In-situ Reactor Radiation-Induced Attenuation in Sapphire Optical Fibers Heated up to 1000 °C

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Abstract

The purpose of this work was to determine the suitability of using instrumentation utilizing sapphire optical fibers in a high temperature nuclear reactor environment. For this, the broadband (500 – 2200 nm, or 0.56 – 2.48 eV) optical transmission in commercially available sapphire optical fibers was monitored in-situ prior to, during, and after reactor irradiation. Portions of the sapphire fibers were heated to temperatures up to 1000 °C during irradiation. The sapphire fibers were irradiated, mostly at a neutron flux of 5.0×10^{11} n/cm²/s and a gamma dose rate of 28 kGy/hr (dose in sapphire), to a total neutron fluence of 6.4×10^{16} n/cm² and total gamma dose on the order of 1 MGy. Results were generally consistent with the results of previous in-situ measurements of the transmission in unheated sapphire fibers during reactor irradiation. Added attenuation at 850, 1300, and 1550 nm, appears to be limited by the growth of radiation-induced defect centers that are located in the ultra violet to the visible range and is therefore less at 1300, and 1550 nm than at 850 nm. A linear increase in attenuation, due to displacement damage effects, was observed with increased irradiation time at constant reactor power. However, the rate of increase of the added attenuation during constant power reactor

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5 irradiation monotonically decreased with increasing temperature up to 1000 °C, with the most
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7 significant decrease occurring between 300 and 600 °C. Additional calculations predicted that
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9 the majority of (if not all of) the observed increases in attenuation during irradiation at 600 and
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11 1000 °C were due to effects in the unheated sections of the irradiated sapphire fibers. These
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13 results suggest that, for a reactor radiation environment similar to that tested in this work, heating
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15 sapphire fibers to temperatures of 600 °C or greater during irradiation would significantly reduce
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17 (or possibly eliminate entirely) the rate of growth of the added attenuation in the sapphire fibers.
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24 **Keywords:** sapphire; optical; fiber; heated; radiation; attenuation
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1. Introduction

The U.S. Department of Energy is interested in the development of in-pile instrumentation that would help support the ultimate goal of understanding the behavior and predicting the performance of nuclear fuel systems at a microstructural level¹. Single crystal sapphire optical fibers are a promising candidate for in-pile instrumentation due to the high melting temperature and radiation hardness of sapphire. In order to extend sapphire fiber-based optical instrumentation from non-extreme environments to high temperature radiation environments, the ability of sapphire fibers to adequately transmit light during reactor irradiation at high temperatures must first be determined. Previous work has shown linear increases in the attenuation of sapphire fibers with increasing time during room temperature reactor irradiation at constant reactor power². This work seeks to determine the effects of temperature on the attenuation in the sapphire fibers during irradiation.

The structure of single crystal sapphire and the various defects that contribute to optical attenuation in sapphire have been studied for several decades. Previous work by Crawford³, Valbis and Itoh⁴, and Evans et al.⁵ offer overviews of lattice defects and color centers in sapphire. The majority of the previous work describing reactor irradiation of sapphire used bulk sapphire crystals in the form of discs or plates, as opposed to sapphire in fiber geometry^{6,7,8,9,10}. One work performed by Sporea et al.¹¹ included ex-situ measurements of the transmission of sapphire fibers after accumulating a relatively small neutron fluence (3.15×10^{13} n/cm²). Sporea et al. did not provide any discussion of the results in their paper. With the exception of our work², all previous work involving broadband monitoring of optical transmission in sapphire during reactor irradiation has thus far been limited to ex-situ measurements of the optical transmission that were made post-irradiation. Measurements of the optical transmission in sapphire following

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5 reactor irradiation primarily focused on the transmission at wavelengths below 1000 nm. The ex-
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7 situ transmission measurements made by Levy following reactor irradiation covered wavelengths
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9 as high as 1240 nm. All ex-situ reactor irradiations of sapphire were performed at temperatures
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11 below 80 °C.
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14 In this work, the added optical attenuation in commercially available 100 µm diameter
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16 sapphire fibers was measured in-situ, during reactor irradiation. Portions of the sapphire fibers
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18 were heated, in steps, up to 1000 °C during irradiation, in order to determine the effects of
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20 temperature on the added attenuation during irradiation. Similar optical transmission experiments
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22 were previously performed using silica¹² and sapphire¹³ fibers under gamma irradiation at high
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24 temperatures. In-situ measurements were also made using sapphire fibers under reactor
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26 irradiation at room temperature². Optical transmission through the fibers was continuously
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28 monitored, over a wavelength region covering 500 nm to 2200 nm, throughout the experiment.
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30 The attenuation data especially cover the three wavelengths that are most commonly used for
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32 commercially available fiber optic-based sensors, namely 850 nm, 1300 nm, and 1550 nm. The
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34 in-situ nature of the measurements also significantly improves upon previous ex-situ
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36 measurements, with heating performed post-irradiation. This is because some of the radiation-
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38 induced attenuation that is observed during in-situ measurements could have annealed during the
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40 time between the end of the irradiation and the ex-situ interrogation of the fiber transmission.
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42 Also, the synergistic effects of temperature and radiation damage could not be observed if the
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44 sapphire samples were heated post-irradiation.
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53 54 55 **2. Experimental Setup and Procedure**

