Upcoming Irradiation of Ultrasonic and Fiber Optic Sensors in the MITR

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ABSTRACT

Fiber optic and ultrasonic technologies offer the potential for high accuracy and resolution in-pile measurement of a range of parameters, including geometry changes, temperature, crack initiation and growth, gas pressure and composition, and microstructural changes. These technologies, which have performed successfully in out-of-pile tests, have not been well qualified in a test reactor environment. The uncertainty of successful operation of instruments at this level of development has typically been a significant barrier to in-core deployment. Many Department of Energy-Office of Nuclear Energy (DOE-NE) programs are exploring the use of these technologies to provide enhanced sensors for irradiation testing. For example, the ability of small diameter ultrasonic thermometers (UTs) to provide a temperature profile in candidate metallic and oxide fuel would provide much needed data for validating new fuel performance models.

The National Scientific User Facility (NSUF) is sponsoring a project to evaluate the performance of promising temperature sensors based on ultrasound and on fiber optics during an upcoming irradiation test in the Massachusetts Institute of Technology Research Reactor (MITR). Several types of thin-wire metallic waveguide ultrasonic thermometers will be tested along with fiber optic temperature sensors using regenerated Fiber-Bragg Grating technology. Additionally, samples of several new optical materials which are potentially much more radiation tolerant than commonly used fiber materials, such as silica, will be included and analyzed post-irradiation. The irradiation is a collaborative effort between researchers from Idaho National Laboratory, the French Alternative Energies and Atomic Energy Commission, the University of Pittsburgh, the Massachusetts Institute of Technology, and AFO Research, Inc.

Key Words: In-Core, Ultrasound, Fiber Optics

1 INTRODUCTION

An effort has been initiated by the Department of Energy-Office of Nuclear Energy (DOE-NE) to better characterize the performance of nuclear fuels and materials during irradiation; for example, accident tolerant fuel tests in Material Test Reactor (MTR) irradiations used to support acceptance of new fuels. Although there are numerous types of sensors available for measuring different properties of interest, most have significant limitations in terms of measurement fidelity and long duration reliability in-core. The development of new sensors to perform a variety of in-core measurements is an ongoing process, typically slowed by the lack of sensor performance testing in prototypic high-radiation environments.

As a follow-up to a recent NSUF irradiation test focused on ultrasonic transducers, a collaborative multi-organizational effort for a temperature sensor irradiation experiment was selected by the Nuclear Scientific User Facility (NSUF) for an irradiation in the Massachusetts Institute of Technology Nuclear Research Reactor (MITR). The goal of this test will be to quantify the radiation tolerance of ultrasonic and fiber optic temperature sensors in prototypic in-core conditions and the effects of the reactor environment on temperature measurements. As such, this experiment will be an instrumented lead test, allowing on-line monitoring of the sensor performance.

2 BACKGROUND

Several US DOE-NE programs are investigating new fuels and materials for advanced and existing reactors. A primary objective of such programs is to characterize the irradiation performance of these fuels and materials. Examples of the key parameters needed to evaluate, as well as the desired accuracies and resolutions, are shown in Table I [1]. Similar measurement parameters exist for structural material tests.

Table I. Summary of desired fuel measurement parameters for irradiation testing.

