INL/EXT-20-57797-Revision-0

Active Irradiation Testing of Temperature Sensing Capability of Clad Sapphire Optical Fibers with Type 2 Bragg Gratings using Optical Backscatter Reflectometry

Christian Petrie, Thomas Blue, Pattrick Calderoni, Kelly M McCary, Brandon Wilson, Tiffany M Adams

March 2020

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Questions? Contact Simon Pimblott (simon.pimblott@inl.gov, 208-526-7499) or Tiffany Adams (tiffany.adams@inl.gov, 208-526-4081).

1. **Project Title** (from your proposal) Active Irradiation Testing of Temperature Sensing Capability of Clad Sapphire Optical Fibers with Type 2 Bragg Gratings using Optical Backscatter Reflectometry
2. **Principal Investigator** Christian M. Petrie
3. **PI Email** petriecm@ornl.gov
4. **NSUF Technical Lead** Raymond Cao **NSUF Project ID** 1424
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6. **NSUF Technical Lead** Click or tap here to enter text. **NSUF Project ID** Click or tap here to enter text.
7. **Team Member/Collaborator Information** Click or tap here to enter text.

For All Team Members/Collaborators			If a Student		
Name	**Role (Team Member or Co-Principal Investigator)**	**Institution**	**Level in School**	**Field of Study/ Degree Seeking**	**U.S. or Non-U.S.**
Thomas Blue	Co-Principal Investigator	Ohio State University	Click or tap here to enter text.	Click or tap here to enter text.	☐ U.S. ☐ Non-U.S.
Pattrick Calderoni	Co-Principal Investigator	Idaho National Laboratory	Click or tap here to enter text.	Click or tap here to enter text.	☐ U.S. ☐ Non-U.S.
Kelly McCary	Team Member	Ohio State University	Ph.D.	Nuclear Engineering	☒ U.S. ☐ Non-U.S.
Brandon Wilson	Team Member	Ohio State University	Click or tap here to enter text.	Click or tap here to enter text.	☐ U.S. ☐ Non-U.S.
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8. **Degrees granted as a result of this research.** (Please list any degrees from the start of your project award, even those from previous years.)

Name	Institution	Degree	Field of Study/Degree Seeking	Date
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9. **NSUF Facility used (check all that apply)** *NOTE: If facilities other than those specified below were used, they can be mentioned in the body text of the accomplishments section.)*

Argonne National Laboratory:

☐ The Intermediate Voltage Electron Microscopy (IVEM) – Tandem Facility

Belgian Center for Nuclear Research (SCK/CEN)

☐ Belgian Reactor 2

☐ Laboratory for High and Medium Activity

Brookhaven National Laboratory:

☐ National Synchrotron Light Source II

Center for Advanced Energy Studies:

☐ Microscopy and Characterization Suite (MaCS)

Idaho National Laboratory:

☐ Advanced Test Reactor (ATR)

☐ Advanced Test Reactor Canal

☐ Advanced Test Reactor Critical (ATRC) Facility

☐ Analytical Laboratory

☐ Electron Microscopy Laboratory (EML)

☐ Experimental Fuels Facility

☐ Fuel Conditioning Facility

☐ Fuel Manufacturing Facility

☐ Fuels and Applied Science Building

☐ High Performance Computing

☐ High Temperature Test Laboratory

☐ Hot Fuel Examination Facility (HFEF)

☐ Irradiated Materials Characterization Laboratory (IMCL)

☐ Neutron Radiography Reactor (NRAD)

☐ Stress Corrosion Cracking Lab

☐ Test-Train Assembly Facility

☐ Transient Reactor Experiment and Test Facility (TREAT)

Illinois Institute of Technology:

☐ Advanced Photon Source

Lawrence Livermore National Laboratory:

☐ Center for Accelerator Mass Spectrometry

Los Alamos National Laboratory:

☐ Chemical and Metallurgical Research Facility (Wing 9)

☐ Lujan Center for Neutron Scattering

☐ Plutonium Surface Science Laboratory

Massachusetts Institute of Technology:

☐ Nuclear Reactor Laboratory

☐ Reactor

North Carolina State University:

☐ PULSTAR Reactor Facility

☐ Positron Intense Beam Facility

Oak Ridge National Laboratory:

☐ High Flux Isotope Reactor (HFIR)

☐ Irradiated Fuels Examination Laboratory (IFEL) Hot Cells

☐ Irradiated Materials Examination and Testing Facility (IMET) Hot Cells

☐ Low Activation Materials Design and Analysis Laboratory (LAMDA)

The Ohio State University:

☒ The Ohio State University Nuclear Research Laboratory

Pacific Northwest National Laboratory:

☐ Materials Science and Technology Laboratory (MSTL)

☐ Radiochemical Processing Laboratory (RPL)

Purdue University:

☐ Interaction of Materials with Particles and Components Testing (IMPACT)

