COMPARATIVE STUDY OF THE RADIATION RESISTANCE OF SELECTED PLASTIC SCINTILLATING FIBERS

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Abstract

The effect of radiation upon various types of plastic scintillating fibers has been investigated. Damage to local scintillation yield as well as absorption by the polymer base have been observed. The Optectron S101-S fiber is most resistant to irradiation, but the Kyowa SCSF-81+Y7 fiber and fibers doped with 3-hydroxyflavone have superior transmission recovery within several days after irradiation. The recovery of irradiated fibers is strongly dependent upon the atmosphere in which they are kept.

Introduction

The radiation resistance of detectors is recognized as an important problem of the upcoming SSC and LHC accelerator facilities. We have been investigating the radiation resistance problem in organic scintillators with specific reference to the radiation hardening of plastic scintillating fibers, which are of current interest in many new detectors.

Our research into radiation resistance problems with plastic and liquid scintillators has been reported elsewhere [1-5]. In brief, the key problem seems to be the creation of absorptive centers in the plastic base, predominantly in the blue end of the spectrum where most scintillators emit. To the first order, most commonly-used fluors (e.g., PTP and bPBD, see Table 1) are more resistant to radiation than plastic bases. That being the case, we successfully tested the idea of shifting the emission spectrum to longer wavelengths where there is far less absorptive damage to the plastic. Specifically, we utilized the large Stokes shift fluor 3HF in PS and PVT bases. The results are summarized in figures 1(a-d). These figures show the effect upon scintillation yield after irradiating small cylindrical samples (height 1 cm, diameter 1.5 cm) using a 150 Ci Co-60 gamma source at a dose rate of 70 krad/hour. In each case, the scintillation pulse height value obtained is normalized to the pre-irradiation value. The samples have either a PS or PVT base and are doped with 3HF, either with or without the primary fluor PTP. A standard PVT-based scintillator, BC408, is shown for comparison. These graphs show that shifting to a green emission is a successful way of increasing the radiation resistance of scintillators. A natural extension of this work is to investigate the resistance of plastic scintillating fibers and thereby verify some ideas concerning the radiation resistance problem and how to overcome it.