Parameter	Representative Peak Value	Desired Accuracy	Desired Spatial Resolution
Fuel Temperature	Ceramic Light Water Reactor (LWR): 1400°C	2%	1-2 cm (axially) 0.5 cm (radially)
	Ceramic Sodium Fast Reactor (SFR): 2600°C		
	Metallic SFR: 1100°C		
	Tristructural-isotropic (TRISO) High Temperature Gas Reactor (HTGR): 1250°C		
Cladding Temperature	Ceramic LWR: <400°C	2%	1-2 cm (axially)
	Ceramic SFR: 650°C		
	Metallic SFR: 650°C		
Fuel Rod Pressure	Ceramic LWR: 5.5 MPa	5%	NA
	Ceramic SFR: 8.6 MPa		
	Metallic SFR: 8.6 MPa		
Fission Gas Release	0-100% of Inventory	10%	NA
Fuel and Cladding Dimensions and Density	Initial Length: 1 cm	1%	NA
	Outer Diameter/Strain: 0.5 cm/5-10%	0.1%	NA
	Fuel-Cladding Gap: 0-0.1 mm	0.1%	NA
	Density: Ceramic: < 11 g/cm^3; Metallic: < 50 g/cm^3; TRISO pebble/compact: 2.25 g/cm^3	2%	NA
Fuel Microstructure	Grain size,10 μm	5%	1-10 μm
	Swelling/Porosity: 5-20%	2%	NA
	Crack formation and growth	2%	10-100 μm

Both ultrasonic an optical fiber sensors can be developed to measure most, if not all, of these parameters with the desired resolutions and improved accuracy compared to existing in-core sensors.

3 EXPERIMENT DESIGN

3.1 MITR

The MITR is a tank-type research reactor [1] operating at atmospheric pressure. It began operation in 1958; and its current license, issued in November 2012, authorizes steady-state 6 MW operation. The reactor has two tanks: an inner tank for light water coolant/moderator and an outer tank for the heavy water reflector. A graphite reflector surrounds the heavy water tank. The MITR is equipped with a wide variety of sample irradiation facilities, with fast and thermal neutron fluxes up to 3.6x 10^{13} and 1.2x10^{14} n/cm^2·s respectively. The test position within the MITR core is shown in Figure 1.

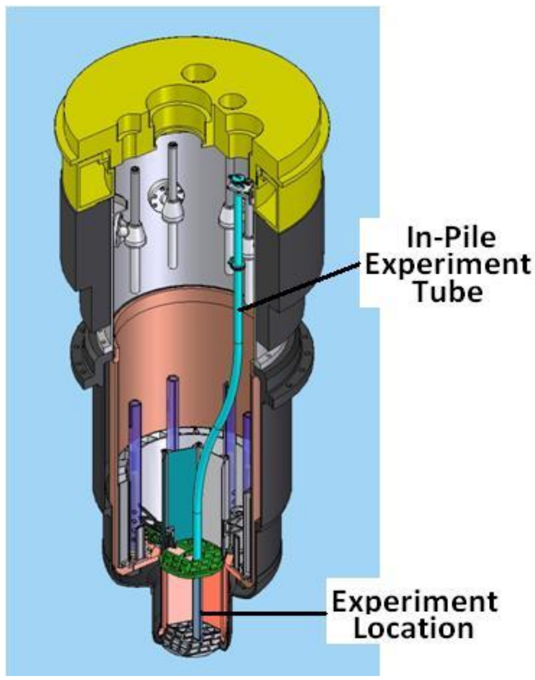

Figure 1. Schematic cutaway view of the MITR reactor showing the locations of the in-pile experiment tube and the experiment location within the core.

3.1.1 Irradiation Test Conditions

Temperature will be controlled by a helium/neon gas gap with adjustable gas composition. The online sensor portion of the test will operate up to a maximum of 800 ^oC. Irradiation samples of several experimental glass compositions will be kept to a lower temperature of less than 450 ^oC. In order to observe rapid changes at relatively low fluences, the test will be started with the reactor slowly ascending to power. The identified irradiation position and flux conditions at the MITR are summarized in Table II.