56 57 58 **2.1. Experimental Setup**

Figure 1 shows a schematic diagram (not to scale) of the experimental setup, including the silica and sapphire fibers, the furnace and supporting rig, the dry tube facility, the reactor core, and the reactor pool. Three sapphire optical fibers were loaded inside a custom rig containing a high temperature tube furnace (ThermCraft Inc. Part #VF-360-1-12-S-V). The furnace consists of an iron-chrome-aluminum wire wrapped around the 2.54 cm inner diameter of a right circular cylindrical annulus of vacuum-formed ceramic fiber insulation. The insulation has an outer diameter of 7.62 cm, and a total length of 38.1 cm. The heated length of the furnace is 30.5 cm. The rig was lowered into a 17.8 cm outer diameter, 17.1 cm inner diameter dry tube facility (henceforth called the dry tube facility) at the Ohio State University Research Reactor (OSURR), which is a 500 kW pool-type reactor¹⁴.

The three sapphire fibers (approximately 2 meter length, 100 μm diameter sapphire fibers (MicroMaterials part number SF100-200)) were each fusion spliced to ~19 m lengths of jacketed silica fiber (Thorlabs, Inc. part number AFS105/125Y) at each end, which served as lead-in and lead-out fibers. Two of the sapphire fiber assemblies (with jacketed silica lead fibers) were loaded axially through the furnace from top to bottom, bent 180 degrees at a radius of ~5 cm below the furnace, and then passed back up through the bottom of the furnace to exit through the top of the furnace. These two fibers are hereafter referred to as “the interior sapphire fibers”. The third fiber (hereafter referred to as “the exterior sapphire fiber”) was loaded axially from the top of the rig to the bottom of the rig outside of the furnace, bent 180 degrees at a radius of ~5 cm below the furnace, and then passed back up to the top of the rig, once again outside of the heated region of the furnace. The exterior sapphire fiber was included to determine the effects of reactor irradiation during the experiment, without the effects of simultaneous heating of portions of the fiber.

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5 The sapphire-to-silica splices were located more than 30 cm above the reactor core, so
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7 that the silica lead fibers were exposed to a neutron flux that was estimated to be less than 10%
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9 of the peak neutron flux in the dry tube facility. To account for changes in the transmission of the
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11 sapphire fiber assemblies due to attenuation in the silica lead fibers, a jacketed silica fiber (of the
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13 same type as the lead fibers that were spliced to the sapphire fibers) was also loaded into the
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15 experiment. This silica fiber was bent through 180 degrees at the location of the sapphire-to-
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17 silica splices and then passed back up to the top of the irradiation facility. The radiation-induced
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19 attenuation in the silica fiber was later determined to be negligible compared to the radiation-
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21 induced attenuation in the sapphire fibers.
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27 The temperature of the interior of the furnace was monitored using three K-type
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29 thermocouples positioned at various axial locations. Additional thermocouples were positioned
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31 outside of the furnace insulation to monitor changes in the temperature of the exterior sapphire
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33 fiber. As the ThermCraft furnace had an actively heated length of 0.31 meters, and the two
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35 heated sapphire fibers each made two passes through the heated region of the furnace,
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37 approximately 0.62 meters of each fiber were loaded inside the high temperature region of the
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39 furnace. Note that a portion of the sapphire fibers was irradiated but not heated. This is because
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41 the sapphire fibers had to be bent 180 degrees at the bottom of the dry tube at a sufficiently large
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43 bend radius (~5 cm) in order to pass back through the furnace and return to the top of the
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45 irradiation facility through the top of the furnace. Figure 2 shows the spatial (in the axial
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47 direction) profile of the normalized neutron energy deposition rate (energy deposition in
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49 sapphire) inside the dry tube facility. Values are normalized to the peak neutron energy
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51 deposition rate in the facility. The heated and unheated regions of the sapphire fibers are also
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53 indicated in Figure 2. The length of fiber that was exposed to a neutron energy deposition rate
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that was greater than 50% of the peak neutron energy deposition rate was approximately 2*55 cm, or 1.1 meters (see Figure 2). The neutron energy deposition rates were determined from Monte Carlo simulations of the OSURR using the MCNP5 software code package¹⁵. The model of the OSURR was validated by performing foil activation experiments inside of the dry tube facility.