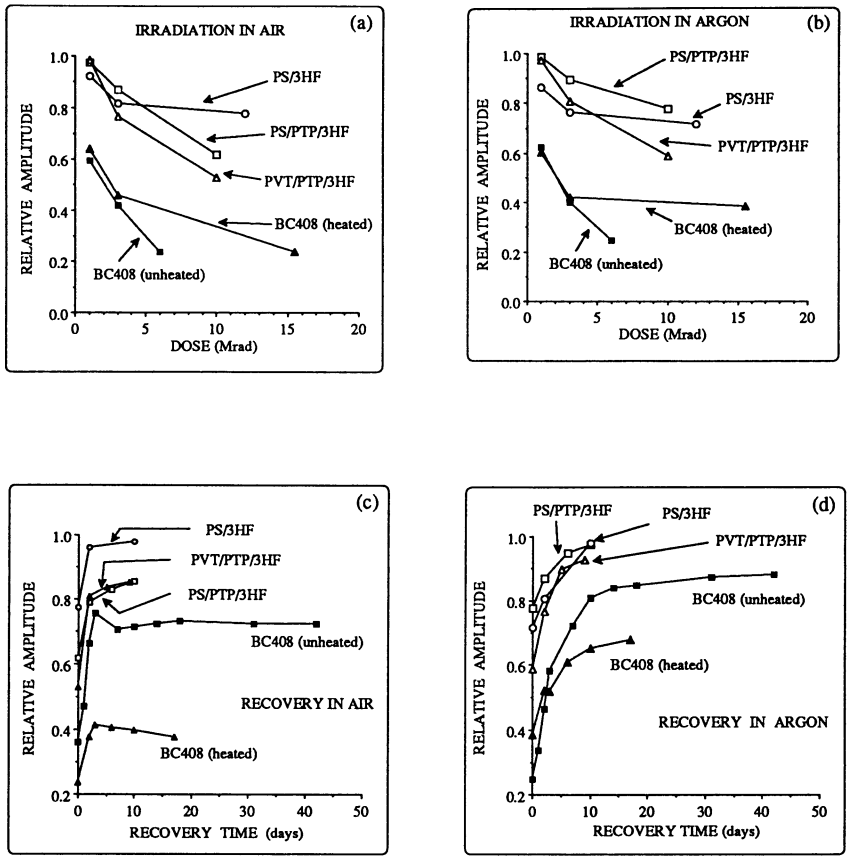

FIG. 1. Irradiation and recovery of small cylindrical samples. (a) Irradiation in Air, (b) Irradiation in Argon, (c) Recovery in Air, (d) Recovery in Argon. All samples were heated at 50°C during recovery. In addition, the 3HF-doped samples and one set of BC408 samples were heated at 50°C during irradiation.

TABLE 1. Abbreviations of Fluors and Plastics

PS = polystyrene
PVT = polyvinyltoluene
FA = fluorinated acrylic
PMMA = polymethylmethacrylate, acrylic
PTP = para-terphenyl
bPBD = 2-(4'-t-butylphenyl)-5-(4"-biphenylyl)-1,3,4-oxadiazole
3HF = 3-hydroxyflavone
dPOPOP = 1,4-bis-2-(4-methyl-5-phenyloxazolyl)benzene
BDB = 4,4'-bis-(2,5-dimethylstyryl)-diphenyl

Experimental Procedure

Seven types of plastic scintillating fibers were obtained for comparison tests. The properties of these fibers are listed in Table 2. The fibers were cut into 1 m long sections for measurement and irradiation. They were irradiated using a 2.5 MeV continuous electron beam (from a Van de Graaff accelerator) located at Florida State University. The current density was varied from 1 to 100 nA/cm^2 giving a dose rate of approximately 1-100 Mrad/hr. Details of the electron beam irradiator are described elsewhere [5]. Most of the electron irradiations were performed in air. For some experiments, however, the fibers were encased, during the irradiation, in a nylon tube through which argon was flowed. After the irradiation, they were briefly exposed to air while being transferred to an argon-filled, oxygen-filled, or vacuum storage case. They were left in this case during the recovery period and were removed only for the brief periods during which the measurements were made.

TABLE 2. Properties of some tested fibers.

Producer (Fiber Name)	Core & Cladding	Diameter	Primary Fluor	Secondary Fluor	Attenuation Length	Decay Time	Ref.
Kyowa	PS PMMA	1 mm	proprietary (350 nm)	3HF (530 nm)	λ(0-1m) = 3.7 m λ(1-5m) = 6.9 m	7.8 nsec	6,7
Bicron	PS PMMA	1 mm	proprietary	3HF (530 nm)	not available	not available	8
Kyowa (SCSF-81+Y7)	PS PMMA	1 mm	proprietary	Y7 (510 nm)	not available	not available	9
Optectron (S101-S)	PS FA	1 mm	bPBD (365 nm)	dPOPOP (450 nm)	not available	3.1 nsec	10
Kyowa SCSF-81	PS PMMA	1 mm	proprietary	proprietary (430 nm)	λ(0-1m) = 1.6 m λ(1-3m) = 3.7 m	2.36 nsec	11
Bicron (BCF-10)	PS PMMA	1 mm	proprietary	proprietary (430 nm)	not available	2.4 nsec	12
Kyowa (SCSF-38)	PS PMMA	1 mm	bPBD (365 nm)	BDB (420 nm)	λ(0-1m) = 1.3 m λ(1-3m) = 3.5 m	2.27 nsec	11

The radiation-induced loss of light output of fibers can be caused by either a drop in the amount of light actually produced by the fluors ("local scintillation yield") or a loss in the ability of light to traverse the length of the fiber. In an effort to distinguish such effects, several electron-beam irradiations were performed by placing a 0.15-inch thick lead shield in front of a 1-inch wide section at the middle of the fibers. The results are clearly visible as a jump in the attenuation curves. As figure 2 shows, the height of this jump in the "shadow" region gives a measure of the loss in local scintillation yield.

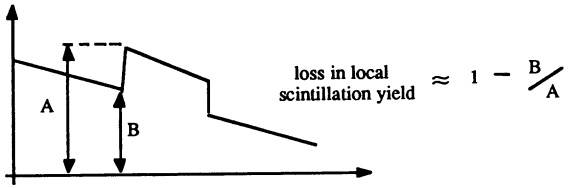

FIG. 2. "Jump" in attenuation curve caused by a 1-inch wide unirradiated region in the middle of an otherwise irradiated fiber.

