SDC-91-00011

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SOLENOIDAL DETECTOR NOTES

RADIATION DAMAGE IN SCINTILLATING PLATES AND FIBERS

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March, 1991

1 INTRODUCTION

Scintillating tiles read out with wave length shifting (WLS) fibers is a strong candidate for SDC calorimetry. The area of concern for this technology is the radiation hardness of scintillator placed at electromagnetic (EM) shower maximum. We have started a program aimed at investigating how an EM module made of scintillating tiles in lead absorber and read out with WLS fibers will survive in the radiation field of the SSC.

Table I recalls the approximate dose rates and total doses expected at EM shower maximum for various SSC operating modes[1].

The first part of the program consisted in choosing the best possible material for the construction of the module. Samples of scintillator plates and fibers from several manufacturers have been exposed to a ^{60}Co source and measured for spectral properties, transmission, and light yield. In this note we report on the results of these measurements.

2 IRRADIATION OF SAMPLES AND DOSIMETRY

Samples of scintillator plates, scintillating fibers, WLS and clear fibers, as well as assembled "tiles" (scintillator plates with WLS fiber read out) were exposed to a ^{60}Co source in several runs. The irradiation took place from December, 1990 to February, 1991 at the DEIN facility at Saclay. All irradiations, annealings, and measurements were done in air at room temperature.

The 42 liter irradiation chamber is a cylinder 36 cm in diameter with several ^{60}Co sources located on the axis. The total activity is 256 Ci. During run # 1 a "low" dose rate was obtained by shielding the sources with a 4 cm thick lead cylinder.

The absorbed doses are derived in three different ways.

In the first method, the doses are calculated with the known activity, the location of the samples with respect to the source, and the curves of equal dose in the chamber.

Second, we used Alanine dosimeters[2] which are plastics that give up free radicals when absorbing radiation energy. The concentration of these radicals is a measure of the absorbed dose.

Finally, we used radiochromic dye films (type FWT 60-00) [3]. The difference in transmission at specific wave lengths before and after irradiation is a function of the absorbed dose.

The three methods agree.

The various types of samples (plates, bars, fibers, tiles) were located at different distances from the source so that, for a given run, doses differ. Table II shows the dose rates and the total doses for the 4 runs for the various samples used. All numbers are rounded off to reflect the 10 % precision (a conservative number) which was assigned to the dosimetry.

[1] Taken from fig. 4 of the SDC LoI.

[2] These dosimeters are supplied and analyzed by DAMRI, Saclay.

[3] Far West Technologies, Go'eta, CA. We thank K. Johnson (FSU) who suggested using this technique and who supplied us with the first films.

3 MEASUREMENTS

The scintillator plates and the fibers were provided by KURURAY, BICRON and our laboratory (Saclay). The list can be seen in Table III. In all cases three samples were made. Samples # 1 were not irradiated and were kept as a reference for each type of scintillator or fiber. The method used makes it possible to measure the two relevant quantities (intrinsic light yield and attenuation length) in scintillator plates in an independant way.

3.1 Scintillator plates

Three measurements were made with scintillator plates of various thickness.

3.1.1 Emission spectra

The emission spectra were measured using an automated luminescence spectrometer (PERKIN-ELMER LS-5B). We used small samples made of (20x20x(2.5, 3, or 5)) mm^3 pieces of scintillator. Figure 1 shows the emission spectra of four scintillators when excited by a 260 nm light source.

The values of the wave length at peak emission are shown in Table III. The decrease of emission due to radiation is not shown but is in agreement with the more precise measurement of the light yield with a β source.

3.1.2 Light yield

The light yield was measured with the same small samples in a set up shown in figure 2. Electrons from a ^{106}Ru source are used to excite the scintillator sample viewed by a XP2262 PMT from Philips. The signal from the PMT gated by a trigger signal provided by two thin counters (# 1 and 2 in figure 2) is analized with a Le Croy QVT. Figure 3 shows the pulse hight spectrum obtained with a non-irradiated sample. A total of 8 different scintillators were measured. This measurement with small samples makes it possible to monitor the intrinsic light yield without perturbation from light attenuation effects in the scintillator.

The relative light yield of the non-irradiated scintillator samples is shown in Table III. NE102 = 100 is chosen as reference. The normalization procedure takes into account the exact thickness of the samples and the quantum efficiency of the PMT taken from the data sheet (25 % at 425 nm, 12 % at 525 nm). The actual emission spectrum should be convoluted with the quantum efficiency (QE) curve of the PMT. Since we took the QE at peak emission there could be a $\sim$ 10 % error of normalization.

The scintillators fall into two categories:

- Those from KURURAY and Saclay (#6, 7, 8) emitting at 525 nm (yellow) yield $\sim$ 1/3 less light than
- those from NET and BICRON (#1, 2, 3, 4) emitting at 425nm (blue).

One exception is KURURAY's SCSN-81, a blue scintillator, which has low light output.

The evolution of the light yield as a function of the dose of radiation is shown in figure 4 for eight types of scintillator plates. Again the two categories behave differently:

- The yellow scintillators from KURURAY and Saclay (3HF) show very little light loss.
- The blue scintillators from NET and BICRON deteriorate considerably at 2 and 5.7 Mrad with various degrees of recovery in air.

KURURAY's blue SCSN-81 stands out with no light loss.

An attempt was made to look for effects of dose rates on the light yield by using results from runs # 1 and # 4 whose dose rates differ by a factor of 15. The results shown in Table IV are not conclusive. This question deserves further studies with longer irradiation times ($\sim$ 1 month).

