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EVALUATION OF FIBER OPTIC PERFORMANCE IN THE ACRR

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ABSTRACT

Four fluorosilica clad, all silica core fibers with polyimide buffers were examined for radiation-induced, transient absorption in the central cavity of the Annular Core Research Reactor. The reactor operated 24 times in the pulse mode, typically yielding gamma doses of 15 krad(Si) and neutron fluences of 1.4×10^{14} nts/cm² (thermal) and 1.0×10^{15} nts/cm² (fast). The two low-OH fibers absorbed 90% of the light in the 400 to 500 nm region and 30% in the 700 to 800 nm region. The high-OH fibers absorbed 20% in the 400 to 500 nm region and 50% in the 700 to 800 nm region. Saturation of the transient induced absorption was observed in all the fibers. No systematic measurements were taken of long term induced absorption. However, excessive absorption was not a problem in any fibers, even those that received total gamma doses of 5 Mrad(Si). Scintillation in the 680 to 820 nm band was observed. This report documents the data from these experiments.

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INTRODUCTION

Fiber optic thermometry and two-color pyrometry are two potential applications for fiber optics in experiments conducted at the Annular Core Research Reactor (ACRR). Fiber optic thermometry requires that under irradiation the fibers remain transparent in the visible wavelengths (~400 to 700 nanometers). Two-color pyrometry for 3000 K objects requires that under irradiation the fibers remain transparent in the near infrared (~0.8 to 1 micron).

Test procedures and standards [Greenwell 1987b] have been developed for measuring the radiation effects in optical fibers and a considerable amount of data is available to guide the selection of optical fibers based on these standards. The radiation sources favored by investigators using these standards are e-beams, Co-60 and x-rays. Tests of optical fibers in nuclear reactors (i.e. gamma and neutrons) have also been undertaken [Partin 1984 and Singh et. al 1990], but not according to the standards mentioned or at the power levels available in the ACRR.

The intent and scope of this work was to examine the response of some commercially available radiation resistant fibers to irradiation in the ACRR environment. These were facility specific tests. The test procedures did not conform to published standards, but were designed to simulate the actual environments of anticipated experiments. Ours was not intended to be an exhaustive investigation, but more a simple evaluation of fibers that have been or will be used in reactor experiments. This report documents the data from this investigation.

A review of the literature [Harrington et. al 1989; Greenwell 1987a; Friebele 1985] and manufacturers data indicates that undoped silica core, fluorosilica clad, polyimide buffer fibers show good radiation resistance. Such fibers from several different suppliers (see Table 1) were looped down into the central cavity of the ACRR. The fibers were evaluated based on their transmission of light from a standard tungsten filament lamp while the ACRR was operated in the pulsed mode. The intent was to measure the transient absorption characteristics of the fibers as a function of wavelength. Therefore, we made no effort to measure on an absolute scale the transmission characteristics of the fibers; all measurements were relative to the fiber transmission just prior to the ACRR pulse. We did not attempt to measure the long-term, radiation-induced absorption in the fibers.

Our results show that fluorosilica clad, all silica core fibers with a polyimide buffer, matched to wavelengths of interest and combined with narrowband filters, can be used successfully in the ACRR for fiber optic thermometry and two color pyrometry. The presence of scintillation needs to be accounted for during the main peak of the reactor power pulse.

EXPERIMENTAL PROCEDURE

The optical fibers were inserted into the central cavity of the ACRR as shown in Figure 1. The central cavity is a 9-inch diameter, 25-ft long vertical pipe with access only at the above water end. The loop in the fibers had a bending radius of approximately 3.5 inches and was maintained by taping the fibers to a piece of cardboard. Radiochromic dosimetry to measure the gamma exposure was placed at the center of the bending radius and at 2, 4, 6, and 8 feet above this point. The radiochromic dosimetry responds to neutrons in a manner which is not well characterized and so the doses quoted cannot be compared reliably to pure gamma irradiation (for example, by Co-60). Best estimates, though, indicate that doses reported here are twice the equivalent gamma dose in silicon (that is, the dose values given should be divided by 2 to get krad(Si)).