Table II. Test conditions for MITR irradiation

MITR In-Core Experimental Facility
Capsule dimensions: 42 mm OD x 152.4 mm long
Thermal Flux: 3.6×10^{13} n/cm^2·sec Fast Flux (>1 MeV): 1.2×10^{14} n/cm^2·sec Gamma dose rate: 1×10^9 r/hr
Temperature: 350 °C - 800 °C

3.1.2 Capsule

The MITR configuration restricts the test capsule size to a cylinder 42 mm in diameter and 152.4 mm in length. Two capsules may be chained together. The capsule uses structural graphite as a holder material. Graphite is an ideal material as it has low density (for reduced gamma heating). In addition, graphite is thermally conductive (to produce a uniform predictable temperature), exhibits low neutron activation, and can be used at very high temperatures. During the irradiation, the graphite holds the test specimens in place while also efficiently conducting heat generated to the coolant. Four type-K thermocouples will be used to monitor temperatures online, two for the sensor capsule and two for the glass sample capsule. The radiation environment of the MITR is well characterized in terms of neutron and gamma flux, but Fe-Co flux wires will be used to verify accumulated fluence.

3.2 INL Developed Ultrasonic Thermometer

Ultrasonic thermometry has the potential to improve upon temperature sensors currently used for in-core temperature measurements [3]. UTs work on the principle that the speed at which sound travels through a material (acoustic velocity) is dependent on the temperature of the material. Temperature may be derived by introducing a short acoustic pulse to the sensor and measuring the time delay of acoustic reflections generated at acoustic discontinuities along the length of the sensor. Typically, these discontinuities are created by machining notches into the sensor rod. UTs can be made with very small diameters while maintaining a high level of durability because the sensor consists simply of a small diameter metallic rod or wire (although a sheath may be required) [4]. There is also no electrical insulation needed in the sensor. Electrical insulation, required for thermocouples, can degrade if subjected to high temperatures (>1800 °C), causing shunting errors. UT temperature measurements may be made near the melting point of the sensor material, allowing monitoring of temperatures potentially in excess of 3000 °C. The primary appeal of the UT is the potential for real time in-core measurement of a temperature profile using a single multi-segment sensor. A conceptual design of a multi-segment UT, with key components identified, is shown in Figure 2.

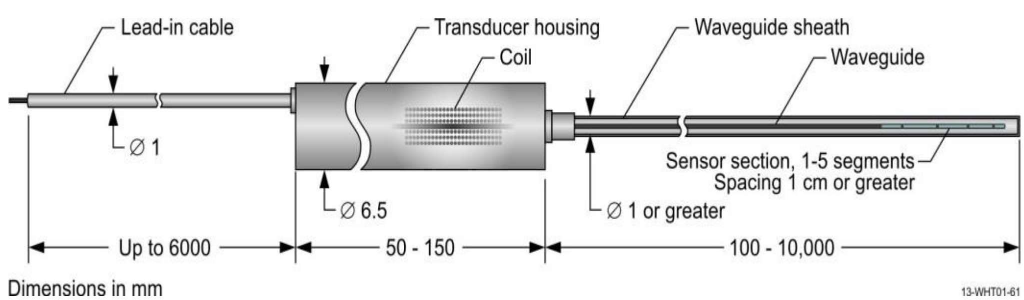

Figure 2. Schematic cutaway view of the MITR reactor showing the locations of the in-pile experiment tube and the experiment location within the core.

INL developed UTs have been tested at high temperatures in furnace environments (i.e. inert gas or vacuum atmosphere), but not in an irradiation environment. The key component of the UT that must be proven for use in the ATR is the transducer, which converts the electrical input signal to an acoustic/mechanical wave, and vice versa. The transducer design was recently tested for radiation tolerance in the Massachusetts Institute of Technology Research Reactor (MITR). The transducer was tested independently, not coupled to a specific sensor. The transducer was irradiated to a total fast fluence of 8.8×10^{20} n/cm^2 (E>1 MeV). Results of the irradiation and subsequent post irradiation examination indicate that there was negligible degradation of the transduction performance over the course of the irradiation [5]. Specifications for the three UTs to be included in this test are shown in Table III.

Table III. Ultrasonic thermometer configurations for irradiation.