Before and after irradiation, the fiber scintillation response was measured as a function of the distance between the excitation point and the face plate of an EMI 9907A photomultiplier tube. Figure 3 shows how fiber scintillation was excited by use of a narrowly collimated (3 mm) continuous 8 keV X-ray beam from an X-Tech Technologies, Inc. X-ray generator. The resulting photomultiplier current was measured with a Keithley Model 617 Electrometer.

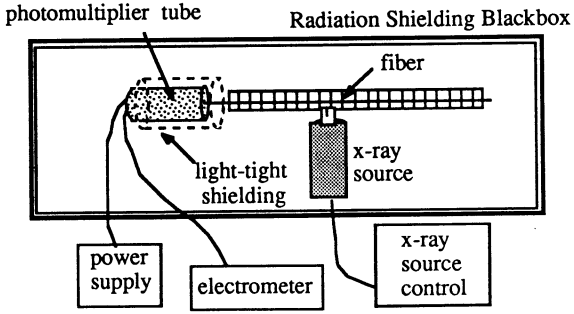

FIG. 3. Fiber testing setup.

Results

Figures 4(a-f) show the variation in attenuation of fibers irradiated in air to 10 Mrad. In each case, the values have been normalized to one for the current measured when the fibers were excited at a position one inch from the face of the phototube. The S101-S fiber had the least initial damage, but the Kyowa 3HF fiber recovered very quickly and completely. Figure 5(a) shows a comparison of the fibers immediately (within one day) after irradiation, and figure 5(b) shows how these fibers compare after 8 days of recovery in air. The attenuation length improves as a function of increasing emission wavelength. This trend is also seen for fibers on the post irradiation graph, with the exception of the S101-S fiber which had comparatively little damage.

The presence of oxygen is well known to affect the rate and amount of recovery of light yield for irradiated plastic scintillators. To extend these results to scintillating fibers, we have irradiated the fibers to 10 Mrad (in air) and then kept them for up to 4 weeks in either vacuum, argon, or air. Some of the results are shown in figures 6(a-d). Fibers kept in vacuum showed little, if any, recovery, whereas fibers kept in argon experienced about the same amount of recovery as fibers kept in air. However, since the measurements were carried out in air, it may be that the brief exposures to oxygen were sufficient to stimulate recovery.

Figures 7(a-c) show the results of irradiating fibers (in argon) to 30 and 100 Mrad. After irradiation, the fibers were kept in vacuum for 9 days before post-irradiation measurements were made, but because of our previous results on recovery atmospheres, we assume that little recovery occurred during this period. After 30 Mrad, all of the fibers had a significant increase in attenuation, but as with the 10 Mrad irradiations, the S101-S fiber did better than one would expect for a blue-emitting fiber. After 2 days in oxygen, the green-emitting fibers (after both 30 Mrad and 100 Mrad) displayed good recovery, whereas the S101-S fiber showed poor recovery.

The graphs for very high dose irradiations and for the effect of atmosphere on recovery show a jump in the attenuation curve around the 10-inch position, caused by the "shadow" region where the fibers had an unirradiated spot. Using the X-ray source to scan this shadow region, we obtained a measure of the damage to the local scintillation yield of the fibers. As seen in figure 8(a), the damage to fibers with various emission wavelengths after irradiation to 10 Mrad and 8 days recovery is very similar. Figure 8(b) compares the level of local scintillation yield for the Kyowa 3HF fiber and the SCSF-81-Y7 fiber after 10, 30, and 100 Mrad. This shows that even after the fibers experience good recovery of their transmission properties, they still have significant damage to their local scintillation yield.

Figure 8(c) shows the scan of the shadow regions of two fibers doped with different concentrations of 3HF (in addition to a primary fluor). The fibers were irradiated to 100 Mrad and recovered (after 9 days in vacuum) for 2 days in oxygen. Fiber A has a 60% loss in local scintillation yield, whereas Fiber B, with 2.5 times the amount of 3HF, has only a 41% loss. Since the attenuation damage to these fibers (not shown) is similar, it seems that a higher concentration of 3HF decreases the overall radiation damage to the fiber. Figure 8(d) summarizes the level of local scintillation yield for these two fibers after 30 and 100 Mrad.