Light was injected into the fiber using the arrangement shown in Figure 2. The light source was a 200 W tungsten filament lamp powered by a 65DS, Optronics Laboratories Inc. constant current power supply operating at 6.6 amps. This light is similar to the calibrated light sources used for photometric measurements. The lens imaged the filament onto the end of the fiber with a magnification of approximately 0.4.

The light transmitted through the fiber was directed toward the entrance slit of a monochromator. A Thermo Jarrell Ash (model 82-498), 1/4-meter monochromator was used with a 600 groove/mm, 700-nm blaze grating and a 25-micron slit. An EG&G Princeton Applied Research (model 1421 UV) OMA head was mounted to the back end of the monochromator. The OMA controller (model 1460/1461) was setup to store 12 successive spectra after receiving a trigger from the ACRR control console.

We encountered considerable difficulty in properly configuring the OMA software to accept an external trigger input. A trigger from the ACRR control panel was initially fed directly into the trigger input of the OMA (shots 5327 to 5329). The OMA was to output when each scan was taken, but this feature did not function. Therefore, note that in Figures 5 and 7 there is an uncertainty in the origin of the light transmission curves of $-0/+17.6$ msec. That is, the OMA could have triggered up to 17.6 msec after the arrival of the ACRR trigger input. The OMA was not used during shots 5330 to 5338 while a new triggering circuit was built using the OMA "SYNC" output. The new triggering circuit and OMA software configuration functioned reliably after setting the trigger pulse duty cycle to 10% on time. Shots 5339 to 5341 had similar timing errors as 5327 while the correct duty cycle was being determined.

Typically the OMA was triggered so as to store 1 or 2 scans prior to the reactor power pulse. These initial scans were used as the baseline for light transmission and the successive scans were normalized by this baseline. A typical reactor power trace, with the OMA integration intervals used, is shown in Figure 3. The reactor was operated in the standard pulse mode and the fat-pulse mode. The standard pulse power-versus-time graph had a shape that was very close to a Gaussian and was characterized by the peak power and the full-width-half-maximum (FWHM).

Table 1 identifies each of the fibers evaluated and Table 2 summarizes the parameters of each reactor operation. The OMA integration times were comparable to the FWHM of the standard power pulse, so that there was no time-resolved behavior of the absorption during the pulse. Shot numbers 5334, 5337, 5340, and 5343 were fat-pulses which had power-versus-time shapes resembling two overlapping gaussian peaks. The FWHM of the fat-pulses were much greater than the OMA integration times which allowed some time-resolved data. However, the OMA memory was limited to 12 scans and that was not enough to cover an entire fat-pulse.

RESULTS

Figures 4 to 34 summarize the light transmission through the fibers as measured by the OMA. The figures are in four groups, one for each of the four fibers irradiated. There are generally two figures for each reactor operation: one plot shows the light transmission versus wavelength and one plot shows the light transmission, averaged over a wavelength range, versus time. The second title line of each figure identifies the ACRR shot number, the reactor peak power, and the FWHM of the pulse. The OMA spectra did not always successfully save to disk, so the light transmission at a few selected wavelengths was recorded by hand. Reactor operation ("shot") 5346 (Figure 10) is an example where only the manually recorded data is available.

The plots labeled "OMA SPECTRA" show a few of the 12 OMA scans from each reactor operation. These plots show the relative change in the light transmitted by the fibers. The integration time of each scan was approximately 17 msec. Except in a few cases, the first scan of the OMA was used as the reference spectrum to normalize the successive 11 scans. The reference spectrum appears as a horizontal flat line at 1 in these plots. During the experiment series the amount of light transmitted at selected wavelengths was recorded by hand well before the reactor pulse. These pre-pulse measurements were compared to the first OMA scan taken during the pulse. No differences were found between the pre-pulse spectrum and the first scan provided the first scan occurred prior to the reactor going prompt critical. In cases where there were differences (shots 5328, 5341, 5344, and 5350) the pre-pulse data was used as the reference spectrum rather than the first scan. The spectra have been smoothed using a 7-point, moving-average filter in order to improve the readability of the plots.

