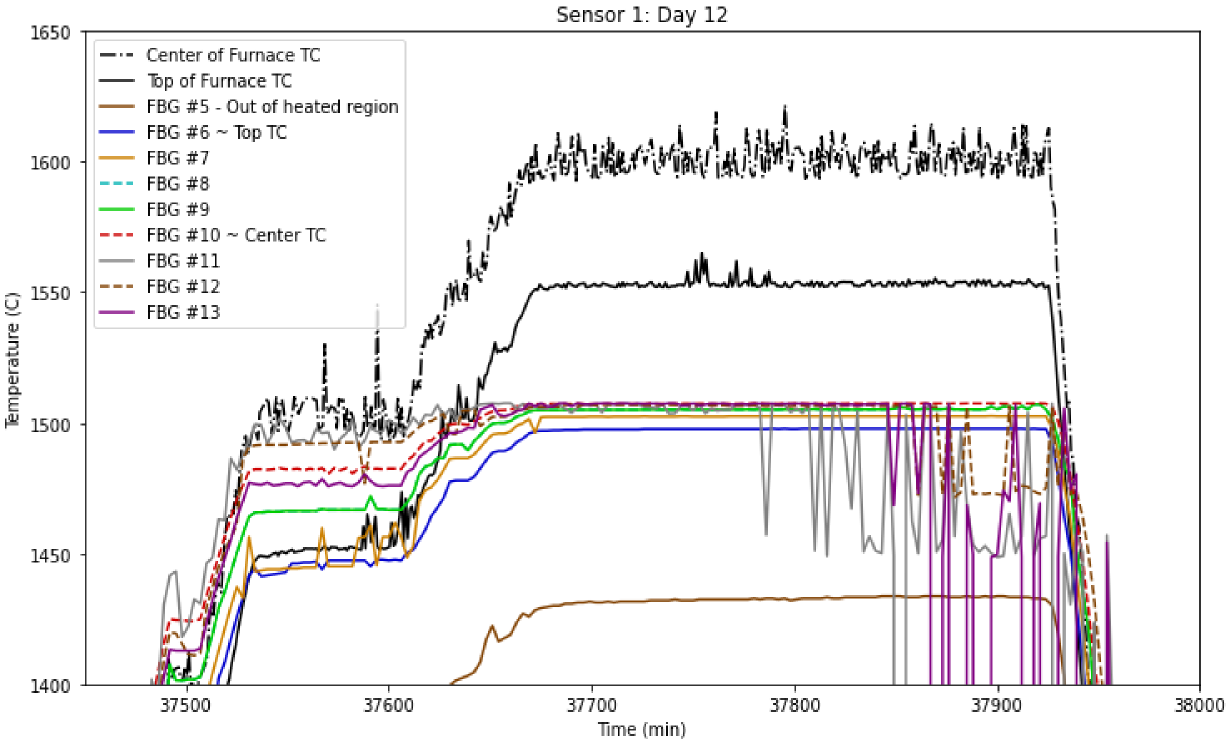




Results: Heated Irradiation

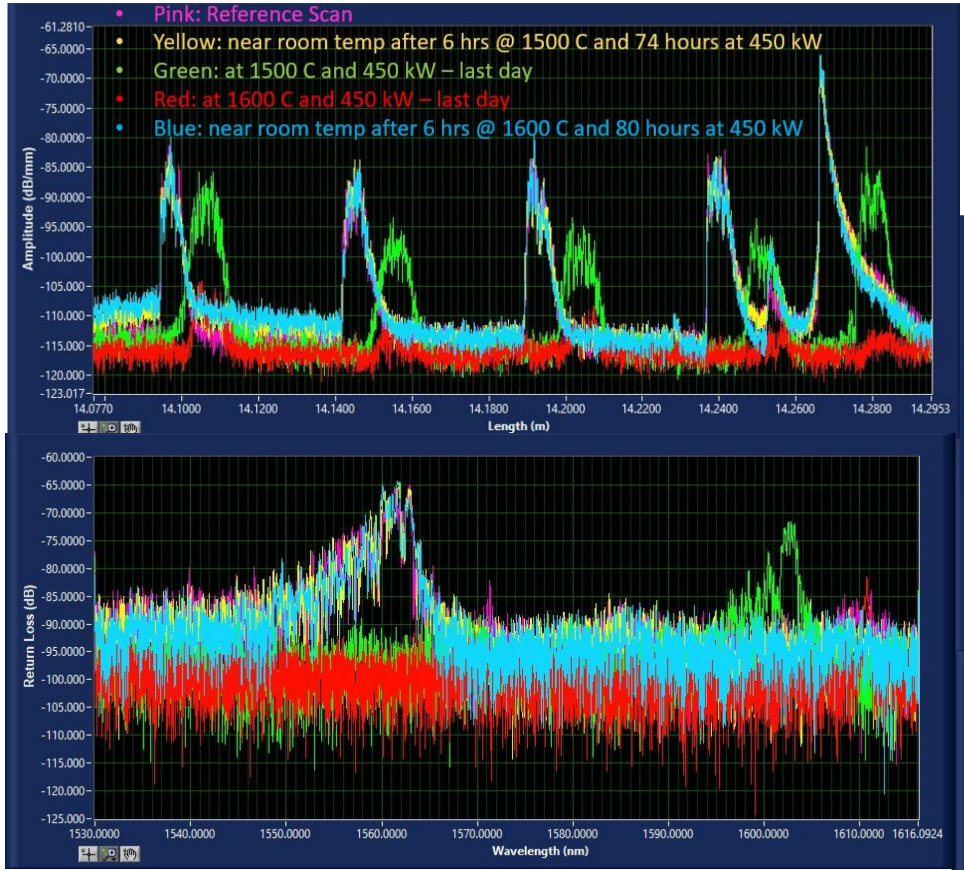
- Similar failure mechanism was observed at 1600ºC in-pile as was observed in out of pile testing.