A broadband optical transmission measurement system was developed to automate the measurement of the optical transmission through multiple multimode optical fibers¹⁶. Details regarding this system can be found in a previous paper¹². The system uses a supercontinuum light source (NKT Photonics Inc. K90-110-10 SuperK Compact) as a broadband photon source. Two fiber-coupled multimode optical multiplexers (Avantes FOM-IR400-2x8) allow interrogation of multiple fibers with multiple devices during one experiment. Two fiber-coupled optical spectrometers (StellarNet models RW-NIRX-SR-1024 and BLK-C-SR) were used to measure the broadband optical transmission through the optical fibers.

2.2. Experimental Procedure

The sapphire fibers were loaded into the irradiation facility in the same condition as when they were delivered from the manufacturer. The interior sapphire fibers were heated to 1000 °C prior to irradiation until the thermally-induced attenuation in the fibers came to a dynamic equilibrium. This was done so that there would be no thermally-induced attenuation during the heated reactor irradiation experiment that could be confused with changes in the radiation-induced attenuation at high temperatures. The optical transmission through the sapphire fibers was continuously monitored throughout the experiment.

Prior to the experiment described in sections 3 and 4 (the primary experiment), the sapphire fibers were first irradiated in a preliminary irradiation experiment at 10% reactor power

for two days for approximately 8 hours per day, resulting in values of 9.6×10^{15} n/cm², 1.2×10^{15} n/cm², and 130 kGy for the total accumulated neutron fluence, fast neutron fluence, and absorbed gamma dose, respectively (indicated values are at the vertical mid-plane of the core). During the primary experiment, the sapphire fibers were irradiated at 30% reactor power for four days for approximately 7-8 hours per day, resulting in additional accumulation of neutron fluence. The values of the total neutron flux, fast neutron flux (neutron energies above 0.1 MeV), and gamma dose rate (dose in sapphire) at the vertical mid-plane of the core, for a reactor operating power of 150 kW (30% power), were 5.0×10^{11} n/cm²/s, 6.3×10^{10} n/cm²/s, and 25 kGy/hr, respectively. Values for the neutron flux were determined by unfolding the neutron flux energy spectra using the results of foil activation measurements. The gamma dose rate in the irradiation facility was measured at various reactor power levels using a Mg-walled ion chamber. Values for the total accumulated neutron fluence, fast neutron fluence, and absorbed gamma dose during the entire experiment (both the preliminary and primary experiments) were 5.4×10^{16} n/cm², 6.9×10^{15} n/cm², and 760 kGy, respectively (indicated values are at the vertical mid-plane of the core). Figure 3 shows the time profile of the total neutron flux (at the vertical mid-plane of the core) and the temperature at the center of the furnace, during the primary experiment. The heating of the interior sapphire fibers to 1000 °C prior to irradiation, and the 10% power reactor irradiations (not discussed in this paper) were performed prior to 130 hours.

The results of the optical transmission measurements are presented in this paper as added attenuation (in units of dB), or the change in the optical attenuation in the sapphire fibers from the time that the fibers were inserted into the irradiation facility. The details of how the added attenuation in the sapphire fibers was calculated can be found in a previous paper¹²; therefore, only a brief summary will be provided in this paper. The broadband change in the optical

attenuation of the sapphire fibers was continuously monitored throughout the experiment using the two optical spectrometers. To account for background effects, a background measurement was taken once per cycle with the light source optically disconnected from the sapphire fibers. In post-processing, the background intensity was subtracted from the active transmission intensity during each cycle. To account for changes in light source intensity or spectrometer sensitivity, a control fiber (a sapphire that was neither heated nor irradiated) was also interrogated once per cycle. Any changes in the transmission intensity measured through the control fiber were assumed to be due to variation in the light source intensity or the spectrometer sensitivities. In post-processing, the control fiber data were used to correct the transmission intensities in the heated/irradiated sapphire fibers (i.e. measured values of the added attenuation in the control fiber were subtracted from the measured values of the added attenuation in the heated/irradiated sapphire fiber assemblies). In order to determine uncertainty in the calculated change in attenuation, multiple transmission intensity and background measurements were made during each 2-3 minute measurement cycle, so that a standard deviation could be formed¹⁶.

