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FTG NOTE

Effects of a high-energy x-ray irradiation of selected scintillating fibers

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ABSTRACT

Tracking detectors based on scintillating-fiber technology are being developed for the Solenoidal Detector Collaboration at the Superconducting Super Collider and for the DØ collaboration at Fermilab. An important aspect of this work is the effect of the intense radiation environment existing in the detector cores on the fibers.

This paper presents preliminary results of a 2 MeV x-ray irradiation of selected fibers to a dose of 140 Krad, corresponding to some ten years of detector operation. Primary emphasis was placed on studying new Kuraray multiclad scintillating and clear fibers which have superior brightness, attenuation lengths, and mechanical robustness. Two types of Bicron single-clad scintillating fibers were also investigated.

Fibers were irradiated in dry nitrogen and in ambient air, and their attenuation lengths and effective light yields were measured before and after irradiation. The time dependence of recovery after exposure to air was also studied. No reduction of effective light yield was observed. However, attenuation lengths decreased noticeably immediately after irradiation, and then recovered partially after several days in air.

While the pre-irradiation attenuation length of the Kuraray multiclad scintillating fiber was significantly longer than that of the Bicron single-clad fibers, it suffered a much larger relative decrease, both shortly after irradiation and afterward. Indeed, after recovery both fiber types exhibited similar attenuation lengths of about 240 cm. The Kuraray multiclad clear fiber suffered a similar large relative decrease in attenuation length. This effect is attributed to the two-layer structure of the multiclad fibers, particularly to the poor radiation resistance of the inner acrylic cladding layer.

In the course of measurements, it was observed that fibers phosphoresce at the start of recovery in air. This phenomenon appears to be associated with recovery resulting from diffusion of oxygen into the fiber core.

1. INTRODUCTION

Scintillating-fiber technology possesses great potential for use in charged-particle tracking systems in detectors at the new generation of accelerators. For example, a system employing 475 K fibers of 925-μm-dia. and 4.3 m maximum length is one of the central-tracking options for the Solenoidal Detector Collaboration (SDC) at the Superconducting Super Collider (SSC).[1] A smaller-scale system, using 80 K fibers of 835-μm-dia. with maximum length of 2.8 m, is being developed for the Fermilab DØ upgrade.[2] Both projects are being carried out by the Fiber Tracking Group (FTG),[3] and an important aspect of the development work is to insure that the fibers will operate satisfactorily in the radiation environment existing in the detector cores.

Considerable work has been done studying the effects of radiation on plastic scintillator.[4] Such studies are difficult, partly because of the many interrelated variables involved. Among the variables are dose rate as well as total dose;[5,6,7] surrounding atmosphere both during irradiation[8] and in subsequent recovery;[9] and the nature of the irradiating particles. Furthermore, not all studies are directly applicable to scintillating fibers, since many have employed small bulk samples for which oxygen diffusion, believed to affect both damage and recovery, is very different than for fibers.

Investigation of these issues is a continuing effort of FTG. A previous study[10] examined the effects of a realistic irradiation -- hadrons, at reasonably typical dose rates, obtained in an exposure at the Fermilab Tevatron C0 area -- of ten different Bicron fiber types[11] 4 m in length. At the total doses achieved (up to about 36 Krad, corresponding to a few years of actual detector operation), no permanent damage was observed.

The FTG studies are continuing, and this paper presents preliminary results for selected fibers irradiated to 140 Krad, corresponding to about ten years of operation. Several differences exist between this and the previous study. In this work emphasis was placed on investigating new multiclad fibers developed by Kuraray,[12] since these are current candidates for the SDC and D0 trackers. Also, because the hadronic flux in the Tevatron C0 area is low during collider operation, the accelerator mode of the past year or so, x-ray irradiation at a higher dose rate was employed. The fibers were irradiated in nitrogen and ambient-air atmospheres. The results are expected to be fully valid for the nitrogen sample because no effects specifically attributable to hadrons were observed in Ref. 10, and because dose-rate effects appear to be absent for irradiation in inert atmospheres.[6]

2. FIBERS AND IRRADIATION

2.1. Fibers

As mentioned, emphasis was placed on Kuraray multiclad fibers. These fibers have a polystyrene core enclosed by two concentric layers of cladding. The inner layer is made of acrylic plastic, the outer of a fluorinated polymer. Their advantage over standard single-acrylic-clad fibers is due to the fact that the refractive index of the fluorinated polymer (1.42) is lower than that of acrylic plastic (1.49), resulting in a larger total-internal-reflection light-capture cone thus producing a considerably brighter fiber.[13] (The inner acrylic cladding layer is required because the fluorinated polymer adheres poorly to polystyrene but well to acrylic plastic.) In addition, these fibers have large attenuation lengths and are mechanically more robust than single-clad fibers. The core of the multiclad scintillating fiber is doped with p-terphenyl (pT) and 1500 ppm of 3-hydroxyflavone (3HF), and the fiber has an outer diameter of 835 μm. The undoped multiclad clear fiber is 965 μm in outer diameter.