Conclusions

Irradiation of these fibers was performed at a dose rate much higher than that to which the fibers will be exposed in actual use. When exposed to irradiation at a low dose rate, the radiation resistance of the fibers will depend more strongly upon the rates of the various chemical reactions occurring in the fibers and upon the supply of surrounding oxygen available for interaction with free radicals produced in the plastic base by the radiation [13]. Therefore, the relative behavior of fibers *after recovery* is a better indicator of how the fibers will withstand radiation in actual use.

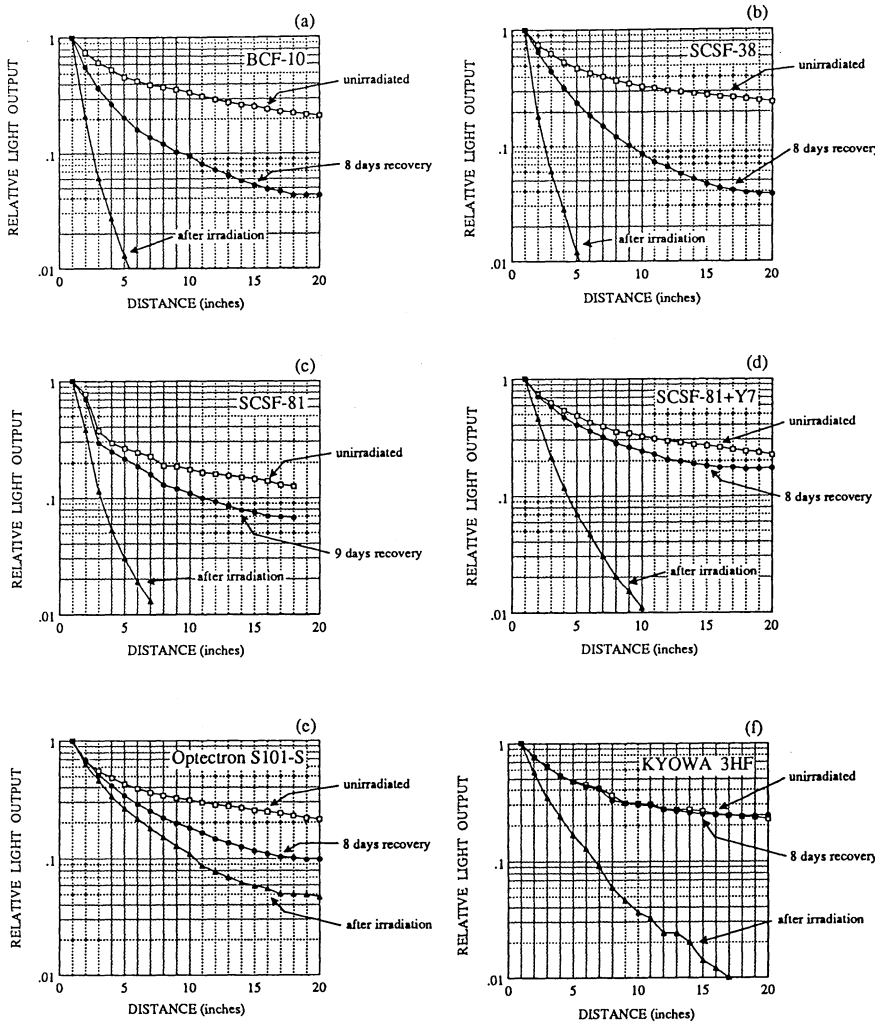

FIG. 4. Attenuation curves for fibers irradiated to 10 Mrad in air and recovered in air. For each curve, the light output of the fiber at its one-inch position has been normalized to one.