3.1.3 Light transmission

The transmission and attenuation length over 25 cm in bulk scintillator was obtained independently from the light yield in the following way. Scintillator was cut into bars of dimension (25x2x2) cm^3.The small faces were polished and the samples were placed on a spectrophotometer using fiber connections. Their transmission relative to air was measured at wavelengths 400-800 nm. Figure 5 shows the set up used. Four different scintillators were measured. The transmission curves before irradiation are shown in figure 6.

The transmission of the scintillator to its own light is calculated by convoluting these transmission curves with the emission spectra (fig. 1). The attenuation length is then calculated to determine the transmission for 5 cm. Table V shows that for blue scintillators (BICRON BC-408 and KURURAY SCSN-81) the attenuation length are respectively 94 and 81 cm.

Visual examination reveals a "darkening" of the scintillator bars after irradiation. The darkness increases with the absorbed dose. The loss of transmission due to radiation is shown in figure 7 for 2 Mrad and 5.7 Mrad and for several annealing periods. A quantitative evaluation of the transmission loss at the relevant wave length is given in table VI. The attenuation length is calculated [4] using these transmissions according to $\lambda_{att} = \frac{25cm}{ln(0.9/T)}$. As can be seen in figure 8, the attenuation length of KURURAY SCSN-81 decreases from 81 cm to 6 cm after 2 Mrad. After a few weeks of annealing in air it recovers to 28 cm.

There are two reasons why this loss in transmission seems tolerable:

- first, the scintillation light in a tile must travel $\sim$ 10 cm before it is absorbed in a WLS fiber.
- second, the above measurements were made with the light beam at the center of the bar. In fact the dark zone was limited to the central part of the bar and was surrounded by clear zones along all six faces. The size of the central dark zone decreased with time as illustrated in figure 9.

  The front of annealing moving inward from the faces is most likely linked to the diffusion of air into the material. Fig. 10. shows the rate of increase

[4] The coefficient 0.9 is the transmission T(0) and represents the loss due to the quartz windows (fig. 5).

of the peripheral clear zone for two scintillators. In all three PS scintillators from KURURAY, in particular SCSN-81, the clear zone extends over 4 mm just after irradiation (2 and 5.7 Mrad) and fills the entire volume after 32 (or 44) days of recovery in air.

The important implication of this observation is that thin (2.5 to 3 mm) scintillator tiles of SCSN-81 would never become "dark" as the annealing would win over damage. Therefore the relevant result for transmission is the measurement after recovery when the dark zone has disappeared: R=0.55 which corresponds to $\lambda_{att} = 28$cm. Although the dark zone disappears completely after 32 days, the transmission does not recover its initial value before irradiation.

The question which could not be studied during these measurements is the degree to which annealing would take place in a tile sealed in an air tight bag.

3.2 Scintillating fibers

The tile/fiber technique uses WLS fibers and not scintillating fibers. In many aspects however the two kinds of fibers behave similarly since they are made of the same plastic base and secundary emitters and they follow the same manufacturing processes.

Scintillating fibers were measured in a setup where a ^{90}Sr β source is moved along 2 meter long, 1 mm diameter fibers and the anode current of the PMT is registered. Both ends of the fibers are polished and there is no reflector at the far end. Figure 11 sketches the quantities which can be derived from the measurements. $L(d)$ represents the light yield when the β source is at a distance d from the PMT.

Table VII shows the measured parameters of blue and green fibers for various doses of irradiation: the relative variation of light yield, averaged over several types of fibers, and the values of the attenuation length. The superiority of green fibers is apparent; compared with blue fibers, their attenuation length deteriorates less under irradiation and the light yield drops much less. As an illustration of the variations among different types of fibers, figure 12 shows that the attenuation lengths are the same, whereas light yields are different.

3.3 Attenuation length of clear fibers

Clear fibers were measured in a setup where laser light is transmitted through the fiber and measured with a Si photodiode (Fig. 13.). Attenuation lengths were obtained from measurements of transmission through 20 cm and 180 cm long fibers.

The attenuation lengths for clear fibers (1 mm diameter PS fibers from KURURAY) are shown in Table VIII. With 1.6 Mrad, the attenuation length is decreased by a factor $\simeq 7$ (4) for blue (green) fibers. This seems a large loss of performance but should not affect a real calorimeter in a significant way for the following reason: clear fibers are used in 2-3 meter length to bring the light signal to the photodetectors located behind the calorimeter; only a small portion of the clear fibers will be subject to intense irradiation in the calorimeter whereas in this measurement the entire fiber was irradiated.

3.4 Tiles

We have measured tile/fiber assemblies of various kinds. This program has only started and we present partial preliminary results.

Three tiles were made at Fermilab with the fiber geometry shown in figure 14-b. The scintillator was SCSN-81 and the WLS fiber was from BICRON. Initially, the tile where the fiber was not glued had half the light output of the two tiles with glue. After 0.25 Mrad at a rate of 1.8 krad/h the two tiles where glue was used lost 30 % of light, whereas the tile without glue lost none. After 3.4 Mrad at 15 krad/h the losses were 70 and 85 % for the tiles with glue and 60 % for the tile without glue.

At Saclay, we made a tile/fiber assembly according to the geometry of figure 14-a. The scintillator was BICRON BC-408 and the glued WLS fiber was BICRON BCF-91. After 6 Mrad at 15 krad/h, the light loss was 70 %.