Two types of standard (single-acrylic-clad) Bicron scintillating fiber were included in these tests, both to allow comparisons with previous measurements[10] and to investigate effects of 3HF concentration. The Bicron BI-6 fiber tested has 100 ppm of 3HF, while the BI-14 fiber has 500 ppm; both contain 1% of pT and are 835 μm in diameter.

Because of various constraints, the fiber lengths were limited to 2.4 m. After being cut to size, each fiber had its ends fixed into 1-in.-long black Noryl[14] ferrules using five-minute epoxy. After the epoxy set, the protruding fiber ends were cut flush with the ferrules with a razor blade and the surfaces polished with fine emery paper. The ferrules served to couple the fibers to the photodetectors and to remove the light traveling in the outer cladding. After being cleaned with ethyl alcohol and having their properties measured (see Section 3) to provide a base line, the fibers were grouped into two bundles, one for irradiation in dry nitrogen, the other for irradiation in ambient air. Each bundle contained four samples of Kuraray multiclad scintillating fiber, two samples of Kuraray multiclad clear fiber, and two samples of each of the Bicron scintillating fibers.

Because fibers containing 3HF are sensitive to light,[15] all work with the scintillating fibers was performed with fluorescent lamps covered with Kodak type 0302 orange filters transmitting only wavelengths greater than 520 nm.[16]

2.2. Irradiation

Some care is required to obtain uniform irradiation doses from x-ray or gamma sources, since, in such exposures, ionization is predominantly caused by electrons produced in Compton-scattering interactions. Uniformity may be improved by employing a "converter" sufficiently thick to provide an almost homogeneous Compton-electron flux. Such converters were constructed by symmetrically splitting two 2.4-m-long by 1½-in.-dia. polyvinylchloride rods along their lengths, and machining ¼-in.-wide by ⅛-in.-deep axial grooves in the pieces. When closed, the two halves of each rod contain a ¼-in. by ¼-in. axial channel into which fibers may be placed. Each fiber bundle described above was enclosed in such a converter.

To allow irradiation in controlled atmospheres, each converter/fiber bundle was placed into a stainless-steel irradiation container 2 in. in diameter (0.065-in. wall thickness) and 2.45 m long. The containers were sealed by O-ring flanges at each end, and had a valve and inlet/outlet port at one end and a bourdon-type pressure gauge at the other. Similar containers were used to store irradiated fibers in selected atmospheres for subsequent recovery studies.

The converters/fiber bundles were outgassed prior to irradiation. The container to be filled with dry nitrogen was subjected to two cycles consisting of daytime pumping (about 8 hrs) to 0.2 torr followed by overnight (about 16 hrs) exposure to nitrogen at 12 psig. The container to be filled with ambient air was subjected to one such cycle and then two cycles consisting of daytime pumping followed by overnight exposure to ambient air at atmospheric pressure. Both containers were then pumped for some 8 hrs, after which one was filled with dry nitrogen at 12 psig and the other with atmospheric-pressure ambient air. The converters/fiber bundles were left in their respective atmospheres for four days before being irradiated.

Irradiation was performed by X.R.I. Testing[17] using a Varian L200 2 MeV x-ray machine[18] designed for radiographic studies of industrial castings. The X.R.I. facility provides a vertically downward, square-pyramidal-shaped beam of 11° maximum half-angle, having a nominal dose rate of 12 Krad/hr at 100 cm from the source. To obtain efficient irradiation, a device was constructed to translate the irradiation containers, lying in a horizontal plane with axes spaced by 4 in., back and forth through the radiation cone. The plane of the containers was 14 in. below the x-ray source. A translation stroke of 1.2 m was used to expose half the fiber lengths to the beam. This procedure allowed the unirradiated fiber halves to serve as integral controls.

The fibers were irradiated for about 9 hrs (200 translation cycles). The accumulated dose was measured using radiachromic film squares, 1 cm by 1 cm in area and 1.7 mils thick,[19] placed between the halves of the converter rods over the fiber bundles at various axial positions. For these detectors the radiation dose is related to the logarithm of the ratio of the unexposed to exposed light transmission measured at 600 nm. The measured irradiation dose profile was essentially identical for both containers; that for the ambient-air container is shown in Fig. 1. The measurement uncertainties are about $\pm$ 5%. The irradiated halves of the fibers received an average dose of 140 Krad, accumulated at a rate of 16 Krad/hr.