The plots labeled "AVERAGE TRANSMISSION" show the light transmission-versus-time for various wavelength regions. The integrated dose-versus-time is also plotted on these figures. The decrease in the transmitted light (absorption) varied as a function of wavelength, as can be seen in the "OMA SPECTRA" plots. Therefore, averages over different wavelength ranges were computed for these cases. Scintillation [Harrington et al. 1989; Lyons 1985] also occurred, and dominated portions of the measured spectrum. Shot 5344 (Figure 15) is an example where scintillation is dominating the spectrum in the 780 to 830 nm range. The "AVERAGE TRANSMISSION" plot for shot 5344 has two traces, one for each of two wavelength regions.

TABLE 1
Fibers evaluated for experiments in the ACRR

<u>Fiber</u>	<u>Manufacturer's ID</u>	<u>Description</u>
FI	AFA 200/220T	200 micron pure silica core (low-OH), fluorine doped silica clad, polyimide jacket. Fiberguide Industries, Stirling, NJ (908) 647-6601
PT	PTA-OKJ0001AA-098-3A	200 micron pure silica core (low-OH), fluorine doped silica clad, polyimide jacket. Polymicro Technologies Inc. Phoenix, AZ (602) 272-7437
DI	FV-D95P/ST200D	200 micron standard silica core, unknown clad, nylon jacket. Diaguide ST series. Mitsubishi Cable America, Inc. New York, NY (212) 888-2270
L	EA-30-10136	200 micron all silica fiber of uncertain manufacturer either 3M Specialty Fibers or Fiberguide Industries. Purchased from Luxtron, Mountain View, CA (408) 727-1600

TABLE 2
Summary of Reactor Operations

<u>Shot #</u>	<u>Fibers in Reactor¹</u>	<u>Fiber Observed by OMA²</u>	<u>Peak Power [MW]</u>	<u>FWHM [msec]</u>	<u>Energy Total [MJ]</u>	<u>Dose Total [krad]^{3,4}</u>
5327	FI,DI	FI	2300	23	63	1450
5328	FI,DI	FI	1170	33	170	3910
5329	FI,DI	FI	2000	22.4	60	1380
5330	FI,DI	---	8300	12.4	127	2920
5331	FI,DI	---	2450	20.5	65	32
5332	FI,DI	---	2400	21	63	31
5333	FI,DI	---	aborted			
5334	FI,DI	---	770	207	150	75
5335	FI,DI	---	9400	11.5	135	67
5336	FI,DI	---	2500	20	65	32
5337	FI,DI	---	680	150	150	75
5338	FI,DI	---	9400	11.6	135	67
5339	FI,DI,PT	DI	2500	20	65	32
5340	FI,DI,PT	DI	690	144	147	73
5341	FI,DI,PT	DI	9400	11.6	135	67
5342	FI,DI,PT	DI	2500	20.5	65	32
5343	FI,DI,PT	DI	590	176	146	73
5344	FI,DI,PT	PT	9300	11.6	134	67
5345	FI,DI,PT	PT	2400	20.6	63	31
5346	FI,DI,PT	FI	2400	20.8	63	31
5347	FI,DI,PT	FI	2400	20.6	63	31
5348	FI,DI,PT	PT	2400	20.8	63	31
5349	FI,DI,PT,L	L	2100	21.5	58	29
5350	FI,DI,PT,L	L	2200	22	60	30
5351	FI,DI,PT,L	FI	2300	21.4	62	31

1 FI-Fiberguide Industries, DI-Diaguide, PT-Polymicro Technologies, L-Luxtron (see Table 2).

2 Dash marks (---) indicate that the data was not recorded successfully.

3 Shots 5327 to 5330 were done with the fibers in the peak of the neutron flux. All other shots were done with the fibers 3 ft above this point.

4 These doses have not been corrected for neutron effects. Best estimates indicate that dividing the doses by 2 gives the equivalent dose in Si.

We confirmed the presence of scintillation by examining the light emitted from a fiber during a reactor operation with the light source turned off (shot 5329). Figure 8 shows the background corrected spectra of the OMA as photon counts versus wavelength. This figure cannot be taken as the actual absolute scintillation spectrum of the fiber since no corrections have been applied for the spectral response of the OMA head and electronics. Figure 35 shows the typical spectral response of the OMA head given by the manufacturer. It is apparent that the sensitivity of the OMA is falling off significantly toward the longer wavelengths. Thus, the actual scintillation spectrum could be much broader than that shown in Figure 8. Interpreting Figure 8 is further complicated in that the scintillation spectra could be a composite of a luminescence peak at 650 nm and a second order peak from the 450 nm luminescence band as noted by Marrone [1981]. Filters to eliminate the second order peak are commercially available, but were not used in our experiments.