Sensor Material and Configuration	**Maximum Operating Temperature (°C), Cause**	**Configuration**
Inconel 600, single segment	1000, excessive signal attenuation	1 sensor segment, 31 mm long
Inconel 600, multiple segment	1000, excessive signal attenuation	3 sensor segments, 31.75, 20.5, and 21.25 mm long
Commercially Pure Titanium, single segment	850, solid state phase change	1 sensor segment, 31.75 mm long

3.3 CEA Developed Regenerated Fiber-Bragg Grating Sensor

In addition to ultrasound based sensors, fiber optics are also considered a very promising technology for distributed in-core measurements, assuming several difficulties can be overcome. Primarily, long term radiation tolerance of the sensor, particularly the ability to transmit light through the fiber, has not been demonstrated. Like the ultrasonic thermometer, temperature measurements are made by observing changes to reflected signals from defects in the fiber. Artificial defects can be made with large reflection coefficients, which help alleviate the problem of radiation tolerance by ensuring that more light is reflected. Inscribing Fiber Bragg Gratings (FBGs) into the fiber is the preferred method, but these gratings tend to anneal and disappear at high temperatures.

3.3.1 Regeneration process

Several methods have been proposed to increase the thermal stability of FBGs especially for sensing applications in harsh environments. The regeneration process occurring in silica glass is an attractive solution suited to the development of wavelength multiplexed FBG sensing lines. This seed FBG is first erased through an annealing at temperature near 900 °C and subsequently a new Bragg peak appears on the spectrum. Its reflectivity increases gradually up to a maximum level depending on the annealing protocol, on the seed grating initial reflectivity and on the fiber's composition and fabrication process. Regenerated Bragg Gratings increase temperature stability (up to 900 °C) and preserve the sharpness of the Bragg peak. Deployment of regenerated FBG arrays for nuclear applications requires not only the development of regeneration methods suited specific fibers, the use of flexible monitoring units to cope with relatively low reflectivity and calibration of the multiple measurement points to ensure accurate temperature measurements when compared to conventional sensors (i.e., thermocouples). Testing of the sensor's behavior (drift, erasure, radiation induced attenuation) under prototypic conditions combining gamma and neutron radiation with high temperature (typically greater than 300 °C). Online measurements during an irradiation test will provide insight into the behavior of the optical fiber sensing probe and enable improvement of their robustness for in-core thermometry.

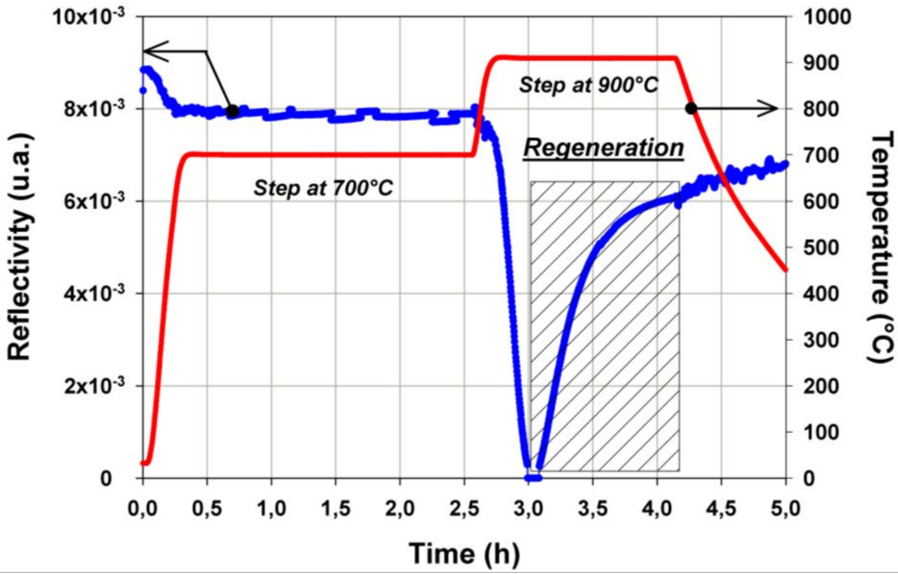

Figure 3. Evolution of the seed FBG reflectivity vs time during the regeneration process.