For comparison, with the SSC operating at the design luminosity of 10^{33} $cm^{-2}s^{-1}$ the anticipated annual dose at the inner radius of the proposed SDC fiber tracker is expected to be 19 Krad, accumulated at 2.2 rad/hr.[10] Hence, the test exposure corresponds to about 7 years of detector operation. The radiation environment at the upgraded DØ detector is less severe. At a luminosity of 6×10^{31} $cm^{-2}s^{-1}$ the anticipated yearly dose to the innermost fibers is 12 Krad, at a rate of 1.3 rad/hr. The dose received by the irradiated fibers tested thus corresponds to almost 12 years.

3. MEASUREMENTS

3.1. Preliminaries

Radiation can affect the operation of scintillating fibers by damaging the core, the dopants, the claddings, and the core-cladding interface. Untangling these effects depends on what fiber properties are measured and how, and on analysis procedures. It should be noted that the effects are generally wavelength-dependent, so the spectral characteristics of the photodetector used greatly influences the results. This investigation studied attenuation length and effective light yield, as described below.

The two irradiation containers arrived back at the laboratory about two hours after the end of the x-ray irradiation. Because recovery occurs fairly quickly after exposure to air,[10] the ambient-air container was evacuated and filled with 12 psig of dry nitrogen. Fibers were removed from their containers just prior to measurement, and measuring time was kept short. Measured fibers were either quickly replaced into their containers or left mounted in the apparatus to study recovery effects in air. The containers were evacuated and refilled with nitrogen after each opening. As mentioned, all handling of scintillating fibers occurred with fluorescent lights covered with orange filters.

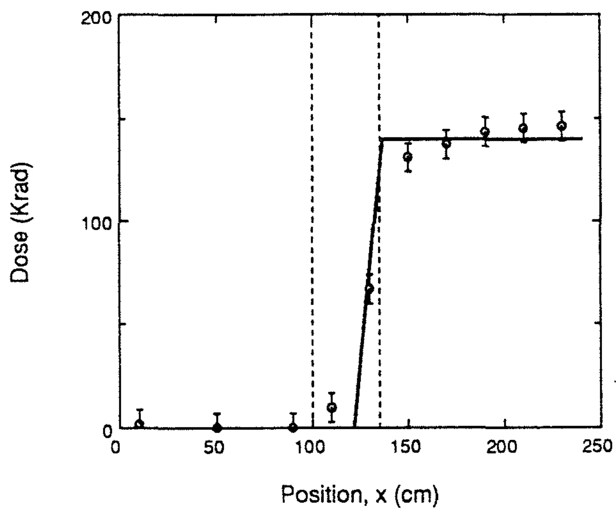

Fig. 1. Dose profile for fibers irradiated in ambient air. The solid curve represents the expected dose. Data from the transition region (between the dashed lines) was excluded from the analysis.

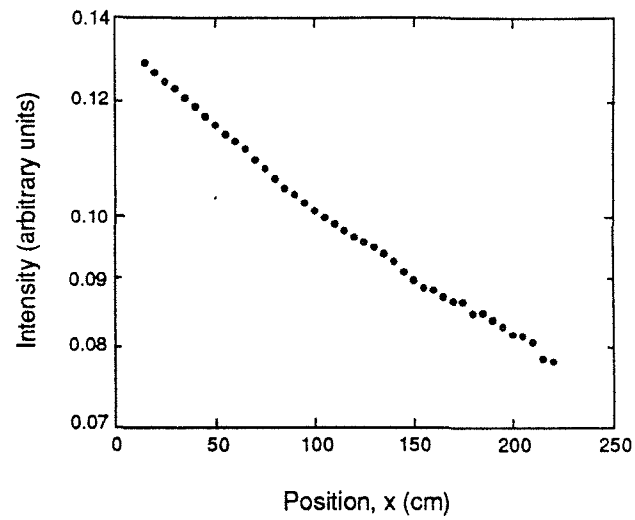

Fig. 2. Typical photodiode output obtained in attenuation length measurements. The data shown are from an unirradiated Kuraray multiclad scintillating fiber excited by uv at 10-cm intervals.

3.2. Scintillating fibers

3.2.1 Attenuation length

Attenuation lengths were measured by exciting the fibers at 10-cm intervals with ultraviolet (uv) light from an Oriel Model 6035 Hg(Ar) pencil lamp.[20] Light output was detected by coupling one or the other ferrule-terminated ends of a fiber to a Graseby Optronics Model 221 silicon photodiode,[21] whose response is essentially flat over the 3HF fluorescence region (green). The detector current was measured by a Keithley Model 485/4853 picoammeter having a GPIB interface.[22] A PC controlled the measurement process and performed the analysis. Because uv light produces damage,[15] the Hg(Ar) lamp output was collimated to a very thin line. A test involving 200 consecutive 4-min scans of a 4-m-long BI-14 fiber produced no change in attenuation length.