3. Results

Two interior (both heated and irradiated) sapphire fibers were included in the experiment described in this paper. However, as the results for both fibers were very similar, added attenuation data are only presented for one of the two interior sapphire fibers. The results that were obtained for the exterior (unheated, but irradiated) sapphire fiber are not shown, as they were largely similar to the results obtained in a previous unheated reactor irradiation experiment².

3.1. Dynamics of the Added Attenuation

Figure 4 and Figure 5 show the added attenuation in the sapphire fiber vs. time throughout the experiment at several discrete wavelengths, as indicated in the plots. The wavelengths that are displayed include those that are most commonly used for commercial optical instrumentation (850 nm, 1300 nm and 1550 nm), as well as one wavelength (650 nm) that is in the low wavelength tail of the spectral attenuation in the sapphire fiber (spectral attenuation data are shown in section 3.2). The time profile of the total neutron flux at the location of the peak neutron flux, and the temperature at the center of the furnace, are also shown in Figure 4 and Figure 5. Figure 4 shows data between 133 and 175 hours, during which time the interior sapphire fibers were irradiated at room temperature and at 300 °C. Figure 5 shows data between 180 and 220 hours, during which time the interior sapphire fibers were irradiated at 600 and 1000 °C. The increase in temperature between 135 and 143 hours was caused by gamma heating when the reactor was operated. All other increases in temperature were caused by electrical heating using the furnace, with only minor contributions from gamma heating. The data in Figure 4 and Figure 5 clearly show that the slopes of the added attenuation are smaller during irradiation at 600 and 1000 °C, compared with the slopes during irradiation at 59 and 300 °C.

3.2. Spectral Features of the Added Attenuation

Figure 6 shows the broadband changes in the optical attenuation of the sapphire fiber at several times throughout the experiment. The spectral added attenuation data were plotted as a function of photon energy, instead of wavelength, because the absorption spectra due to many known defect centers in sapphire have previously been found to have approximately Gaussian distributions when plotted vs. photon energy⁶. Figure 6 shows added attenuation spectra at four

times during the experiment as indicated in the figure caption. Note that the reader should be careful not to draw conclusions from any data with added attenuation above ~20 dB. This is because these large increases in attenuation reduced the transmitted light signal to the point that the measured light intensities became too susceptible to noise in the measurement system. The large spectral fluctuations in the data for curves 2-4 above ~2.2 eV in Figure 6 are an example of noisy data caused by excessively large added attenuation. The data in Figure 6 show the same trends (i.e. smaller increases in added attenuation during irradiation at 600 and 1000 °C, compared to increases during irradiation at 59 and 300 °C) that can be observed in Figure 4 and Figure 5. The differences between curves 1 and 2 shown in Figure 6 (measured at two times during irradiation at ~59 °C, separated by 6 hours) are much larger than the differences between curves 3 and 4 shown in Figure 6 (measured at two times during irradiation at ~1000 °C, separated by 6 hours).

4. Discussion

These in-situ measurements provide new information regarding the dynamics of reactor radiation-induced attenuation in sapphire fibers when portions of the fibers are heated to temperatures up to 1000 °C. Previous ex-situ measurements made by others were only able to measure the radiation-induced attenuation post-irradiation, after some reduction of the attenuation had already occurred. Heating the fibers post-irradiation does not allow one to observe the synergistic effects of radiation and temperature. The results presented in this work show the importance of making in-situ measurements when determining the suitability of using sapphire optical fibers, or sapphire optical fiber-based instrumentation, in a high temperature reactor radiation environment.

The dynamic behavior of the added attenuation immediately before, during, and after reactor irradiation at temperatures close to room temperature has been discussed previously². Consistent with previous work, the results of this work (see Figure 4 and Figure 5) show that the added attenuation, particularly at 650 and 850 nm, increased linearly with irradiation time. Figure 6 shows that reactor radiation had much less of an effect on the optical transmission in sapphire at energies below 1 eV, compared to higher energies that are closer to known defect centers (e.g. F_2^+ and F_2^{2+} defect centers, with peak absorption energies of 3.5 and 2.8 eV, respectively^{10,17}). These results suggest that sapphire optical fiber-based instrumentation should be designed to operate at wavelengths of 1300 or 1550 nm, as opposed to 850 nm, if it is to be used in a reactor radiation environment. Potential for use of sapphire optical fiber-based instrumentation, operating at any wavelength between 500 and 2200 nm (including 850, 1300, and 1550 nm), in a reactor radiation environment, would ultimately be limited by the growth of radiation-induced defect centers located in the ultra violet to the visible range (200 to 450 nm). This is because all of the radiation-induced attenuation at wavelengths above 500 nm appears to be due to tails from defect centers located below 500 nm. The results presented here show that the growth of these low-wavelength defect centers is significantly reduced when the temperature is increased.