An example of a multipoint, high temperature resistant sensor based on the regeneration process will be irradiated in the MITR as part of this effort. The tested sensor will have 10 sensing positions spaced one centimeter apart along a single fiber. The reflection spectra for this 10-sensor fiber before and after regeneration are shown in Figure 4.

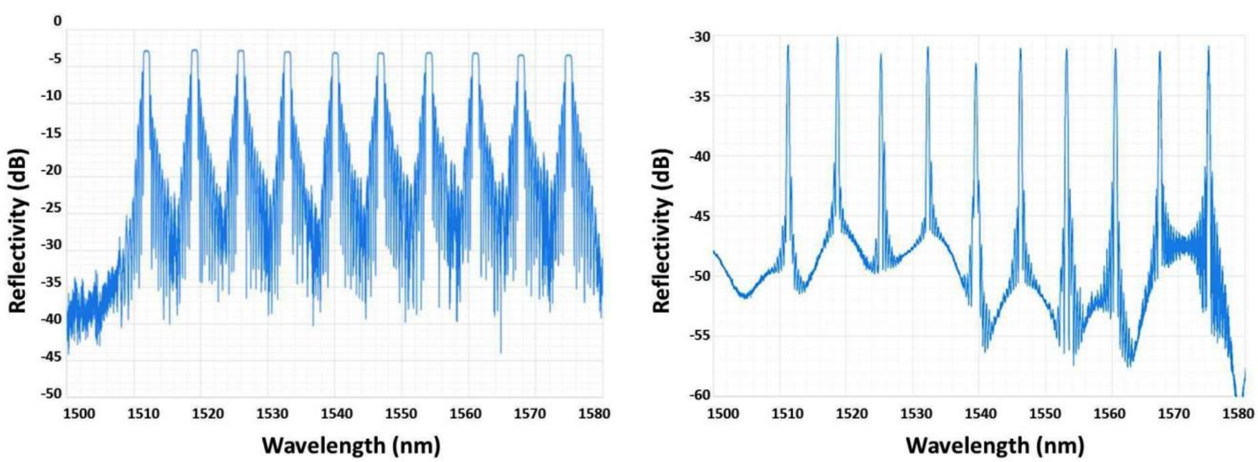

Figure 4. Reflection spectra before and after regeneration for a line of ten wavelength multiplexed Fiber Bragg Gratings.

3.4 University of Pittsburgh Developed Optical Sensors

The University of Pittsburgh fiber sensors to be tested in MITR are distributed sensor based on Rayleigh backscattering. They will be interrogated using Optical Frequency Domain Reflectometery (OFDR) with ~5-mm spatial resolution. One of the key challenges of distributed sensing using the Rayleigh backscattering is the weak Rayleigh-backscattering features originating from structural imperfections of conventional optical fibers. At high operating temperatures, or in radiation environments, the intrinsic crystalline flaws that give rise to the Rayleigh scattering in fiber cores undergo permanent changes [6]. These changes will eventually compromise sensitivity and reliability of the distributed measurements.

In this work, femtosecond ultrafast laser irradiation was used to produce enhanced Rayleigh scattering profiles in optical fibers that have shown excellent stability at high temperatures. The schematic of the experimental setup is presented in Figure 5, where (a) shows OFDR system (LUNA OBR 4600 with internal components [8]: TLS: tunable laser source, FC: Fiber Coupler PC: polarization controller, PBS: polarizing beam splitter). Part (b) shows a schematic sketch of the ultrafast laser irradiation on the optical fibers. Part (c) shows the nanograting formed in fiber core during laser irradiation with S: The direction of laser scanning, E: The direction of the electrical field. k: nanograting orientation and the direction of light propagation.. The ultrafast laser is known to be a useful tool to produce FBG point-sensors with superior temperature stability compared to FBGs produced by UV lasers [7]. In contrast to the laser-fabrication of Bragg gratings, a simpler manufacturing scheme was developed to produce distributed fiber sensors using 300–nJ laser pulses. Using these enhanced fibers, distributed temperature measurements were demonstrated with 5-mm spatial resolution at 800 °C in highly reactive fuel gas (hydrogen) stream. The same sensors have shown excellent stability in Gamma radiation.