As described, ferrules were attached to both ends of the fibers. This allowed either end of a fiber, irradiated along half its length, to be coupled to the photodetector. As a consequence, a fiber being measured had a polished surface at its far end, resulting in reflected light, as well as a direct light, reaching the detector. The presence of reflection, studied by Chung and Margulies,[23] increases the light intensity received from the far end of a fiber, thereby increasing its apparent attenuation length. While reflection from a polished end has a negligible effect for 4-m-long fibers, it was found to cause not only spurious enhancements in attenuation length but also fiber-to-fiber variations for the 2.4-m-long fibers studied here. The effect was eliminated by placing a small daub of optical grease on the far fiber ends.

The result of a typical pre-irradiation measurement of a Kuraray multiclad scintillating fiber is shown in Fig. 2. Such data are frequently fit with the sum of two decreasing exponentials. The larger slope at small distances from the detector is predominantly due to preferential absorption of the shorter wavelength components of the wave-shifted light and to non-meridianal rays. Of interest is the smaller slope at larger distances from the detector, which represents attenuation of light traveling long distances as in actual tracking systems. It has been our experience that this parameter is more reliably determined by fitting a single exponential,

$$I(x) = I_0 \exp(-x/\lambda) \ , \tag{1}$$

where x is the distance between the photodetector and the excitation point, to the distant region than by fitting the sum of two exponentials over the entire fiber length. Our procedure, used in what follows, tends to produce smaller values of λ as compared to the alternative.

Typical effects of irradiation are shown in Fig. 3. The data are from a Kuraray multiclad fiber irradiated in nitrogen, with the non-irradiated half coupled to the photodiode. Radiation damage and subsequent partial recovery of the irradiated half after exposure to air is evident; the unirradiated half remained unchanged. The corresponding result for a BI-14 single-clad fiber irradiated in nitrogen is shown in Fig. 4. The behavior of the fibers irradiated in ambient air was similar. Indeed, in this study no significant differences were observed between corresponding fiber types irradiated in the two atmospheres.

Effects of irradiation and subsequent recovery on attenuation length were determined by fitting single exponentials, as given in Eq. (1), to the unirradiated ($x < 100$ cm) and irradiated ($x > 135$ cm) fiber sections; that is data from the irradiation transition region (see Fig. 1) were not used. The uncertainty the attenuation lengths so obtained is about

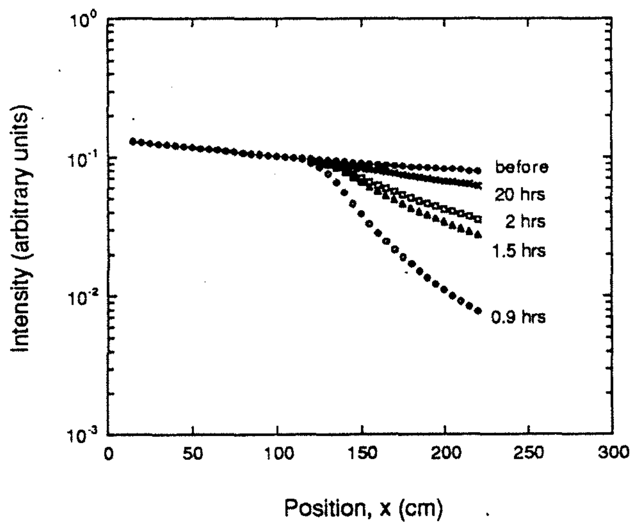

Fig. 3. Effect of irradiation on a Kuraray multiclad fiber irradiated in a nitrogen atmosphere. Partial recovery of the irradiated far half after various times in air is evident; the attenuation length of the non-irradiated near half remains unchanged.

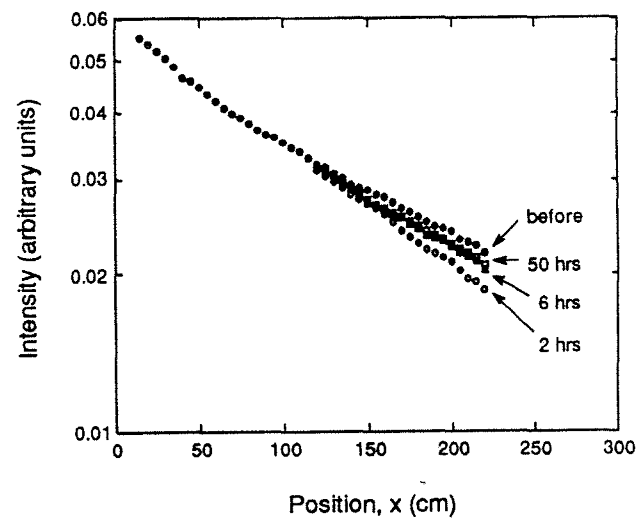

Fig. 4. Effect of irradiation on a Bicron BI-14 single-clad fiber irradiated in a nitrogen atmosphere. Partial recovery of the irradiated far half after various times in air is evident; the attenuation length of the non-irradiated near half remains unchanged.