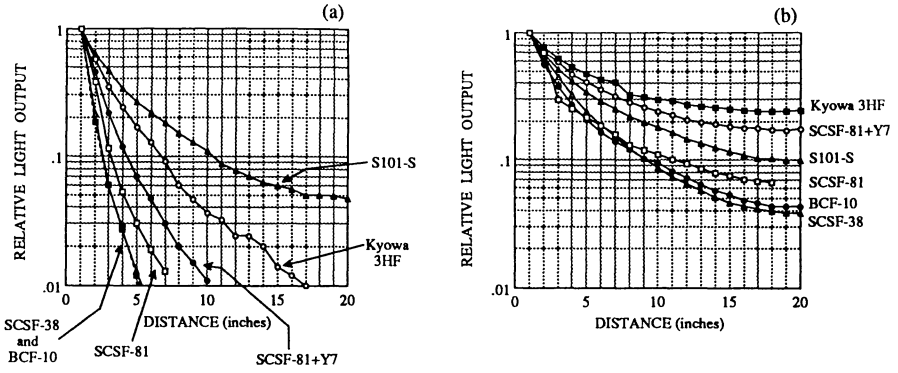

FIG. 5. Comparison of fibers after (a) Irradiation to 10 Mrad in air, and (b) Recovery (8-9 days) in air. For each curve, the light output of the fiber at its one-inch position has been normalized to one.

With this in mind, the best fibers overall are those which emit at the longest wavelength, specifically, 3HF-doped fibers. Although the S101-S fiber has less attenuation damage immediately after irradiation, the 3HF fibers recover much better. At least for 1 m fibers, the attenuation curves of fibers doped with 3HF recovered completely after a 10 Mrad irradiation.

For all tested fibers other than the S101-S, the amount of attenuation damage was correlated with the fiber's peak emission wavelength. A notable difference in the S101-S fiber is that it is clad with fluorinated acrylic, whereas the other fibers have a PMMA cladding. It is possible that this difference accounts for the superior resistance of the S101-S fiber.

The recovery experiments performed by placing irradiated fibers in various atmospheres confirm our previous results. Very little, if any, recovery occurs in vacuum, but recovery in argon and air is similar. The rate of recovery in argon and air is yet to be investigated. Studies with bulk samples [3,14] have indicated that although the presence of oxygen results in a high rate of recovery, the scintillation yield is finally better in an atmosphere (argon or nitrogen) in which the oxygen content is minimized.

Irradiation of fibers to 30 and 100 Mrad show that present fiber formulations are inadequate for such high doses. The results are sufficiently promising, however, to suggest that with prudent choices for fiber base, cladding, and fluors, very high radiation resistance can be achieved.

Our future plans are to continue testing various types of fibers for radiation resistance. We will soon test PS-based fibers doped with PTP and 3HF, with a fluorinated acrylic cladding. We suspect that these fibers will have good radiation resistance (like the S101-S fibers) and good recovery (like the present 3HF-doped fibers). We also plan to test fibers with higher 3HF concentrations to reduce the loss of local scintillation yield during irradiation. It is clear from our results that red-emitting fibers should be very radiation resistant, so we hope to obtain and test such fibers when they become available. Finally, our recent work [15] on spaghetti-type calorimeters using Kyowa 3HF fibers is very encouraging. We plan to continue building and testing modules with new and improved fibers.