4 CONCLUSION AND PROSPECTS

With the results of these measurements we have chosen the scintillator plates and WLS fibers which we are using in the construction of an EMC module. This module will be exposed to an electron beam at Orsay and tested for radiation hardness.

Among the commercially available plates we have chosen two blue scintillators:

- BICRON RH-5 which shows little light loss after 2 Mrad at 9 krad/h and after annealing.
- KURURAY SCSN-81 which produces less light but does not deteriorate after 5.7 Mrad; its attenuation length decreases from 81 cm to 28 cm (12 cm) after 2 (5.7) Mrad and after annealing.

The measurements with fibers confirms the superiority of green fibers. We have chosen to use BICRON BCF-91 WLS fibers for the tile fabrication.

From the irradiation of scintillator bars, it appears that the diffusion of air into the material controls the degree of damage. We will investigate this in more detail with further irradiation tests.

Besides the crucial test of the presently available EMC modules in an electron beam, we plan to continue testing assembled tiles with a cobalt source. The influence of parameters such as the type of glue used, the radius of curvature of the WLS fiber in the tile, the splicing to clear fibers, the shape of the groove, the fiber diameter etc.... will be tested. The aim is to design an EMC module with good light output, adequate radiation hardness and a practical routing of fibers to the rear of the module in which slots in the lead plates are avoided and cracks between towers minimized. We feel that there is room for improvement of the material used and in the design of a practical calorimeter for SDC.

Acknowledgements

We would like to thank C. Hurlbut (BICRON), T. Shimizu and Y. Okabayashi (KURURAY) for making various scintillator plates and fibers available to us. The assistance provided by M. Perrault (DEIN-Saclay) during the irradiation process is gratefully acknowledged. We also thank A. Giganon, D. Gauthereau, C. Jeanney, and D. Pierrepont for their help in preparing the samples and in performing many measurements.

	DOSE RATE (krad/h)		DOSE (Mrad)	
SSC luminosity	10^{33}	10^{34}	10 yrs@10^{33}	5 yrs@10^{34}
$\eta = 1.5$	0.002	0.02	0.05	0.25
$\eta = 3$	0.2	2	5	25

TABLE II.

Dose rates and total doses for four runs with a ^{60}Co source, for various types of samples.

RUN	PLATES AND BARS a)	FIBERS	TILES b)	
Low dose rate	0.6	0.6	1.8	**krad/h**
# 1	0.1	0.1	0.3	**Mrad**
High dose rate	9	7	15	**krad/h**
# 2	2	1.6	3.4	**Mrad**
#3	3.6	2.8	6.0	**Mrad**
#4	0.8	0.6	-----	**Mrad**

a) The doses in this collumn are relevant to measurements of scintillator plates: emission spectra, light yield, transmission.

b) These numbers are average doses. Due to the relatively large size of a tile (12.5 cm x 12.5 cm) all spots were not at the same distance from the source so that the doses vary by ≈ 20 % accross the tile area.

TABLE III.

Relative light yield of 8 non-irradiated scintillator samples.

		BASE	WAVE LENGTH AT PEAK EMISSION (nm)	RELATIVE LIGHT YIELD a) (%)
1	NE 102	PVT	425	100
2	BICRON BC 408	PVT	425	88 ± 3
3	PS/NA	PS	425	98 ± 3
4	RH-5/NA	PS/PVT	425	98 ± 3
5	KURURAY SCSN-81	PS	430	58 ± 3
6	SCSN-81-Y8	PS	520	61 ± 3
7	SACLAY PS/3HF	PS	525	62 ± 5
8	PVT/3HF	PVT	525	66 ± 5

a) A possible ≈ 10 % normalization error is not shown.

TABLE IV.

Light loss of two blue scintillators in "low" and "high" dose rates.

RUN		DOSE RATE (krad/h)	DOSE (Mrad)	% LIGHT LOSS BICRON RH-5	KURURAY SCSN-81
1	"low"	0.6	0.1	10 ± 8	4 ± 5
4	"high"	9	0.8	5 ± 6	0 ± 5

The attenuation length (λ_{att}) is derived.

	BICRON	KURURAY	
	BC 408	SCSN-81	SCSN-81-Y8
Average wave length (nm)	435	450	540
T(25 cm)	0.69	0.66	0.46
λ_{att} (cm)	94	81	37

TABLE VI.

Ratio of light transmission (T) along the axis of 25 cm long scintillator bars before and after irradiation: R=T(after) / T(before).

	BICRON [a]		KURURAY	
	BC 408	SCSN-81	SCSN-81-Y8	SCSN-81-Y8-R3
Average wave length (nm)	435	450	540	635
		R=T(after) / T(before)		
0.1 Mrad (0.6krad/h)	0.85	0.89	0.98	0.94
2 Mrad (9 krad/h)	0	0.03	0.30	0
+ 10 days	0	0.12	0.55	0.89
+ 32 days	0	0.55	0.91	1.
5.7 Mrad (9 krad/h)	0	0	0.08	0
+ 11 days	0	0.04	0.31	0.81
+ 44 days	0	0.18	0.71	1.
+ 65 days	0 (0.06) [b]			

a) BICRON RH-5 scintillator was not available in the form of bars at the time of the measurement.
b) This measurement (R=0.06) was made with a 5 cm long bar.

TABLE VII.

Measured parameters of blue and green fibers for various doses of irradiation. L(d) are relative light yields. λ_{att} is the attenuation length in meters (see text and fig. 11).