$\pm$ 2%. Recovery was studied by plotting the irradiated-section attenuation lengths as functions of fiber time spent in air after irradiation. This dependence for the Kuraray multiclad fiber is shown in Fig. 5. The corresponding dependence for the Bicron BI-14 single-clad fiber is shown in Fig. 6; the behavior of the BI-6 single-clad fiber is basically similar and is not shown. Data for nitrogen-irradiated and air-irradiated fibers have been combined after including in the latter the time these fibers spent in air between the end of the irradiation and the time the irradiation tube was pumped out and the air replaced by nitrogen. After this adjustment, there is no difference between the recovery of these fibers and those irradiated in nitrogen.

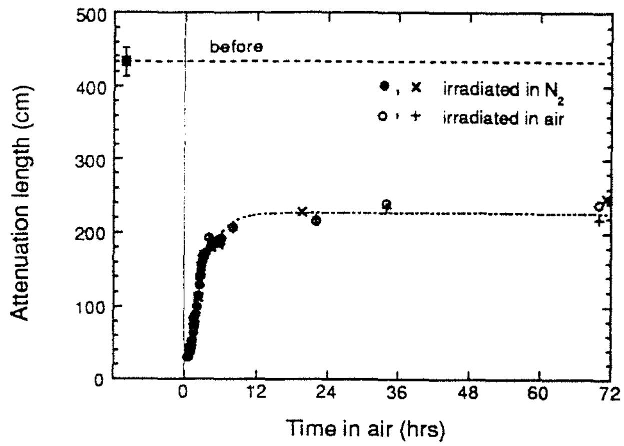

Fig. 5. Recovery of attenuation length of Kuraray multiclad fibers irradiated in nitrogen and air atmospheres after exposure to air. The times for the air-irradiated fibers include the interval spent in the air-filled irradiation tube (see text). A smooth curve has been drawn through the data.

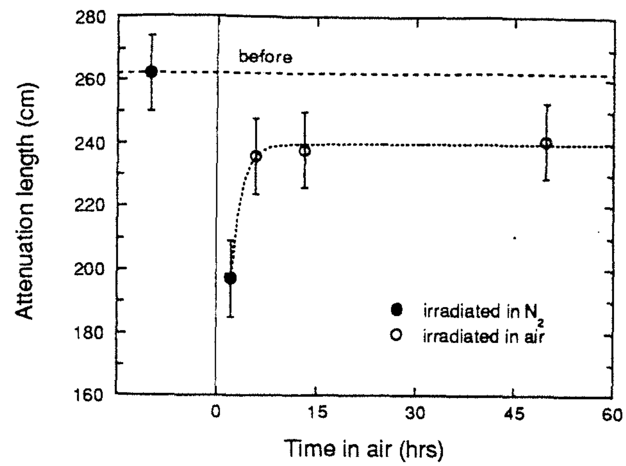

Fig. 6. Recovery of attenuation length of Bicron BI-14 single-clad fibers irradiated in nitrogen and air atmospheres after exposure to air. The times for the air-irradiated fibers include the interval spent in the air-filled irradiation tube (see text). A smooth curve has been drawn through the data.

As may be seen from Figs. 5 and 6, the effects of radiation on Kuraray multiclad and Bicron single-clad fibers are quite different. Shortly after the end of the irradiation, the attenuation length of the multiclad fiber decreased from 433 cm to 29 cm, a decrease of 93%. After exposure to air in darkness, the attenuation length exhibited a rapid initial recovery for the first 4 hours followed by a slower phase having a characteristic time of about a day. After three days in air, the recovery was virtually complete at a value of 230 cm, a permanent decrease of 47%. Although the data are sparse, the single-clad BI-14 fiber exhibited similar rapid and slow recovery phases. However, the attenuation length change between the initial value of 263 cm and 197 cm measured shortly after irradiation represents a decrease of only 25%. After 60 hrs in air, the BI-14 attenuation length had levelled off at about 240 cm, corresponding to a permanent decrease of only 9%. The changes in the single-clad BI-6 fiber were similar. These observations are summarized in Table I.

Table I. Changes in attenuation length due to irradiation and subsequent recovery in air.

Fiber type (3HF concentration in ppm)		Attenuation length				
		Before irradiation	After irradiation		After recovery in air	
		(cm)	(cm)	Decrease (%)	(cm)	Decrease (%)
Kuraray multiclad (1500)		433	29	93	230	47
Bicron single-clad	BI-6 (100)	266	197	26	246	8
	BI-14 (500)	263	197	25	240	9

It is interesting to note that the unirradiated attenuation length of the Kuraray multiclad fiber is significantly larger than that of the Bicron single-clad fibers; the effect of the double cladding more than compensates for the higher 3HF concentration. However, shortly after irradiation, and also after recovery in air, the multiclad fiber shows considerably more *relative* damage than do the single-clad fibers. Indeed, the *absolute values* of the recovered attenuation lengths are essentially the same for both fiber types.