The real purpose in examining scintillation was to verify that the increased light measured by the OMA was actually coming from scintillation and not from increased transmission by the fiber of the source lamp. Figure 9 shows the ratio of the scintillation light to the transmitted light from the source lamp. The source lamp light spectrum used to produce Figure 9 was recorded when the reactor was NOT operating. This figure shows that the scintillation light represents a significant fraction of the spectrum at wavelengths longer than 730 nm in the "OMA SPECTRA" plots. Scintillation could be a serious limitation during the reactor pulse (see Figures 9, 12, 16, and others).

No systematic effort has been made to monitor the recovery of the fibers used in this experiment after their irradiation. However, an estimate of the long-term induced absorption can be attempted by examining changes in the shape of the transmitted spectra for the same fiber after many reactor operations (Figure 36). This figure is based on the manually recorded data prior to any irradiation and after 5 Mrad(Si) dose. The two spectra were produced by taking as a point of reference in each data set the amount of light measured at 440 nm and setting this value to 1. The other points in the spectrum were generated by ratioing the light measured at the other wavelengths to that at 440 nm. So this figure indicates how the relative spectral transmission of light through the fiber changed due to irradiation, but does not give an absolute measure of the change.

DISCUSSION

It is customary to categorize fibers as low water content (low-OH) and standard fibers. The low-OH fibers are used in the infrared where water is a strong attenuator. The standard fibers have a few parts per million of water. This categorization is also convenient in discussing the radiation response characteristics of the fibers. Water in a fiber helps to anneal out the transient absorption at visible wavelengths due to irradiation. The low-OH fibers do not benefit from this annealing effect. Consequently, the two low-OH fibers show poor transmission characteristics in the 400 to 500 nm range under irradiation. The low-OH transmission drops by a factor of 100 (99% absorption) for these wavelengths compared to a 15 % drop for the standard fiber obtained from Luxtron. The second standard fiber, obtained from Diaguide, was not tested in the

400 to 500 nm range due to time constraints. Similarly, the Luxtron fiber was not able to be tested at long wavelengths.

The low-OH fibers exhibited less absorption (30 to 50%) at longer wavelengths (700 to 850 nm). The standard fiber from Diaguide showed similar absorption characteristics. Experiments on the transient absorption characteristics of fused silica optics [Brannon et al. 1992a]¹ and fiber optics [Rao et al. 1979; Brannon et al. 1992b] has also demonstrated this improvement in radiation response at longer wavelengths. That is, the transient radiation induced absorption is more severe in the blue than in the red.

The plots showing the light transmission versus time for all of the fibers consistently shows a saturation effect. The transmission drops at the start of the reactor operation and quickly saturates to a constant value. The absorption does not appear to be a strong function of the total integrated dose, since absorption does not increase significantly during the peak of the pulse or during the long pulse tail. Saturation of the induced absorption has been observed by many researchers particularly at wavelengths longer than 600 nm [Karasawa et al. 1990]

Photobleaching has been identified as a factor affecting the saturation of radiation-induced absorption at 870 nm and -55°C [Evans 1989]. The photobleaching effect becomes significant at transmitted power densities above $13\text{E-}6 \text{ W/cm}^2\text{-nm}$ and does show some influence at power densities 100 times lower than this. The power density incident on the end of the fibers in this experiment varied from $6.5\text{E-}6 \text{ W/cm}^2\text{-nm}$ at 400 nm to $21\text{E-}6 \text{ W/cm}^2\text{-nm}$ at 800 nm (see Figure 37). These power densities were estimated from the manufacturers stated lamp output and the optical geometry. Photobleaching could, therefore, have been an influence in the saturation of the induced absorption.

Scintillation occurs during the reactor pulse consistently in the 700 to 850 nm band and there is evidence of scintillation in the 350 to 450 nm band. The amplitude of the scintillation varies proportionately with the reactor power. The scintillation portion of the signals has an asymmetric shape which is consistent with the transient absorption in the fiber being proportional to the dose.