	BLUE FIBERS			GREEN FIBERS		
DOSE (Mrad)	0	1.6	2.7	0	1.6	2.7
L(1)	0.57	0.10	0.02	0.55	0.3	0.2
L(0)	1 a)	0.46	0.13	1 b)	0.7	0.55
λ_{att} (m)	1.8	0.7	0.5	1.7	1.2	1

a) For blue fibers, L(0) = 1 corresponds to 7.7 photo-electrons.
b) For green fibers we do not quote an absolute value for the light yield as the quantum efficiency of the PMT needs to be checked in the 530 nm region.

TABLE VIII.

Attenuation length of clear PS fibers from KURURAY before and after irradiation.

DOSE *) (Mrad)	BLUE LIGHT ≈ 450 nm	GREEN LIGHT ≈ 550 nm
	λ_{att} (m)	
0	6.3 m	7.4 m
1.6	0.9 m	1.9 m

*) The dose rate was 7 krad/h.

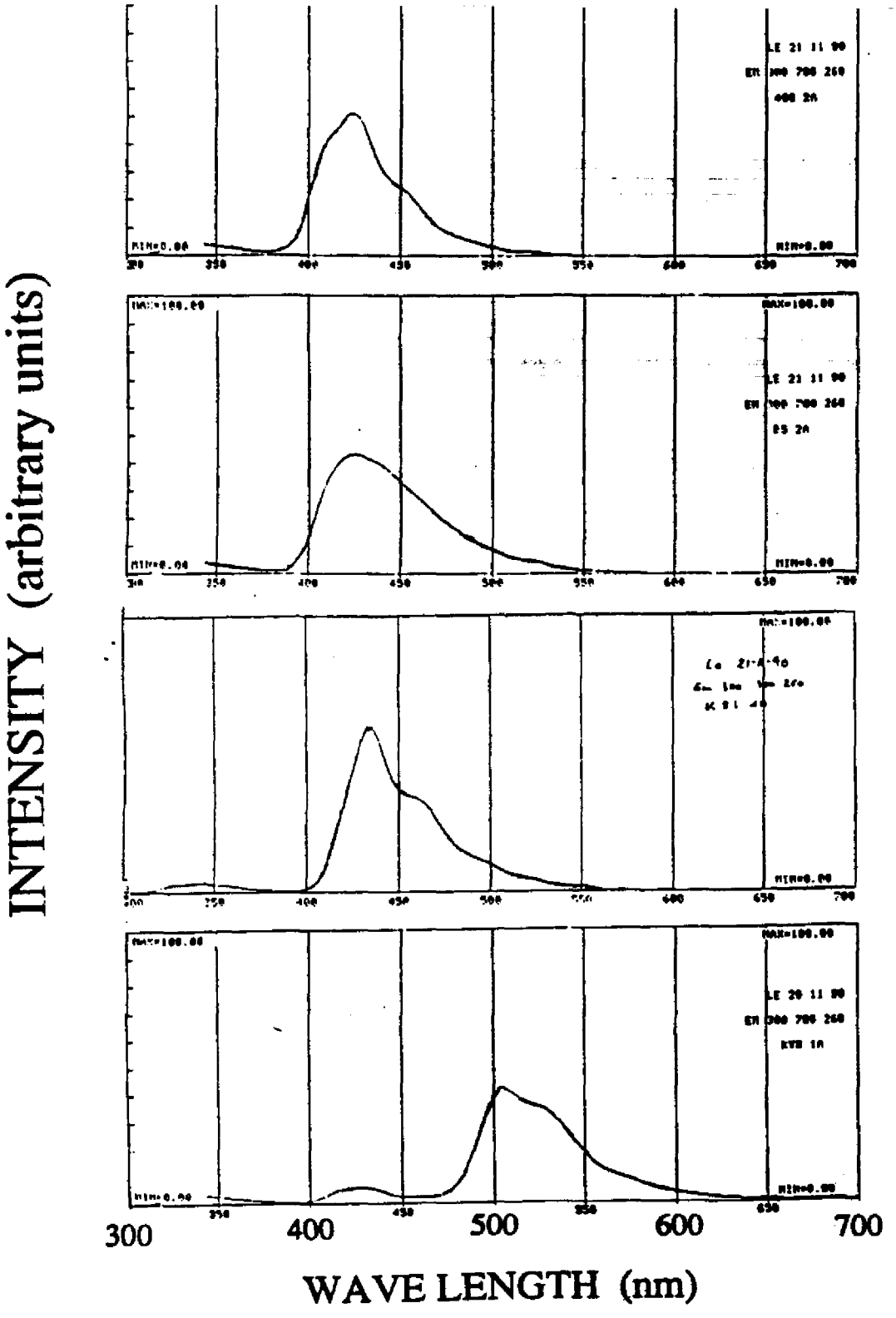


Figure 1.
Emission spectra of 4 scintillators excited by a 260 nm light source: BICRON BC-408, BICRON RH-5, KURURAY SCSN-81, and KURURAY SCSN-81-Y8.