4.1. Dynamic Growth of the Added Attenuation

The added attenuation in the interior sapphire fiber between 133 and 175 hours (Figure 4) shows dynamic behavior similar to what was observed in a previous unheated reactor irradiation experiment². The reader is referred to this previous work for a more detailed explanation of the dynamic behavior of the added attenuation immediately before, during, and after reactor irradiation. Only a brief discussion of this dynamic behavior is provided here. When the

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5 irradiation was started at 135.2 hours, the added attenuation first increased rapidly, but then
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7 immediately started to decrease due to increased temperature that was caused by gamma heating
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9 inside the furnace insulation. The transient decrease in the added attenuation concluded by about
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11 136.5 hours, and after this time the added attenuation increased with a constant slope. The
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13 transient behavior can be explained by rapid ionization of existing defect centers, when the
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15 irradiation first started, in competition with increased charge recombination when the
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17 temperature increased. Constant accumulation of defect centers via displacement damage, and
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19 their immediate activation (due to ionizing radiation), is responsible for the linear increase in
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21 added attenuation following the transient. The added attenuation decreased when the reactor was
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23 shut down (at 143.1 hours). This decrease was due to charge recombination at defect centers
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25 exceeding the rate of ionization, once the reactor was shut down and the ionization dose rate
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27 decreased. Increasing the temperature at 158.7 hours, prior to resuming the reactor irradiation,
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29 caused further increases in charge recombination, which further decreased the added attenuation.
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31 Resuming the reactor irradiation at 159.5 hours caused rapid ionization of a large number of
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33 defects, which caused the added attenuation to rapidly increase. When the reactor was shut down
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35 at 167.4 hours, the added attenuation decreased rapidly while the temperature was maintained at
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37 300 °C. When the furnace was shut down and the temperature started to drop at 168 hours, the
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39 added attenuation increased temporarily and then approached a steady-state value, after the
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41 temperature reached room temperature near 171 hours. As is the case for when the reactor was
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43 shut down at 143.1 hours, the dynamic behavior after the reactor was shut down at 167.4 hours
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45 can be explained by competition between ionization and thermally-induced charge
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47 recombination.
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The added attenuation in the interior sapphire fibers between 180 and 230 hours (Figure 5) generally shows dynamic behavior similar to what was observed between 133 and 175 hours. The higher temperatures that were tested between 180 and 230 hours caused more significant decreases in the added attenuation when the temperature was increased prior to irradiation (i.e. at 182.3 and 206.1 hours). Also, the slopes of the added attenuation vs. time data during constant power irradiation at 600 and 1000 °C appear to be smaller than the slopes during constant power irradiation at 59 and 300 °C. The added attenuation data in the interior sapphire fiber at 650 nm were fit for each constant temperature irradiation period to determine the slope of the added attenuation vs. time data as a function of temperature for constant reactor power. Table 1 shows the slope of the added attenuation vs. time data at 650 nm, the goodness of fit parameter for the linear fit, and the temperature for each data set that was fit.

Table 1 shows that increasing temperature caused a monotonic decrease in the slope of the added attenuation at 650 nm. This is consistent with the idea that increased temperature reduced the formation of optically active defect centers either by annealing of point defects, increased charge recombination at existing point defects, or some combination of both processes. The slope of the added attenuation decreased most significantly when the temperature during irradiation was increased from 300 to 600 °C. However, the ability to draw conclusions from the data presented in Table 1 is limited by the fact that only a portion of the interior sapphire fiber was heated. Because only a portion of the interior sapphire fiber was heated, there was a section of the interior sapphire fiber that was exposed to reactor irradiation at approximately room temperature, even when the furnace temperature was increased as high as 1000 °C. The slopes that were determined for the increase in added attenuation, during reactor irradiation at each

temperature, include effects both in the heated portion of the fiber and the unheated portions of the fiber.