CONCLUSIONS

We have determined that fiber optics can be employed in reactor experiments in the ACRR by following these guidelines:

- Match the fiber to the wavelength of interest, low-OH fibers for the near-IR and standard fibers for the blue and visible.
- Avoid having to depend on the fibers during the leading edge of the reactor pulse when the transmission characteristics change the most and scintillation is occurring.

¹All of the fibers used in this experiment were of the undoped silica core variety which is very similar to fused silica in composition.

- Use narrowband (for example, 50 nm FWHM) filters to isolate the variations in transmission characteristics versus wavelength that occurs.
- Use fluorosilica clad, all silica core fibers with a polyimide buffer, as other investigations have shown these to be the most radiation resistant.
- The photobleaching effect should be used whenever feasible to enhance the performance of the optical fibers. This can be accomplished by injecting a bright light into the fiber using a beam splitter.
- Chopping the information signal prior to injecting it into the fiber is an effective technique to isolate the scintillation component of the signal.

Figure 1. Experimental Setup in Core

Figure 2. Optical Table Setup

Figure 3. Timing Sequence of OMA & Reactor Power

OMA SPECTRA

Shot 5327:2.3GW 21msec

Figure 4. Fiberglass Industries, low-OH fiber in peak flux. The fiber darkens uniformly with scintillation clearly evident below 470 nm.

AVERAGE TRANSMISSION

Shot 5327:2.3GW 21msec

Figure 5. Fiberglass Industries, low-OH fiber in peak flux.

OMA SPECTRA

Shot 5328:Fat Pulse

Figure 6. Fiberguide Industries, low-OH fiber in peak flux. A Hg-lamp to calibrate wavelength is present. OMA scans are at the 30 and 60% points thru the pulse.

AVERAGE TRANSMISSION

Shot 5328:Fat Pulse

Figure 7. Fiberguide Industries, low-OH fiber in peak flux. Averages are computed after eliminating the Hg-lamp light. Scintillation is not as pronounced as in Figure 5.

SCINTILLATION SPECTRA

Shot 5329:2GW 22.4msec

Figure 8. Fiberguide Industries, low-OH fiber in peak flux. Data taken with the source lamp off so only scintillation light is present.

SCINTILLATION SPECTRA

Shot 5329:2GW 22.4msec

Figure 9. Fiberguide Industries, low-OH fiber in peak flux. Ratio of scintillation light to source lamp light.

LIGHT TRANSMISSION

Shot 5346:2.4GW 20.8msec

Figure 10. Fiberglass Industries, low-OH fiber 3 ft above peak flux. Only hand recorded data available. Note scintillation near 800 nm and the late time recovery.

OMA SPECTRA

Shot 5347: 2.4 GW 20.6msec

Figure 11. Fiberglass Industries, low-OH fiber 3 ft above peak flux. The fiber darkens non-uniformly with scintillation above 770 nm.

AVERAGE TRANSMISSION

Shot 5347: 2.4 GW 20.6msec

— 700 to 770 nm
 770 to 850 nm

Figure 12. Fiberguide Industries, low-OH fiber 3 ft above peak flux. Note the late time recovery in the 700 to 770 nm interval.

OMA SPECTRA

Shot 5351: 2.3GW 21.4msec

Figure 13. Fiberglass Industries, low-OH fiber 3 ft above peak flux. The fiber darkens uniformly (33 krad curve) with scintillation occurring (0.06 krad curve).

AVERAGE TRANSMISSION

Shot 5351: 2.3GW 21.4msec

Figure 14. Fiberguide Industries, low-OH fiber 3 ft above peak flux. Compared to Figure 5 the final transmission is similar but scintillation appears muted.

OMA SPECTRA

Shot 5344:9.3GW 11.6msec

Figure 15. Polymicro Technologies, low-OH fiber 3ft above peak flux. The fiber darkens slightly more towards 700 nm. Scintillation is pronounced above 760 nm.

AVERAGE TRANSMISSION

Shot 5344:9.3GW 11.6msec

Figure 16. Polymicro Technologies, low-OH fiber 3ft above peak flux. Scintillation is evident in all wavelength intervals. Note late time recovery toward 700 nm.