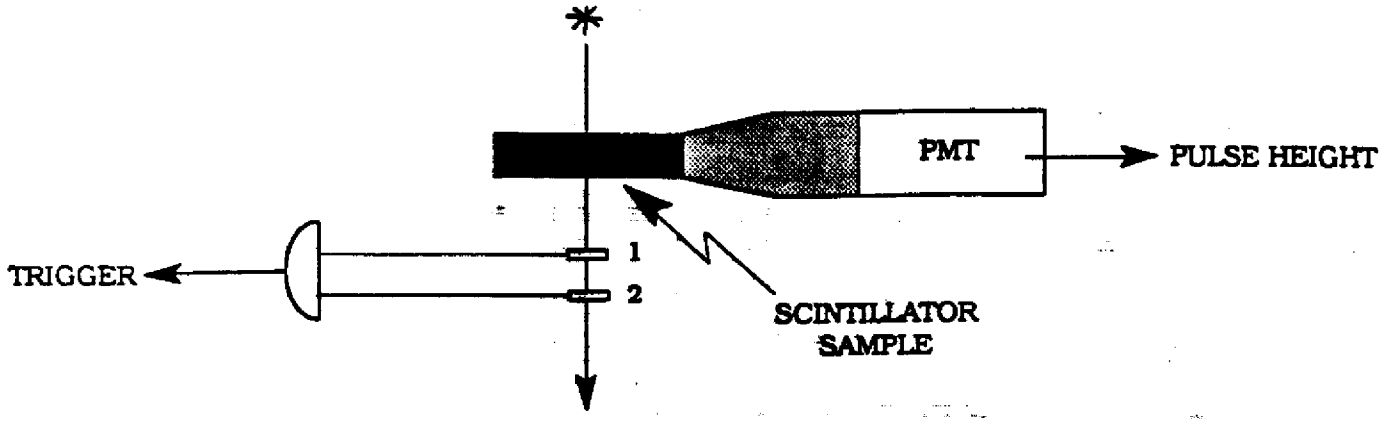


Figure 2.
Set up used in the measurement of scintillator light yields.

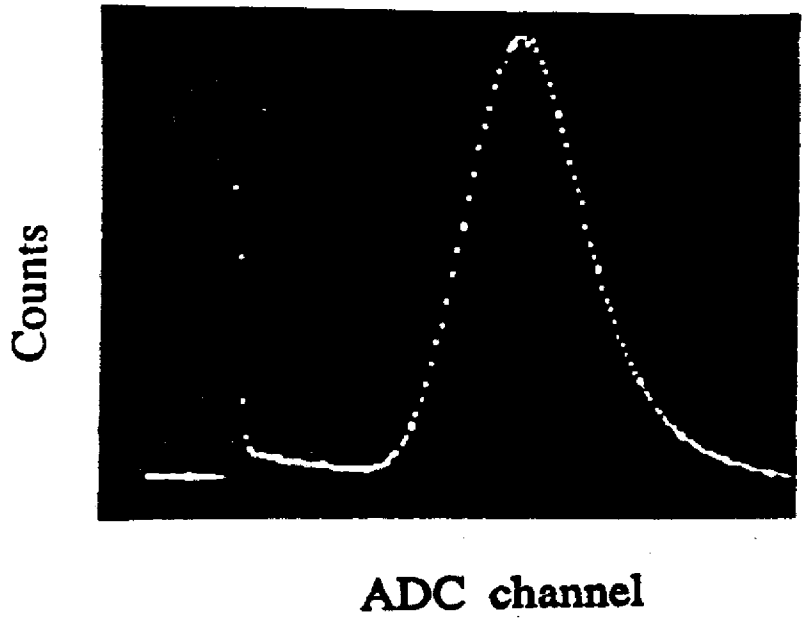


Figure 3.
Pulse hight spectrum obtained with a ^{106}Ru source on a sample of BICRON RH-5 scintillator.