4.2. Separation of the Effects in the Heated and Unheated Regions of the Fiber

The separate effects of reactor irradiation on the heated and unheated portions of the interior sapphire fiber were estimated using a simple calculation. This calculation first assumed that during constant power reactor irradiation at some temperature, the time derivative of the added attenuation per unit length of fiber is proportional to the neutron energy deposition rate. This assumption is supported by previous reactor irradiation experiments¹⁸. The neutron energy deposition rate is proportional to the total neutron flux, so long as the neutron flux energy spectra do not vary significantly with location in the irradiation facility. It was further assumed that the temperature was spatially constant over the heated region of the fiber (with the temperature equal to the measured temperature at the center of the furnace for each constant temperature irradiation period), and spatially constant over the unheated region of the fiber (with the temperature always equal to room temperature in this section of the fiber). These assumptions are summarized in Equations [1] through [4].

$$\frac{dA_{total}}{dt}(T) = \frac{dA_H}{dt}(T) + \frac{dA_{UH}}{dt} \quad [1]$$

$$\frac{dA_H}{dt}(T) = \oint_{L_H} \frac{da(x,T)}{dt} dx \quad [2]$$

$$\frac{dA_{UH}}{dt} = \oint_{L_{UH}} \frac{da(x,T = 22 \text{ }^{\circ}\text{C})}{dt} dx \quad [3]$$

$$\frac{da(x,T)}{dt} = R(T(x))\phi(x) \quad [4]$$

where:

A_{total} = Total (integrated over the entire length of the sapphire fiber) added
attenuation at 650 nm (dB)

A_H = Added attenuation at 650 nm (dB) in the heated portion of the sapphire fiber

A_{UH} = Added attenuation at 650 nm (dB) in the unheated portion of the sapphire fiber

t = Time (seconds) during constant power reactor irradiation

T = Temperature (°C)

a = Added attenuation per unit length at 650 nm (dB m⁻¹)

x = Position along the length of the sapphire fiber (m)

L_H = Length of the heated region of the sapphire fiber (m)

L_{UH} = Length of the unheated region of the sapphire fiber (m)

R = Response function accounting for temperature dependence
of the radiation-induced attenuation (dB m⁻¹ cm²)

ϕ = Total neutron flux (cm⁻² s⁻¹)

Between 137 and 143 hours, both the heated and unheated sections of the fiber were irradiated at constant reactor power at close to room temperature. The temperature of the interior of the furnace increased during this time to about 59 °C (due to gamma heating), but these temperature effects are neglected in the present analysis. Between 137 and 143 hours, the following relations can be written.

$$\frac{dA_H}{dt}(T = 22 \text{ }^\circ\text{C}) = R(T = 22 \text{ }^\circ\text{C}) \oint_{L_H} \phi(x) dx \quad [5]$$

$$\frac{dA_{UH}}{dt} = R(T = 22 \text{ }^\circ\text{C}) \oint_{L_{UH}} \phi(x) dx \quad [6]$$

$$\frac{dA_T}{dt}(T = 22 \text{ }^\circ\text{C}) = R(T = 22 \text{ }^\circ\text{C}) \left[\oint_{L_H} \phi(x) dx + \oint_{L_{UH}} \phi(x) dx \right] \quad [7]$$

$$\frac{\frac{dA_{UH}}{dt}}{\frac{dA_{total}}{dt}(T = 22 \text{ }^{\circ}\text{C})} = \frac{\oint_{L_{UH}} \phi(x) dx}{\oint_{L_H} \phi(x) dx + \oint_{L_{UH}} \phi(x) dx} = F_{UH} \quad [8]$$

$$\frac{\frac{dA_H}{dt}(T = 22 \text{ }^{\circ}\text{C})}{\frac{dA_{total}}{dt}(T = 22 \text{ }^{\circ}\text{C})} = \frac{\oint_{L_H} \phi(x) dx}{\oint_{L_H} \phi(x) dx + \oint_{L_{UH}} \phi(x) dx} = F_H(T = 22 \text{ }^{\circ}\text{C}) \quad [9]$$

Using the relations shown in Equations [5] through [9], the following relations can be written for $\frac{dA_H}{dt}(T)$.

$$\frac{dA_H}{dt}(T) = \frac{dA_{total}}{dt}(T) - \frac{dA_{UH}}{dt} \quad [10]$$

$$\frac{dA_H}{dt}(T) = \frac{dA_{total}}{dt}(T) - \frac{dA_{total}}{dt}(T = 22 \text{ }^{\circ}\text{C})F_{UH} \quad [11]$$

As described previously (see section 2.1), the spatial profile (in the axial direction) of the neutron energy deposition rate (assumed to be proportional to $\phi(x)$) in the dry tube facility of the OSURR was determined from MCNP simulations. Figure 2 shows the axial profile of the normalized neutron energy deposition rate (neutron energy deposition in sapphire) obtained from the MCNP simulations. The energy deposition rates presented in Figure 2 are normalized to the peak energy deposition rate in the facility. Also shown in Figure 2 are the locations of the heated (L_H) and unheated (L_{UH}) regions of the sapphire fibers.