OMA SPECTRA

Shot 5345:2.4GW 20.8msec

Figure 17. Polymicro Technologies, low-OH fiber 3ft above peak flux. The fiber darkens slightly more towards 700 nm. Scintillation is pronounced above 760 nm.

AVERAGE TRANSMISSION

Shot 5345:2.4GW 20.8msec

Figure 18. Polymicro Technologies, low-OH fiber 3ft above peak flux. Note similar response in Figure 16 where total dose is 2 times higher.

OMA SPECTRA

Shot 5348: 2.4GW 20.8msec

Figure 19. Polymicro Technologies, low-OH fiber 3ft above peak flux. The fiber darkens nonuniformly and note the tilt in the 0.1 krad curve.

AVERAGE TRANSMISSION

Shot 5348: 2.4GW 20.8msec

Figure 20. Polymicro Technologies, low-OH fiber 3ft above peak flux. These curves do not show a characteristic bump due to scintillation.

OMA SPECTRA

Shot 5339:2.5GW 20msec

Figure 21. Diaguide standard fiber 3 ft above peak flux. The fiber darkens nonuniformly. Scintillation is pronounced above 760 nm.

AVERAGE TRANSMISSION

Shot 5339:2.5GW 20msec

Figure 22. Diaguide standard fiber 3ft above peak flux. The OMA did not trigger reliably and the transmission curves should probably be shifted to the right 50 msec.

OMA SPECTRA

Shot 5340:Fat Pulse

Figure 23. Diaguide standard fiber 3 ft above peak flux. The fiber darkens nonuniformly.

AVERAGE TRANSMISSION

Shot 5340:Fat Pulse

Figure 24. Diaguide standard fiber 3 ft above peak flux. Due to the limited storage of the OMA only the leading edge of the pulse was captured.

OMA SPECTRA

Shot 5341:9.4GW 11.6msec

Figure 25. Diaguide standard fiber 3 ft above peak flux. The fiber darkens nonuniformly.

AVERAGE TRANSMISSION

Shot 5341:9.4GW 11.6msec

Figure 26. Diaguide standard fiber 3 ft above peak flux. The OMA did not trigger correctly (see text and Figure 22).

OMA SPECTRA

Shot 5342:2.5GW 20.5msec

Figure 27. Diaguide standard fiber 3 ft above peak flux. The fiber darkens nonuniformly. Scintillation is pronounced above 760 nm.

AVERAGE TRANSMISSION

Shot 5342:2.5GW 20.5msec

Figure 28. Diagonal standard fiber 3 ft above peak flux. Note the late time recovery toward 700 nm.

OMA SPECTRA

Shot 5343:Fat Pulse

Figure 29. Diaguide standard fiber 3 ft above peak flux. The fiber darkens nonuniformly.

AVERAGE TRANSMISSION

Shot 5343:Fat Pulse

Figure 30. Diaguide standard fiber 3 ft above peak flux. Only the leading edge of the pulse was captured.

OMA SPECTRA

Shot 5350: 2.2GW 22msec

Figure 31. Luxtron supplied standard fiber 3 ft above peak flux. The transmission drops slightly toward 400 nm. There is no indication of scintillation.

AVERAGE TRANSMISSION

Shot 5350: 2.2GW 22msec

Figure 32. Luxtron supplied standard fiber 3 ft above peak flux. This is the best demonstrated performance for the 400 to 550 nm interval.

OMA SPECTRA

Shot 5349:2.1GW 21.5msec

Figure 33. Luxtron supplied standard fiber 3 ft above peak flux. The transmission drops slightly toward 400 nm. There is no indication of scintillation.

AVERAGE TRANSMISSION

Shot 5349:2.1GW 21.5msec

Figure 34. Luxtron supplied standard fiber 3 ft above peak flux.

Figure 35. OMA Head Response

SPECTRAL SHAPE

Fiberguide Industries Low-OH Fiber

Figure 36. Spectrum Shape

SPECTRAL IRRADIANCE

Light Incident on Fiber End

Figure 37. Lamp Spectral Irradiance

Radiochromic Dosimetry Results

Figure 38. Radiochromic Dosimetry Results

OMA RESPONSE

Lamp Irradiance * P-M Tube Sensitivity

Figure 39. OMA Response

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