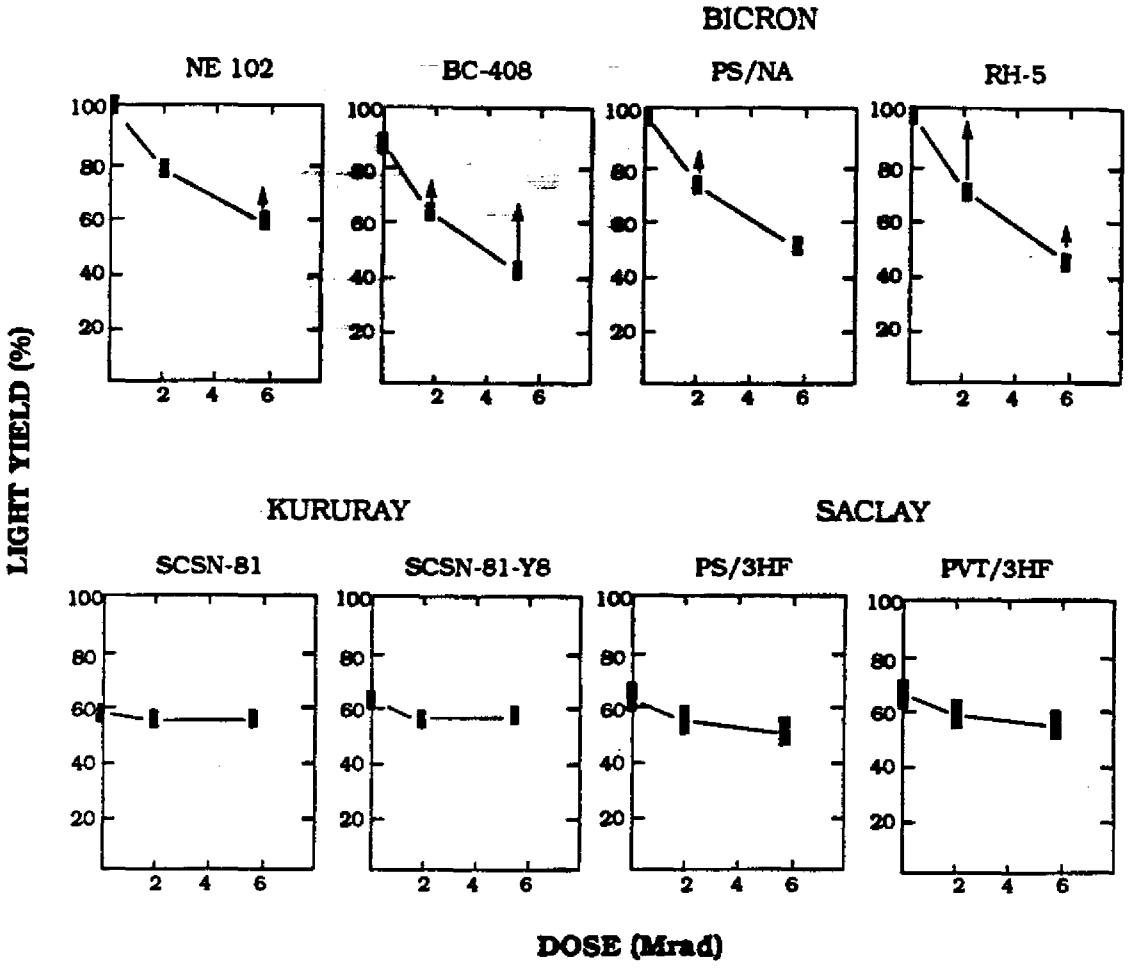


Figure 4.

Relative light yield as a function of absorbed radiation dose for 8 types of scintillator plates. Light yields are normalized to NE 102 = 100 %

- A before irradiation
- C 2 Mrad at 9 krad/h
- C' 2 Mrad + 3 days of annealing in air
- D 5.7 Mrad at 9 krad/h
- D' 5.7 Mrad + 29 days of annealing in air

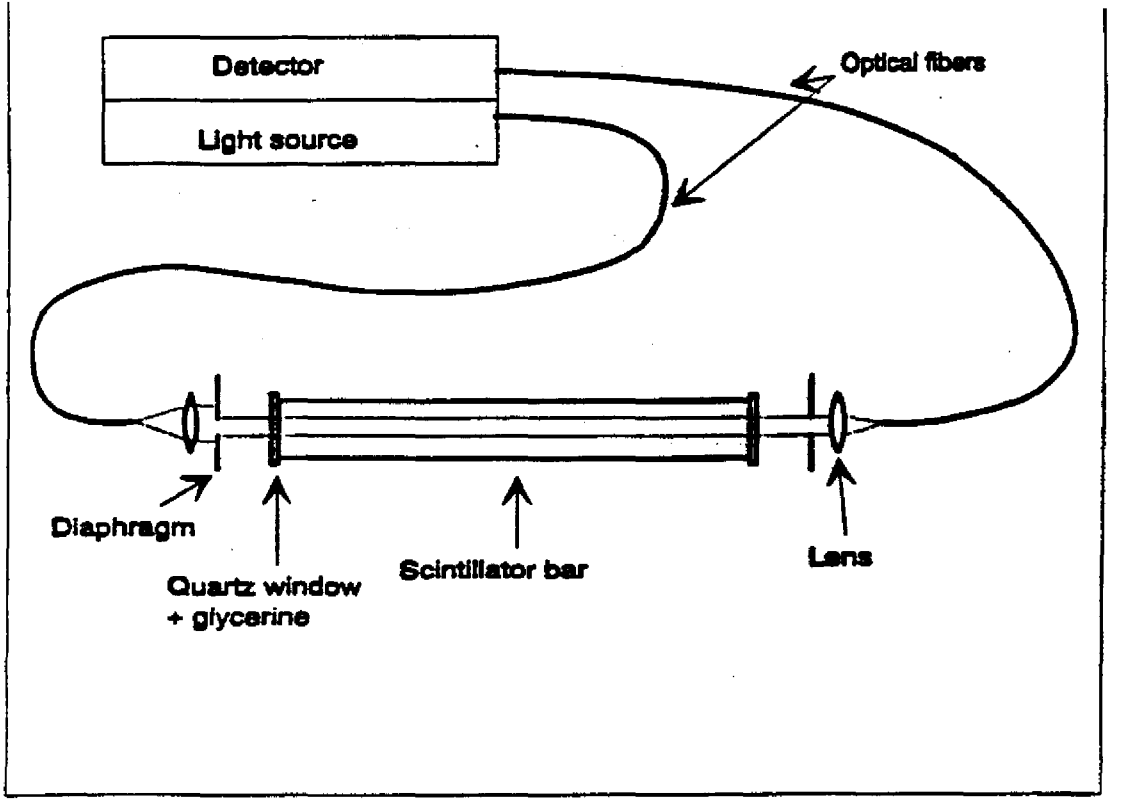


Figure 5.

Set up used for measuring the light transmission of scintillator bars with an optical waveguide spectrum analyzer.