The principal differences between the multiclad and single-clad fibers are the cladding structures and the 3HF concentration. The greater relative damage exhibited by the multiclad fiber is more likely due to the former -- particularly to the inner acrylic cladding layer -- than to the latter. That is, acrylic has poor radiation resistance as compared to polystyrene,[9] and the Kuraray multiclad clear fiber studied showed similar large relative damage (see Section 3.3); also, scintillators made with 3HF pre-irradiated to 100 Mrad showed normal unirradiated characteristics.[24]

Our observation, mentioned above, of the close similarity in behavior -- within fiber cladding types -- of the fibers irradiated in nitrogen and in air is consistent with previous work showing that radiation damage in air is related to dose rate.[5-8] These studies have shown that, for irradiation to a given dose in the presence of oxygen, damage is significantly greater at low than at high rates. At high rates the dissolved oxygen contributing to the radiation damage process is rapidly depleted, and the irradiation is over before sufficient additional oxygen can diffuse in. This effect limits the damage, and such high-rate tests underestimate the damage that would occur at lower rates. Also, radiation damage in inert atmospheres, such as nitrogen, should be independent of dose rate. Our observations are consistent with this explanation, and indicate that 16 Krad/hr, as employed here, constitutes a high dose rate.

3.2.2. Effective light yield

Effective light yields were measured by coupling the desired ferrule-terminated end of a fiber to the face of a Hamamatsu R2165-01 photomultiplier tube,[25] and exciting the fiber with conversion electrons from a 54 μCi source a distance of 10 cm from the PMT face. The tube's quantum efficiency peaks near 350 nm and decreases by a factor of two between the blue and the green.

The PMT output was connected directly to a LeCroy Model 3001 qVt multichannel analyzer[26] operated in the charge mode and self gated. As shown by the pulse-height spectrum of Fig. 7, the tube is capable of resolving individual photoelectrons. As is well known, the average value, $\bar{n}$, for a Poisson distribution is given by $\bar{n} = (n+1)P_{n+1}/P_n$, where P_n is the probability of observing n events. Although the spectrum from a round fiber is not Poisson in shape,[27] the ratio of adjacent photopeak areas should nevertheless be a measure of the average number of photoelectrons. In our measurements, the light yield of a fiber was taken to be proportional to the ratio of the third to the second photopeak areas, thus avoiding complications associated with the $n = 1$ peak discussed below.

The average number of photons, $\bar{n}$, measured shortly after irradiation was found to be noticeably lower than that before irradiation, the decrease depending on the fiber studied. However, in every case the reduction was consistent with that expected from Eq. (1) with $x = 10$ cm and λ having the reduced value measured shortly after the end of the irradiation (see Table I). Furthermore, the value of $\bar{n}$ increased with fiber time in air corresponding to the recovery of the attenuation length, as described in Section 3.2.1. It appears, therefore, that under the conditions of this test there was little, if any, reduction in effective light yield, and all loses may be attributed to decreases in attenuation length.

While performing these light yield measurements, an interesting phenomenon was observed: the fibers phosphoresce at the start of recovery in air. This feature was found by noting that the $n = 1$ photopeak (see Fig. 7) increased in size when an irradiated fiber was coupled to the PMT even with the ^{207}Bi source removed. This phenomenon, effectively absent when fibers that had been exposed to air for several hours were measured, was dramatic at the start of measurements of fibers that had been stored in nitrogen. The time dependence of this phosphorescence for a Kuraray multiclad fiber measured after 15 days storage in nitrogen is shown in Fig. 8. Like recovery, the

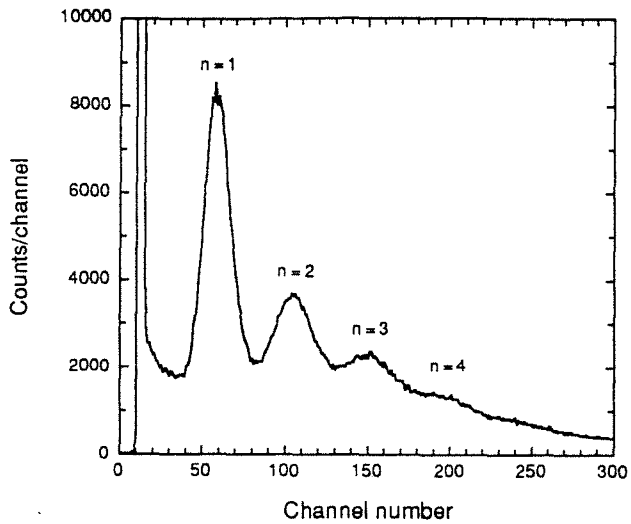

Fig. 7. Typical pulse-height spectrum obtained in effective light yield measurements. The data shown are from an unirradiated Kuraray multiclad scintillating fiber excited by conversion electrons from ^{207}Bi.