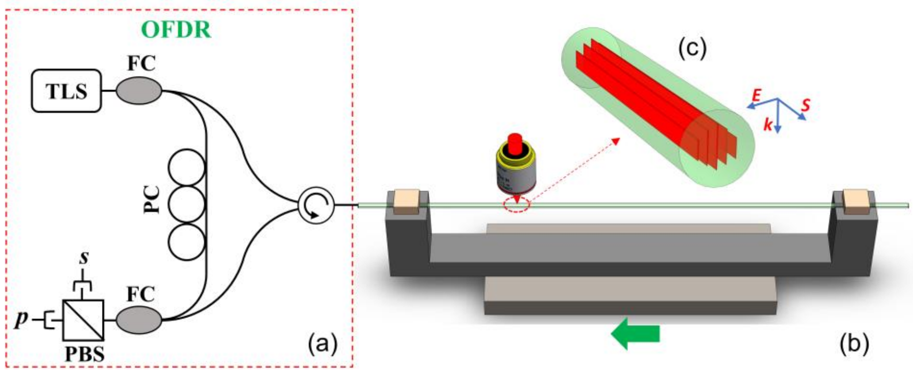

Figure 5. Schematic sketch of the Rayleigh Enhancement setup.

Figure 6(d)-(f) show SEM cross-section images of the fiber core regions after the gratings are inscribed. The ultrafast laser enhancement of the Rayleigh profile is closely linked to the formation of laser-induced nano-gratings inside the fiber core. These nanogratings were only observed in fibers which exhibited enhanced Rayleigh back-scattering after processing.

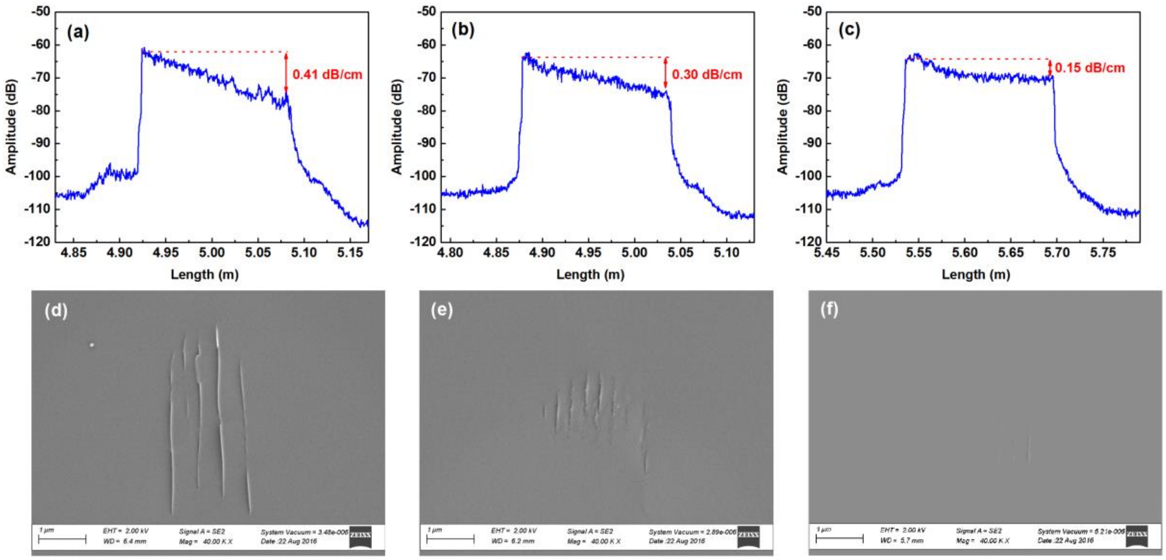

Figure 6. Laser-induced Rayleigh scattering enhancement and the formation of nanogratings. (a)-(c) Ultrafast laser-enhanced Rayleigh backscattering profiles and (d)-(f) scanning electron microscope (SEM) images of the cross-sectional morphologies of nanogratings .