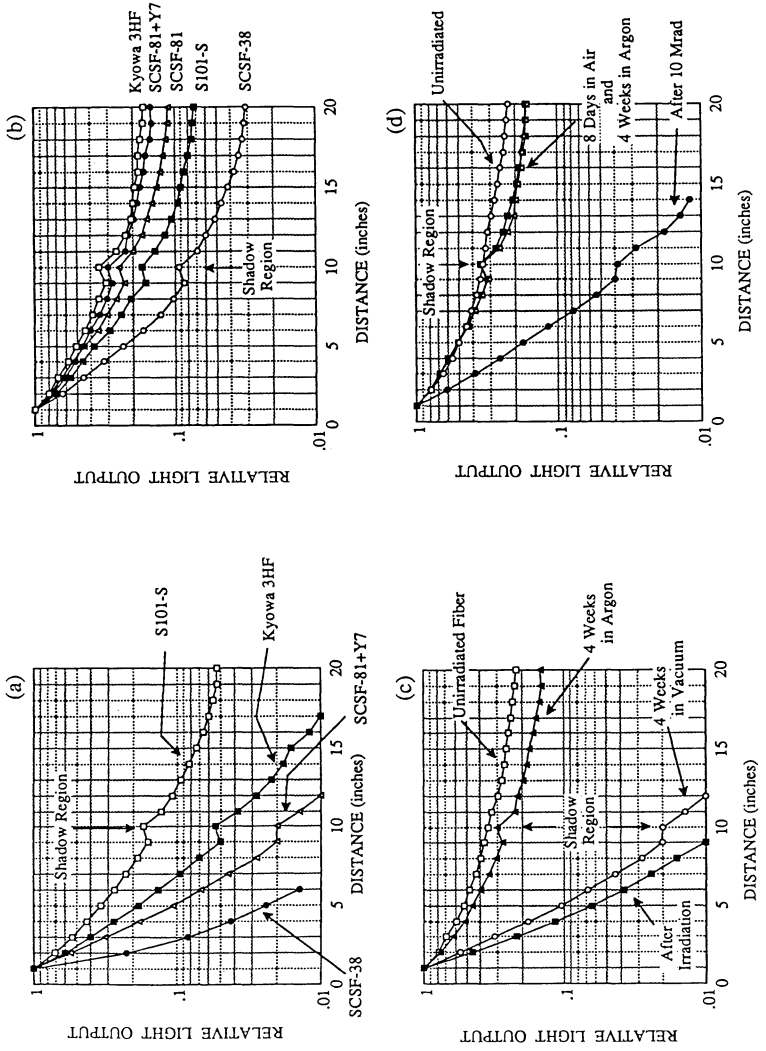

FIG. 6. Recovery of fibers in air, argon, and vacuum. (a) Irradiation 10 Mrad in air, recovery 4 weeks in vacuum, (b) Irradiation 10 Mrad in air, recovery 4 weeks in argon, (c) SCSF-81+Y7 fiber, irradiation 10 Mrad in air, recovery 4 weeks in argon and vacuum, (d) Kyowa 3HF fiber, irradiation 10 Mrad in air, recovery 8 days in air and 4 weeks in argon. For all curves, light output of the fiber at its one-inch position is normalized to one.