The data shown in Figure 2 were used to calculate $F_H(T = 22 \text{ }^{\circ}\text{C})$ and F_{UH} . These values were calculated to be 52% and 48%, respectively. Using these values and the data

presented in Table 1 for $\frac{dA_{total}}{dt}(59\text{ }^{\circ}\text{C})$ (assumed to be equal to $\frac{dA_{total}}{dt}(22\text{ }^{\circ}\text{C})$), $\frac{dA_{UH}}{dt}(22\text{ }^{\circ}\text{C})$ can be calculated using Equation [9] to be $0.48*0.524\text{ dB/hr}$, or 0.252 dB/hr . Table 1 shows values of $\frac{dA_{total}}{dt}(T)$ for T equal to 59, 300, 600, and $1000\text{ }^{\circ}\text{C}$. By subtracting $\frac{dA_{UH}}{dt}(22\text{ }^{\circ}\text{C})$ from these values (see Equation [11]), $\frac{dA_H}{dt}(T)$ can be calculated for T equal to 59, 300, 600, and $1000\text{ }^{\circ}\text{C}$. Table 2 shows $\frac{dA_H}{dt}(T)$ for temperatures of 59, 300, 600, and $1000\text{ }^{\circ}\text{C}$.

Table 2 clearly shows that for temperatures of 600 and $1000\text{ }^{\circ}\text{C}$, $\frac{dA_H}{dt}(T)$ is reduced to approximately zero. Therefore, according to the calculations presented in this section, essentially all of the increase in the added attenuation of the interior sapphire fiber that was observed at 650 nm during reactor irradiation at temperatures of 600 and $1000\text{ }^{\circ}\text{C}$ was due to reactor radiation-induced attenuation in the unheated portion of the sapphire fiber. While the results presented in this section are not completely conclusive, it appears that heating the interior sapphire fibers to temperatures of $600\text{ }^{\circ}\text{C}$ or greater during reactor irradiation caused significant reduction (or possibly entire elimination) of the rate of growth of the added attenuation at 650 nm in the heated portion of the interior sapphire fiber.

5. Summary and Conclusions

In this work, in-situ measurements of the broadband (500 – 2200 nm, or 0.56 – 2.48 eV) optical transmission in two commercially available sapphire optical fibers were made during exposure to reactor irradiation. A portion of the fibers was heated to various temperatures up to $1000\text{ }^{\circ}\text{C}$ in order to determine the suitability of using sapphire optical fibers in a high temperature reactor radiation environment. Approximately 1.33 meters of each sapphire fiber

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5 were exposed to a neutron flux that was greater than 50% of the peak neutron flux in the
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7 experimental facility (5.0×10^{11} n/cm²/s). The fibers were irradiated for approximately 8 hours for
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9 each temperature that was tested (59, 300, 600, and 1000 °C). At the location of the peak neutron
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11 flux and peak gamma dose rate, the fibers were exposed to a total neutron fluence of 6.4×10^{16}
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13 n/cm² and total gamma dose on the order of 1 MGy. The added attenuation in the sapphire fibers
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15 generally showed dynamic behavior similar to what was observed in a previous unheated reactor
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17 irradiation experiment². The added attenuation showed a linear increase with increasing time at
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19 constant reactor power for each of the temperatures that were tested. The added attenuation vs.
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21 time data in the interior sapphire fiber at 650 nm (a wavelength that lies in the low-wavelength
22
23 tail of the attenuation spectra) were fit for each constant temperature irradiation period. This
24
25 fitting was performed in order to determine the rate of growth of the added attenuation as a
26
27 function of temperature, for constant reactor power. The rate of increase of the added
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29 attenuation, during constant power reactor irradiation, monotonically decreased with increasing
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31 temperature up to 1000 °C, with the most significant decrease occurring between 300 and 600
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33 °C.
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42 The ability to draw conclusions from the fitting was limited by the fact that only a portion
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44 of the interior sapphire fiber was heated. The separate effects of reactor irradiation on the heated
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46 and unheated portions of the interior sapphire fiber were estimated using a simple calculation
47
48 that assumed that, for constant power reactor irradiation, the time derivative of the added
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50 attenuation is proportional to the neutron flux. Using data for the spatial (in the axial direction)
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52 profile of the neutron energy deposition rate in the irradiation facility (determined from MCNP
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54 simulations), it was estimated that the heated and unheated regions of the sapphire fiber were
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56 exposed to 52% and 48% of the total neutron energy deposition rate integrated over the entire
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5 region of the sapphire fiber, respectively. Using this approximation, it was found that the slope of
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7 the added attenuation in the interior sapphire fiber, during reactor irradiation at temperatures of
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9 600 and 1000 °C, was approximately equal to the estimated contribution to the measured added
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11 attenuation, at room temperature, from effects in the unheated region of the interior sapphire
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13 fiber alone. Therefore, according these calculations, the majority of (if not all of) the increase in
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15 the added attenuation, of the interior sapphire fiber that was observed at 650 nm during
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17 irradiation at temperatures of 600 and 1000 °C, was due to reactor radiation-induced attenuation
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19 in the unheated portion of the sapphire fiber. While the analysis presented here is not completely
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21 conclusive, it appears that heating the interior sapphire fibers, to temperatures of 600 °C or
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23 greater during the reactor irradiation, caused significant reduction (or possibly entire elimination)
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25 of the rate of growth of the added attenuation at 650 nm in the heated portion of the interior
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27 sapphire fiber. Added attenuation at 850, 1300, and 1550 nm, appears to be limited by the growth
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29 of radiation-induced defect centers that are located in the ultra violet to the visible range and is
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31 therefore less at 1300 and 1550 nm than at 850 nm; and less at 850 nm than at 650 nm.
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57 graduate student at The Ohio State University) also contributed. This material is based upon
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Table 1: Results of the linear fitting to the dynamic added attenuation data at 650 nm during the heated reactor irradiation experiment. Data were fit for each constant temperature reactor irradiation period.