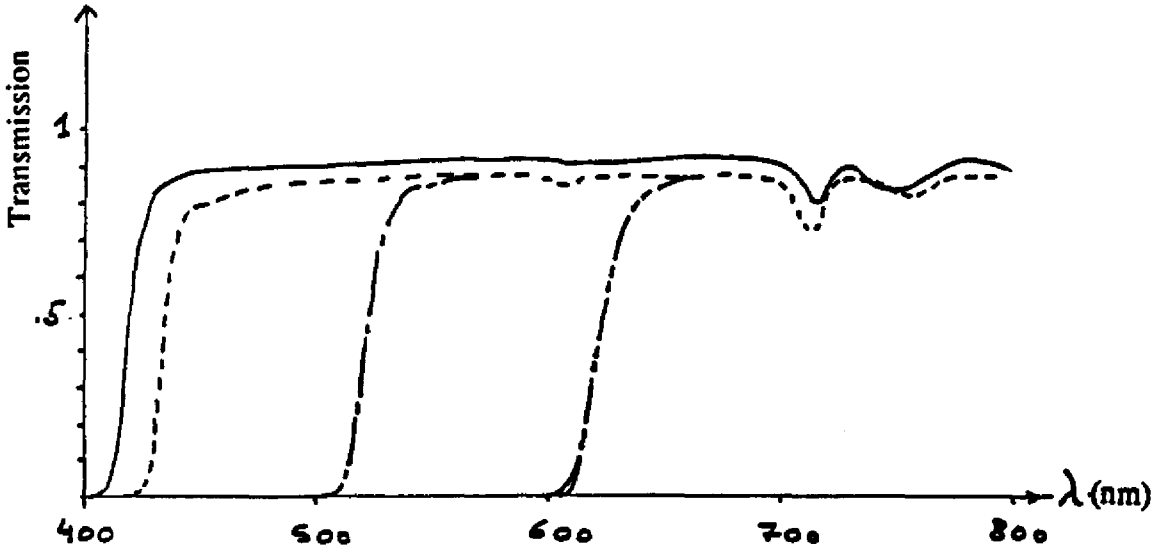


Figure 6.

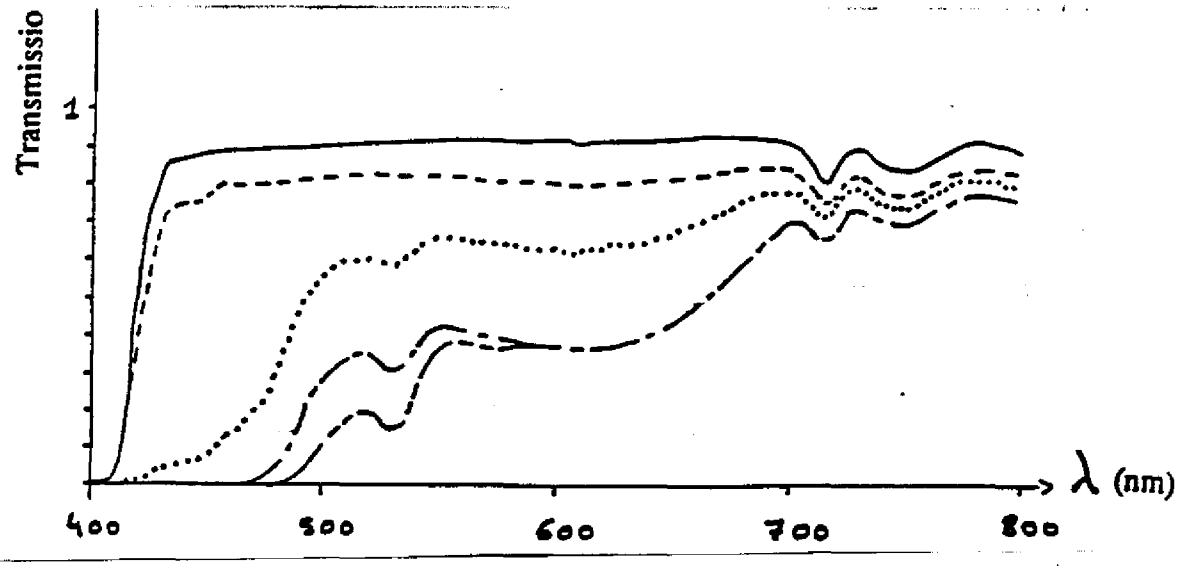
Transmission curves before irradiation over 25 cm in bulk scintillator.