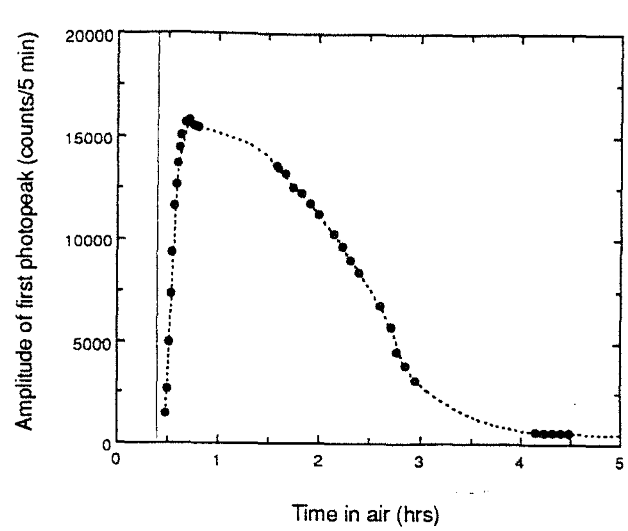

Fig. 8. Phosphorescence of an irradiated Kuraray multiclad fiber as a function of time in air. The vertical line corresponds to removal of the fiber from storage in nitrogen for 15 days. Earlier times represent exposure to air due to removal of other fibers from the storage tube.

phosphorescence is inhibited by nitrogen and enabled by exposure to air; presumably, it is related to oxygen diffusion. Phosphorescence has recently been observed during the recovery in darkness of fibers exposed to fluorescent light.[15] In that study, however, photon emission was observed immediately after exposure to light ceased, and was not retarded by storage in nitrogen.

3.3. Clear fibers

As described previously, 2.4-m-long sections of Kuraray multiclad clear fibers having ferrules at both ends were also irradiated along half their lengths in nitrogen and ambient-air atmospheres. Attenuation lengths were measured before and after irradiation by injecting scintillation light into one end and measuring the transmitted light emerging from the other end using the photon counting system described in Section 3.2.2.

Prior to irradiation, one end of each sample was coupled to the Hamamatsu PMT and the other end to a 53-cm-long Kuraray multiclad scintillating fiber also having ferrules at each end. Light was generated by exciting the scintillating fiber with electrons from ^{207}Bi at 10 cm from the joint. Alignment between the clear and scintillating fiber was achieved by mounting the abutting ferrules in an accurately machined sleeve. The reproducibility of this system was measured to be better than 95%. If the length of the clear fiber is L, its pre-irradiation attenuation length is λ_o, and the average number of scintillation photons at its midpoint traveling toward the PMT is $\bar{n}_{L/2}$, then, using the model of Eq. (1), the average number of photons at the PMT is

$$\bar{n}_{PMT}^{before} = \bar{n}_{L/2} \exp(- L/2\lambda_o) \quad . \tag{2}$$

Following irradiation, the clear fiber samples tested were again mounted as described above. Now, however, the fibers' linear inversion symmetry was broken, and a fiber to be measured was mounted with its irradiated half coupled to the PMT. Since the far half, coupled to the scintillating-fiber light source, was unirradiated, its attenuation length was still λ_o; thus, because of the high degree of reproducibility of the fiber coupling joint, the average number of scintillation photons at the fiber midpoint was still $\bar{n}_{L/2}$. For the post-irradiation measurement, then, the average number of photons at the PMT is

$$\bar{n}_{\rm PMT}^{\rm after} = \bar{n}_{L/2} \exp(-L/2\lambda_{\rm after}) \quad , \tag{3}$$

where $\lambda_{\rm after}$ is the attenuation length of the irradiated half. Combining Eqs. (2) and (3) gives

$$\lambda_{\rm after} = \frac{\lambda_o}{1 + \frac{2\lambda_o}{L} \ln\left(\frac{\bar{n}_{\rm PMT}^{\rm before}}{\bar{n}_{\rm PMT}^{\rm after}}\right)} \quad . \tag{4}$$

A typical result of this analysis is shown in Fig. 9. The figure shows the damage to a Kuraray multiclad clear fiber irradiated in nitrogen, and the subsequent recovery of the attenuation length after exposure to air. (The data are based on the pre-irradiation value λ_o = (1040 ± 50) cm measured at Fermilab.[27]) The recovery is effectively complete after two days, and the final attenuation length of 480 cm represents a decrease of 54%. This reduction is essentially the same as that experienced by the Kuraray multiclad scintillating fiber. This suggests that the considerably larger relative damage suffered by the multiclad fibers as compared to the single-clad fibers is due to the double cladding structure, and that the higher 3HF concentration has little, of any, effect on the damage to the scintillating fiber.

The phosphorescence phenomenon observed while studying the scintillating fibers was also noted for the clear fiber. The magnitude of the effect, however, was much smaller for the clear fiber.