Time period	Temperature (°C)	$\frac{dA_{total}}{dt}(T)$ Slope of added attenuation at 650 nm (dB/hr)	Goodness of fit parameter
137 to 143 hours	56	0.524 ± 0.003	0.999
160 to 167 hours	300	0.489 ± 0.003	0.999
184 to 190 hours	600	0.273 ± 0.005	0.990
208.5 to 215 hours	1000	0.228 ± 0.003	0.993

Table 2: Estimated contributions to the rate of growth of the added attenuation in the sapphire fiber at 650 nm, during reactor irradiation, due to effects only in the heated portion of the sapphire fiber ($\frac{dA_H}{dt}(T)$). $\frac{dA_H}{dt}(T)$ was calculated as a function of temperature in the heated portion of the sapphire fiber.

Temperature (°C)	$\frac{dA_H}{dt}(T)$ (dB/hr)
56	0.273 ± 0.003
300	0.238 ± 0.003
600	0.022 ± 0.004
1000	-0.024 ± 0.003

Figure 1: Schematic diagram (not to scale) of the experimental setup, including the silica and sapphire fibers, the furnace and supporting rig, the dry tube facility, the reactor core, and the reactor pool.

Figure 2: Spatial (in the axial direction) profile of the normalized neutron energy deposition rate (energy deposition in sapphire) inside the irradiation facility. Values are normalized to the peak neutron energy deposition rate in the facility. The heated and unheated regions of the sapphire fibers are also indicated in the figure. These data were obtained from validated Monte Carlo simulations.

Figure 3: Time profile of the total neutron flux (at the vertical mid-plane of the reactor core) and the temperature at the center of the furnace, during the heated reactor irradiation experiment described in this work.

Figure 4: Added attenuation in the sapphire fiber at various wavelengths as a function of time between 133 and 175 hours, during which time the sapphire fibers were irradiated at room temperature and at 300 $^{\circ}\text{C}$. The neutron flux at the location of the peak flux and the temperature at the center of the furnace are also shown as a function of time. The widths of the lines for the added attenuation data shown in this figure indicate one sigma uncertainties.

Figure 5: Added attenuation in the sapphire fiber at various wavelengths as a function of time between 180 and 220 hours, during which time the sapphire fibers were irradiated at 600 and 1000 °C. The neutron flux at the location of the peak flux and the temperature at the center of the furnace are also shown as a function of time. The widths of the lines for the added attenuation data shown in this figure indicate one sigma uncertainties.

Figure 6: Added attenuation in the sapphire fiber as a function of photon energy at various times during the irradiation experiment. The indicated temperatures are at the center of the furnace. The indicated values of the accumulated fluence are at the axial location corresponding to the peak neutron flux. The widths of the lines shown in this figure indicate one sigma uncertainties. Times that are shown include: 1. After approximately 2 hours of irradiation at a temperature of 57-59 °C, 2. After approximately 8 hours of irradiation at a temperature of 57-59 °C, 3. After approximately 1.5 hours of irradiation at a temperature of 1000 °C, and 4. After approximately 7.5 hours of irradiation at a temperature of 1000 °C.

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