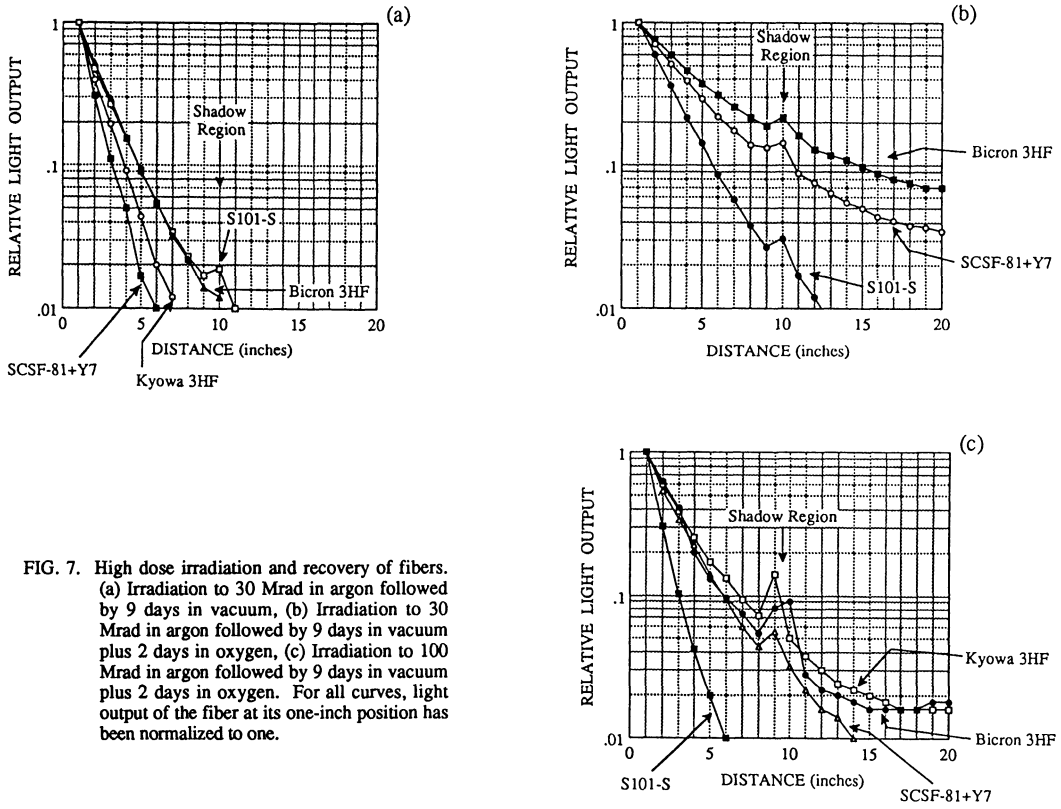

FIG. 7. High dose irradiation and recovery of fibers. (a) Irradiation to 30 Mrad in argon followed by 9 days in vacuum, (b) Irradiation to 30 Mrad in argon followed by 9 days in vacuum plus 2 days in oxygen, (c) Irradiation to 100 Mrad in argon followed by 9 days in vacuum plus 2 days in oxygen. For all curves, light output of the fiber at its one-inch position has been normalized to one.

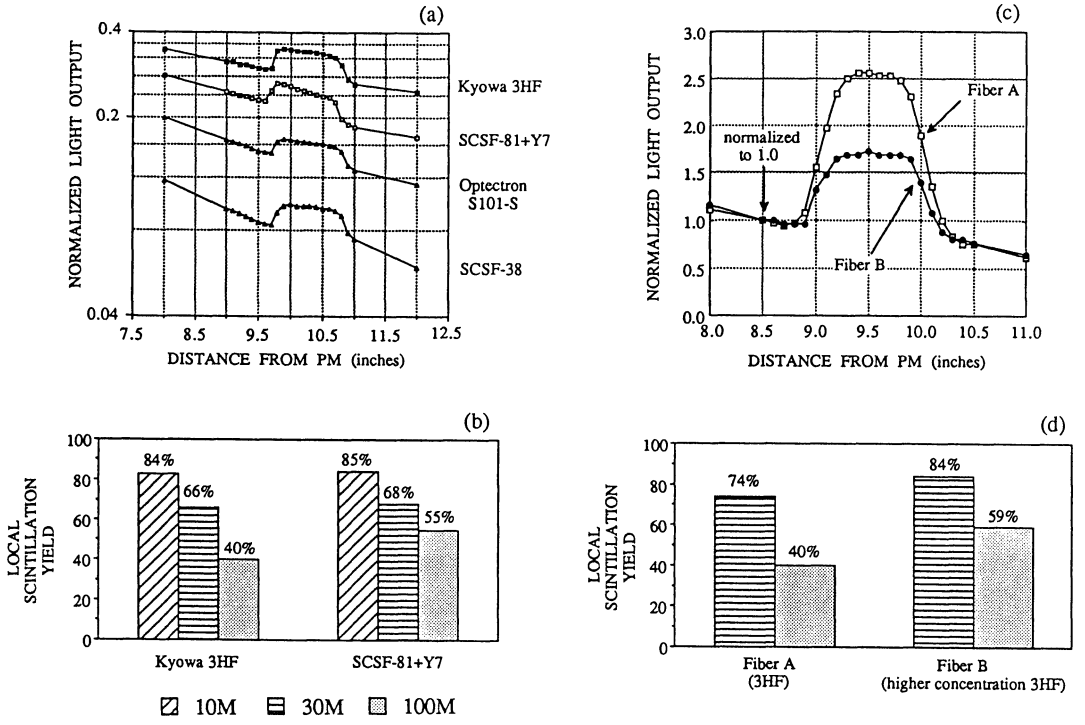

FIG. 8. Effect of irradiation on local scintillation yield. (a) Scan of shadow region after 10 Mrad irradiation in air and 8 days recovery in air, Kyowa 3HF (16% loss), SCSF-81+Y7 (15% loss), S101-S (12% loss), and SCSF-38 (11% loss), (b) Local scintillation yield after irradiation and recovery, taking 100% as the pre-irradiation level for each fiber, (c) Scan of shadow region for 3HF-doped fibers after 100 Mrad irradiation in argon and recovery of 9 days in vacuum plus 2 days in oxygen, Fiber A (60% loss), Fiber B (41% loss), (d) Local scintillation yield after irradiation and recovery for 3HF-doped fibers, taking 100% as the pre-irradiation level for each fiber.

References

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