Sandia National Laboratory:

☐Annular Core Research Reactor

☐ Gamma Irradiation Facility

☐ Ion Beam Laboratory

Texas A&M University:

☐ Accelerator Laboratory

University of California, Berkeley:

☐ Nuclear Materials Laboratory

University of Florida

☐ Nuclear Fuels and Materials Characterization Facility

University of Michigan:

☐ Irradiated Materials Testing Laboratory

☐ Michigan Ion Beam Laboratory

University of Wisconsin:

☐ Characterization Laboratory for Irradiated Materials

☐ Ion Beam Laboratory

Westinghouse:

☐ Churchill Laboratory Services

10. **Experimental or Technical Approach:** Describe the experimental or technical methods of the research project (150-200 words)

This work investigated the temperature-sensing capabilities of Type II fiber Bragg gratings (FBGs) inscribed in sapphire optical fiber in the Ohio State University Research Reactor (OSURR). A Luna Innovations 4600 optical backscatter reflectometer (OBR) was used to interrogate FBGs in three sapphire optical fibers with an internal cladding that was developed by Ohio State [1]. The sapphire fibers were fusion-spliced to silica lead fibers. In addition to the sapphire fibers, two silica fibers with the same Type II FBGs were included in the experiment as a reference. The fiber-based sensors were irradiated in the Central Irradiation Facility (CIF) of the OSURR for a total of 40 hours over 5 days at a reactor power of 450 kW, resulting in a total neutron fluence of approximately 2.5×10^{18} n/cm^2 and a gamma dose of approximately 3.48 Grad. Two K-type thermocouples were included within the rig: one at the core centerline and the other 12 inches above the top of the core. The temperature was not actively controlled, but the thermocouples were used to provide a reference to which the fiber-based temperature measurements could be compared.

11. **Results**: Summarize what was measured, the readings taken, and observations made (150-200 words)

The FBGs located closest to the silica-to-sapphire fiber splices generally performed much better than the FBGs located further from the splice. All measurements for FBGs located more than ~5−10 cm from the silica-to-sapphire splice either failed or showed prohibitive noise, perhaps indicating that the cladding of the sapphire fiber was not effective in achieving single-mode operation. However, for two of the three sapphire fibers, the FBG located closest to the silica-to-sapphire splice performed well, with the magnitude and time response of the fiber-optic measurements generally matching those of the thermocouples for all 5 days of irradiation. Some of the observed differences between the various sapphire fibers could be attributed to pre-irradiation heat treatment. The two sapphire fibers that showed better performance were heat treated at >1300°C prior to irradiation while the remaining fiber was heat-treated at 1000°C. The thermal annealing of the clad optical fiber may have a significant effect on transmission in the fiber, due to the creation of nanovoids [2]. The FBGs inscribed in the silica fibers showed no significant noise or signal drift over 5 days of irradiation, indicating that the Type II gratings themselves perform well under irradiation.

12. **Discussion/Conclusion**: Describe the impact and meaning of the results of your project (75-100 words)

This work showed that temperature sensing using FBGs in sapphire optical fiber is possible given that at least one FBG in two of the three sapphire fibers survived and gave reliable readings up to a total neutron fluence of approximately 2.5×10^{18} n/cm^2. There is still a need to reduce the modal volume and the intrinsic attenuation in the sapphire fibers. However, if these challenges can be overcome, the high melting temperature of sapphire (>2000°C) makes sapphire optical-fiber sensors a potential candidate for monitoring of centerline temperatures during irradiation testing of advanced fuels for high-temperature reactor applications.

13. **References**

1. Brandon A. Wilson and Thomas E. Blue, “Creation of an Internal Cladding in Sapphire Optical Fiber Using the ^{6}Li(n,α)^{3}H”, IEEE Sensors Journal, vol. 17, no. 22, pp. 7433-7439, Nov. 15, 2017.
2. B. A. Wilson, S. Rana, H. Subbaraman, N. Kandadai and T. E. Blue, "Modeling of the Creation of an Internal Cladding in Sapphire Optical Fiber Using the ^{6}Li(n,α)^{3}H Reaction," in Journal of Lightwave Technology, vol. 36, no. 23, pp. 5381-5387, 1 Dec.1, 2018.

14. **Publications:** Include conference, journal, textbook and special workshop reports. **List the citations in text form here <u>and</u> use the “Load a Publication” link on the website**. Publications are tracked electronically to be included in the publications archive on the NSUF website and used for metric analysis. Only publications from the current fiscal year will be included in the annual report, but all publications need to be loaded on the website so they are included in the archive.

K.M. McCary, B.A. Wilson, J.E. Daw, P. Calderoni, C. Petrie, T.E. Blue, “In-Pile OFDR Sensing with Fiber Bragg Gratings in Sapphire Optical Fiber,” American Nuclear Society Winter Meeting, Washington D.C. (2019), p. 159-163.