To characterize the induced Rayleigh scattering stability, the annealed fibers were used as temperature sensors over a range of temperatures from 24 °C to 800 °C. Figure 7 shows the scattering profiles measured using the annealed fibers in a 10% H2 atmosphere. No significant scattering amplitude changes were observed as compared to the post-annealed fiber.

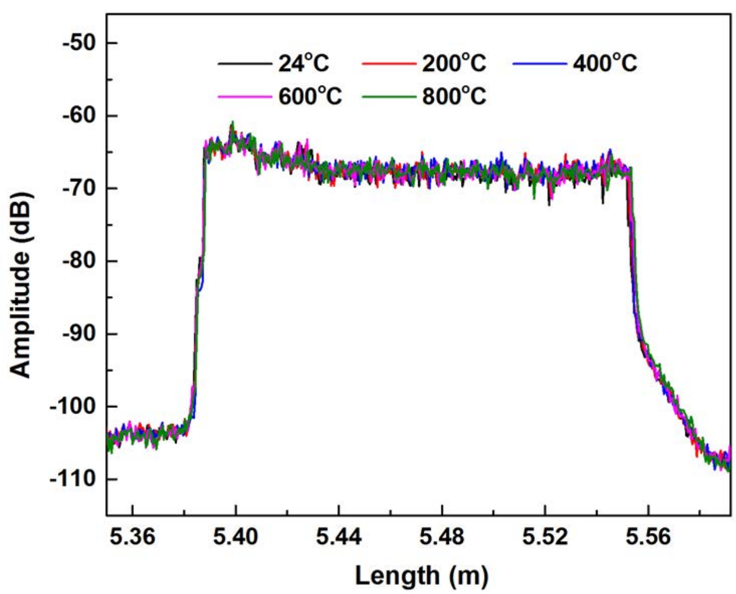

Figure 7. Thermal stability of scattering features after an annealing process in 10% hydrogen at 800oC.

The same distributed fiber sensors were also tested under gamma irradiation. The setup is shown in Figure 8, with dummy Co-60 radiation sources in position to mimic the experimental layout used. Two 60Co radiation pencils are placed on each side of the three fiber sections under test (pointed out by red arrows), namely the bare germanium doped single mode fiber, the weakly and strongly Rayleigh enhanced D-fiber sections. The sample was fusion spliced to lead-in cables with APC connectors, then connected to an Optical Backscattering Reflectometer, which is a commercially available instrument that utilizes OFDR to measure the Rayleigh scattering profile on the length of the optical fiber up to a preset 0.5 mm spatial resolution.