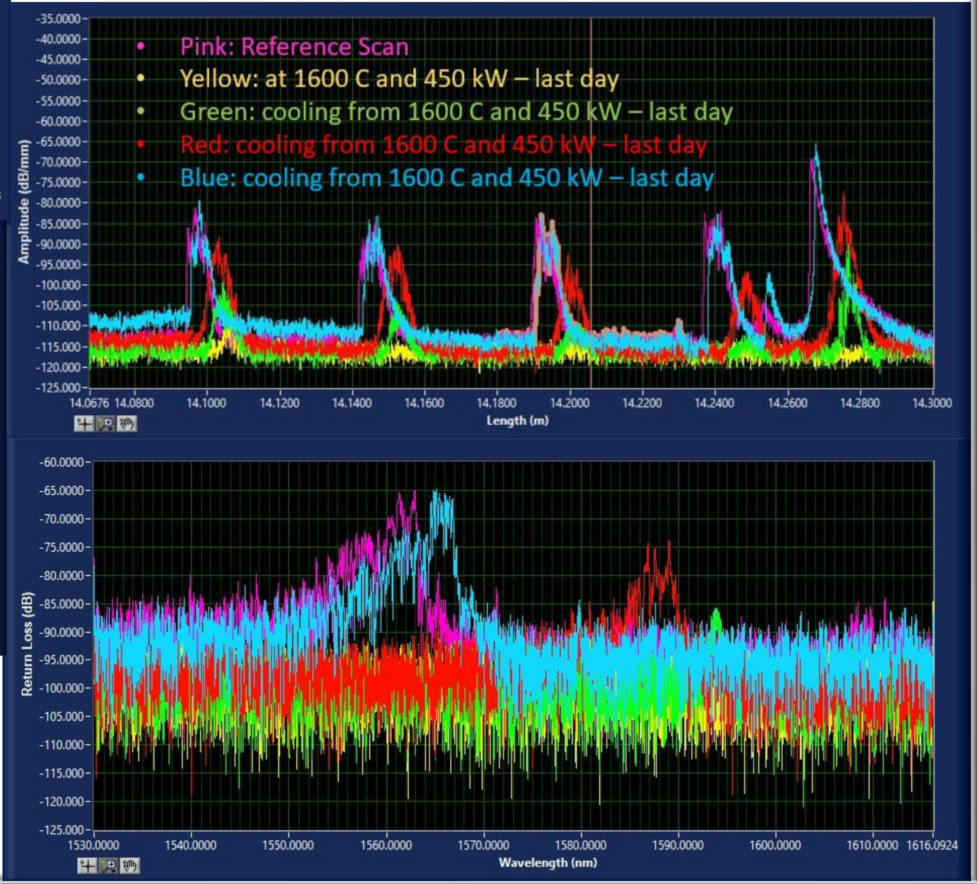
Results: Heated Irradiation

- After signal loss and amplitude reduction the FBGs recover as the fiber cools to room temperature
- Similar amplitude reduction up to 1500ºC that was seen in furnace testing



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.



Conclusion

Challenges:

- Procurement, inscription, and processing of sapphire
  - Non-commercial supplier of sapphire fibers experienced unforeseen issues
  - Inscription of sapphire fibers is not a trivial task
  - Splicing fibers can produce variable results
- Handling tritium-implanted fibers at INL
- Navigating through travel restrictions and shutdowns

Conclusions:

- Objectives 1-3 have been completed
- Heated irradiation indicates potential for sapphire fiber-based sensors to be sued in extreme environments beyond silica fiber limits

Future Work:

- Further evaluation of un-clad sapphire fibers to determine source of attenuation in fiber
- High-fluence irradiation at MITR

Kelly McCary

PhD Candidate, OSU
Research Scientist, Radiation Measurements
Idaho National Laboratory
Kelly.Mccary@inl.gov
W (208)-526-2601

We would like to acknowledge the support of The Ohio State University Nuclear Reactor Laboratory and the assistance of the reactor staff members, Andrew Kauffman, Dr. Susan White, Kevin Herminghuysen, Matthew Van Zile, and Maria McGraw for the irradiation services provided.

Special thanks to Dr. Blue, Josh Jones, and Dr. Birri for their assistance at Ohio State.

This work was supported by the U.S. Department of Energy, Office of Nuclear Energy as part of a Nuclear Science User Facilities experiment

NSUF Nuclear Science User Facilities

ASI Advanced Sensors and Instrumentation

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

U.S. DEPARTMENT OF
ENERGY
Office of
NUCLEAR ENERGY