K.M. McCary, B.A. Wilson, A.H. Birri, T.E. Blue, and C. Petrie, “Suitability of Type-II Fiber Bragg Gratings in Silica Optical Fiber for Temperature Sensing in TREAT,” Nuclear Power Instrumentation, Control, and Human Machine Interface Technologies, Orlando, FL (2019), p. 469-477.

15. **Patents applied for because of this research.**

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16. **Principal Investigator Bio Photo.** Please provide a professional bio photo that may be used to accompany the article.

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17. ***(Optional)*** **Graphics (only high-resolution, 300 dpi, .jpeg, .tif, .pdf, and eps file formats only).** Please include pertinent, high-quality graphics with captions. Please also provide a high-resolution image (300 dpi or higher) showing research being done by team members using an NSUF capability for possible inclusion in an Annual Report highlight graphic. If you need assistance with your figures, please contact Tiffany Adams (tiffany.adams@inl.gov). **Limit of one graphic for short communications.**

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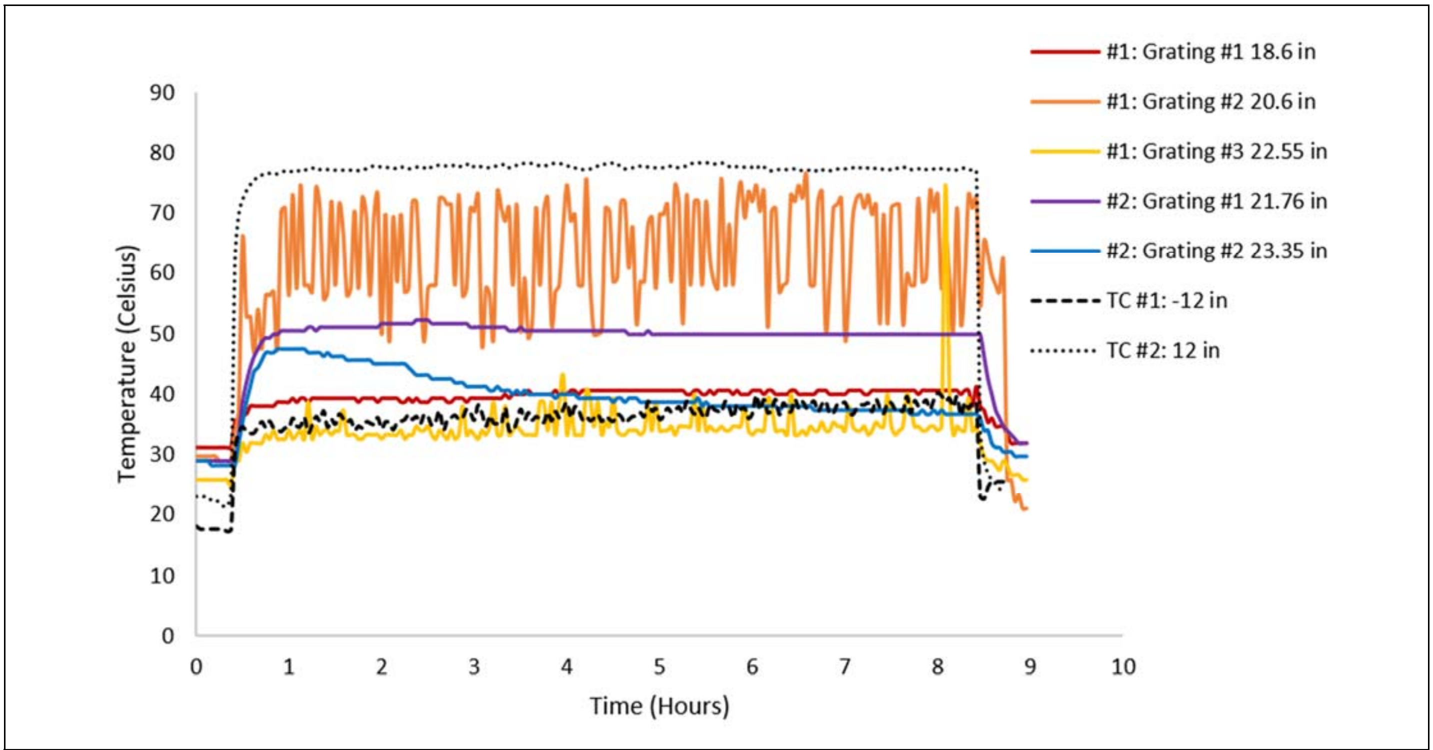

Figure 1. Temperatures measured by FBGs in sapphire Fibers 1 and 2, as well as thermocouples as a function of time on the fifth day of irradiation. Measurements were made at various distances below the top of the OSURR core, with the reactor midplane located 12 inches below the top of the core.