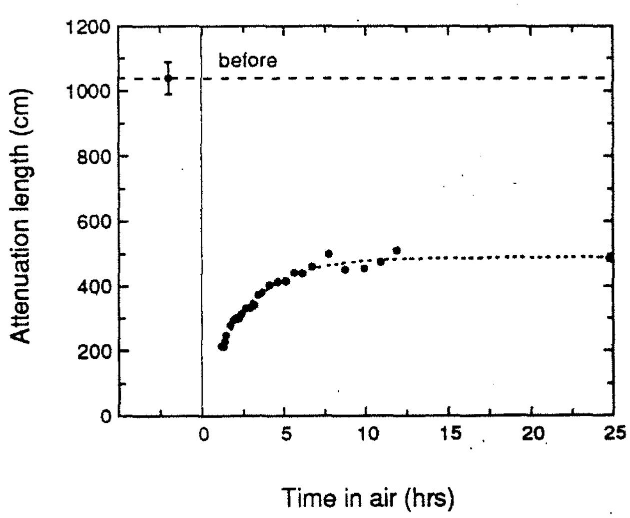

Fig. 9. Recovery of attenuation length of Kuraray multiclad clear fiber irradiated in nitrogen after exposure to air.

4. SUMMARY

This paper presents preliminary results of a 2 MeV x-ray irradiation of selected fibers to a dose of 140 Krad, corresponding to some ten years of fiber-tracking detector operation. Emphasis was placed on studying new Kuraray multiclad scintillating and clear fibers which have superior brightness, attenuation lengths, and mechanical robustness. For comparison, Bicron BI-6 and BI-14 single-clad scintillating fibers were also studied. Fibers were irradiated in dry nitrogen and in ambient-air atmospheres. The effects of the irradiation, and subsequent recovery in air, were determined by measuring effective light yields and attenuation lengths, the principal fiber characteristics.

The most significant effects were found in attenuation lengths. Initial reductions were essentially the same for corresponding fiber types irradiated in nitrogen and in air. This observation is consistent with expectations based on the role of diffused oxygen in contributing to radiation damage and the consequent effect of dose rate in irradiation in different atmospheres. It also indicates that 16 Krad/hr, as employed here, constitutes a high dose rate in this context.

All fibers exhibited partial recovery of attenuation length after exposure to air. This recovery was similar for all fibers studied: recovery began with a rapid phase lasting about 4 hours, and then continued at a slower rate. Attenuation lengths approached saturation in about two days. However, the effects were quite different for the Kuraray multiclad fibers than for the Bicron single-clad fibers. Before irradiation, the 433-cm attenuation length of the multiclad scintillating fiber was significantly larger than that, about 265 cm, measured for the single-clad fibers. Shortly after irradiation, however, the multiclad fiber's attenuation length decreased to 29 cm, while that of the single-clad fibers dropped only to 197 cm. This corresponds to decreases of 93% for the multiclad fiber and about 25% for the single-clad fibers. This difference in performance persisted after recovery: the attenuation length decreases were 47% and about 9% for the recovered multiclad and single-clad fibers, respectively. After recovery, the absolute values of the attenuation lengths were about the same for both fiber types.

The Kuraray multiclad clear fiber behaved similarly to its scintillating partner, showing an initial attenuation length decrease of almost 100% and a 54% decrease after recovery. This result suggests that the considerably larger relative damage suffered by the multiclad fibers as compared to the single-clad fibers is due to the double cladding structure. The inner acrylic cladding layer is particularly suspect. Its role in a multiclad fiber is quite different from that of the acrylic cladding in a single-clad fiber, and acrylic is known to have poorer radiation-damage resistance than either the outer fluorinated-polymer cladding or the polystyrene core.

In light yield measurements the average number of photons measured was noticeably smaller after than before irradiation for all scintillating fibers. However, all decreases were consistent with light losses resulting from the reduced attenuation lengths produced by the irradiation. Thus, little -- of any -- reduction of effective light yield occurred.

During the light yield measurements it was noted that fibers phosphoresce after irradiation. This phenomenon is inhibited by storage in nitrogen and accompanies recovery in air. Thus, this effect may be related to recovery of the fiber core resulting from diffusion of oxygen. This hypothesis is supported by the following observations (see Fig. 8): 1) photon emission is not immediate, but starts about 7 minutes after exposure to air, consistent with oxygen diffusing through the fiber cladding layers; 2) the onset of phosphorescence is well fit by a $t^{1/3}$ dependence, consistent with oxygen diffusing into the fiber core and quenching color centers produced by irradiation. Both of these features have corresponding phases at the very start of the recovery of attenuation length. The fact that the observed phosphorescence was much stronger in scintillating than in clear fibers may be due to transfer to the fluors of energy generated in the polystyrene core recovery process. Studies of phosphorescence and its relation to recovery are continuing.

5. ACKNOWLEDGEMENTS

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