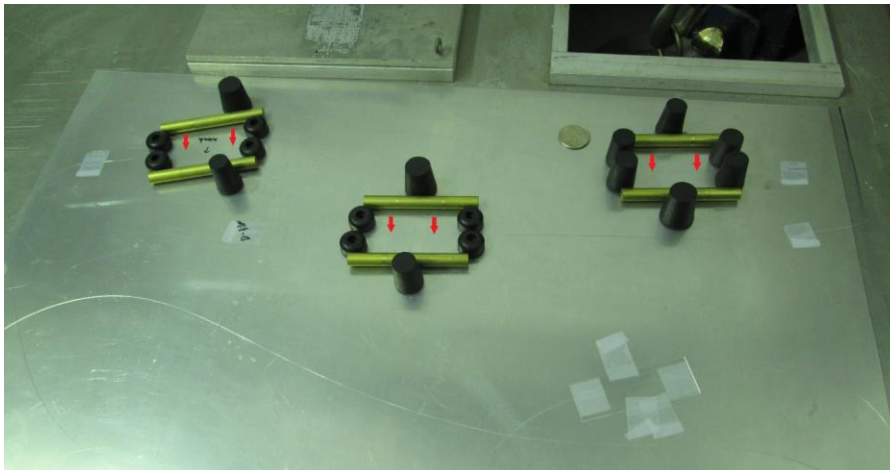

Figure 8. A photograph of the optical fiber sample laid inside the hot cell with mock-up sources depicting the chosen format for the gamma radiation exposure.

The sample was set in position inside the hot cell and the gamma radiation pencils were brought into their locations mechanically then the Rayleigh measurements commenced. The sample was monitored and the measurements were taken for a 12 days, where the sample got exposed to a total of > 1MGy of ionizing radiation. The effect on the Rayleigh scattering profile is given in Figure 9.

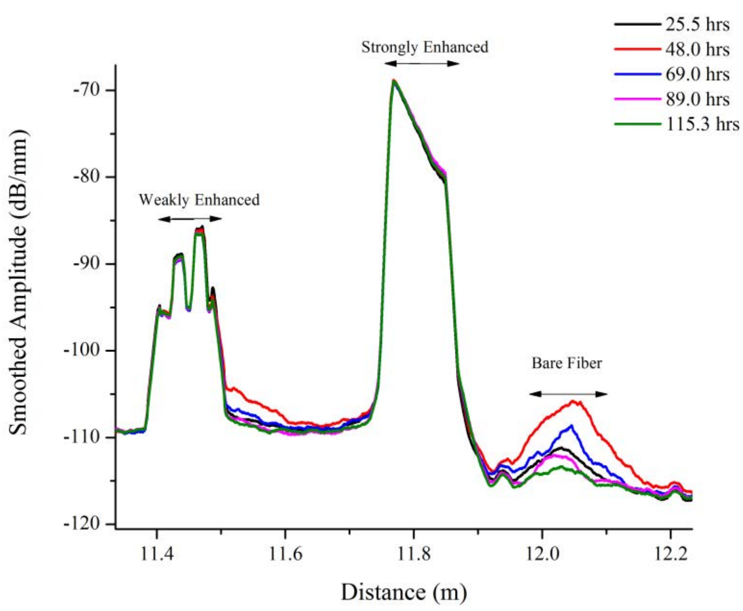

Figure 9. Smoothed Rayleigh profiles at different duration of exposure to ionizing radiation fromCo-60.

The obtained measurements were averaged to produce smooth curves for interpretation. Both sections of fibers with various degrees of Rayleigh enhancements show excellent stability under gamma radiation, while fiber without laser enhancements exhibits a great deal of susceptibility to ionizing radiation, while the enhanced sections have shown no change at all.

Despite the outstanding thermal and gamma stability of the distributed fiber sensors, performance in neutron radiation environments must be demonstrated prior to use in irradiation tests.

3.5 Piggyback Glass Samples

In addition to the sensors that will be monitored online, several samples of promising glasses will be irradiated and evaluated through post irradiation examination. The glasses of interest are flourophosphate glass samples doped with varying amounts of yttrium or cerium. Several of these glass types were previously irradiated in several tests using mixed beam, particle, and gamma irradiation facilities with promising results. The glass samples will be in the form of 1 cm cubes.

4 SUMMARY

In summary, the National Scientific User Facility is sponsoring an irradiation test at the Massachusetts Institute of Technology Research Reactor designed to evaluate the performance of promising temperature sensors based on ultrasound and on fiber optics. Several types of thin-wire metallic waveguide ultrasonic thermometers will be tested along with fiber optic temperature sensors using regenerated Fiber-Bragg Grating and laser enhanced Rayleigh scattering technologies. Additionally, samples of several promising new radiation tolerant optical materials will be included and analyzed during post-irradiation-examination.

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