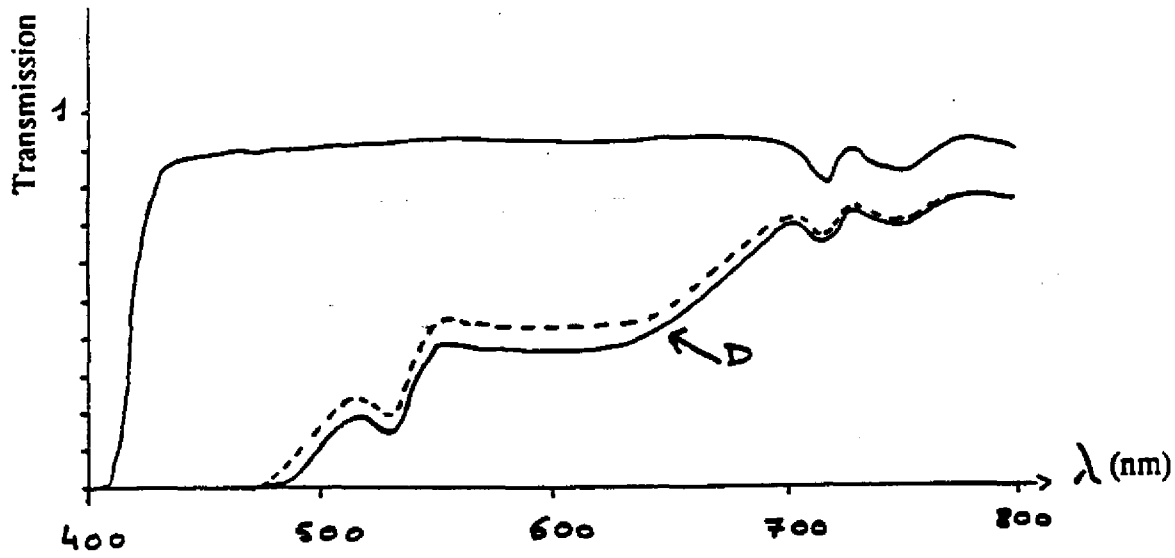
——— a) BICRON BC-408

- - - - - b) KURURAY SCSN-81

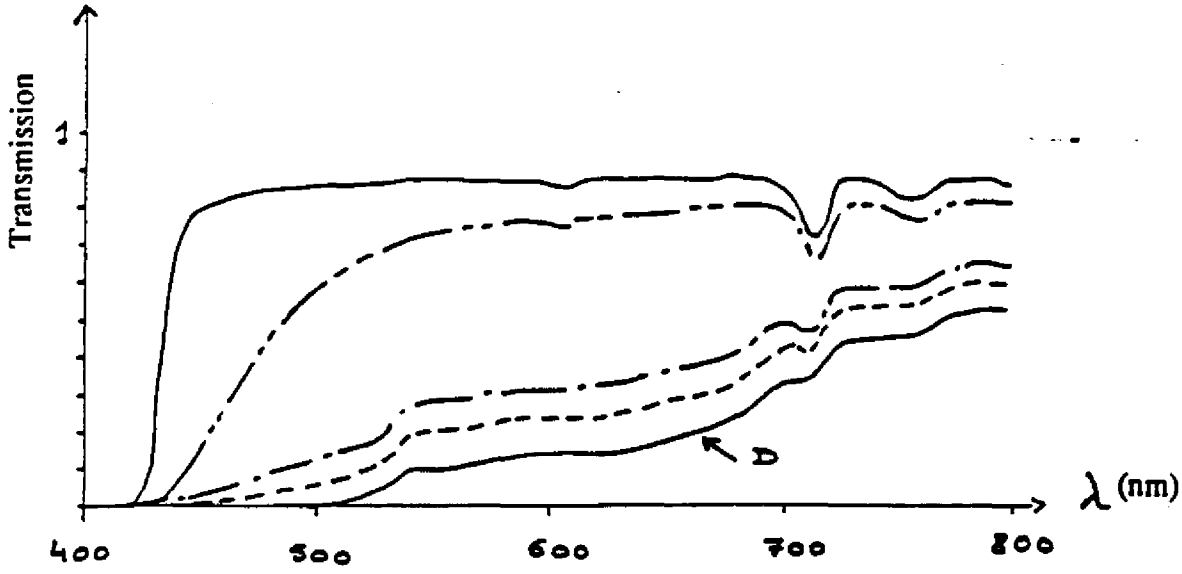
—·—· c) KURURAY SCSN-81-Y8

—··— d) KURURAY SCSN-81-Y7-R3





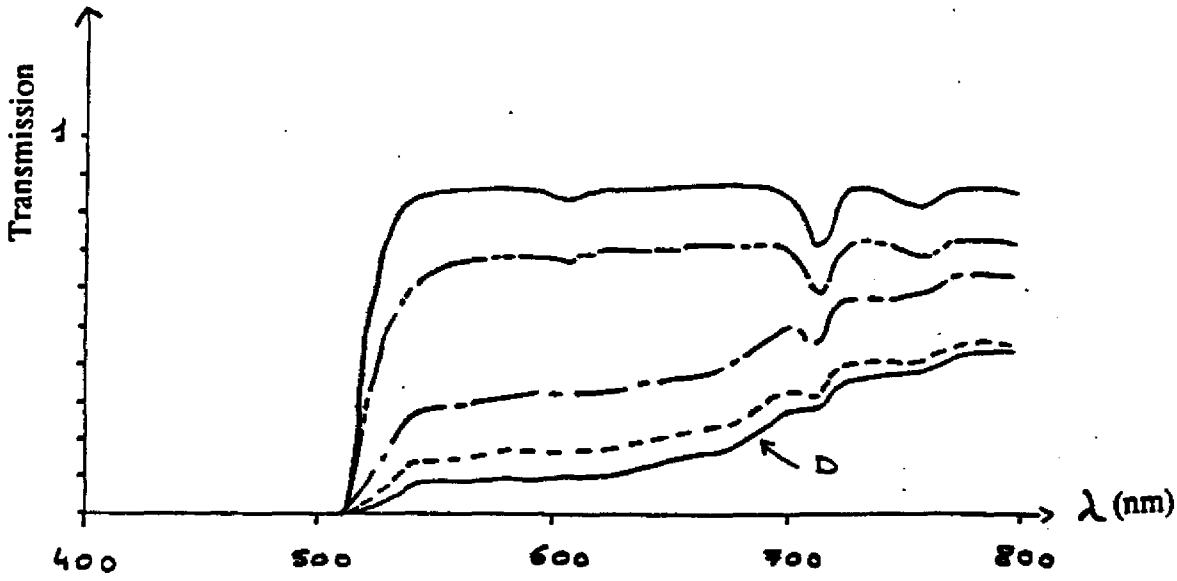
a - Bicron HP-BC 408



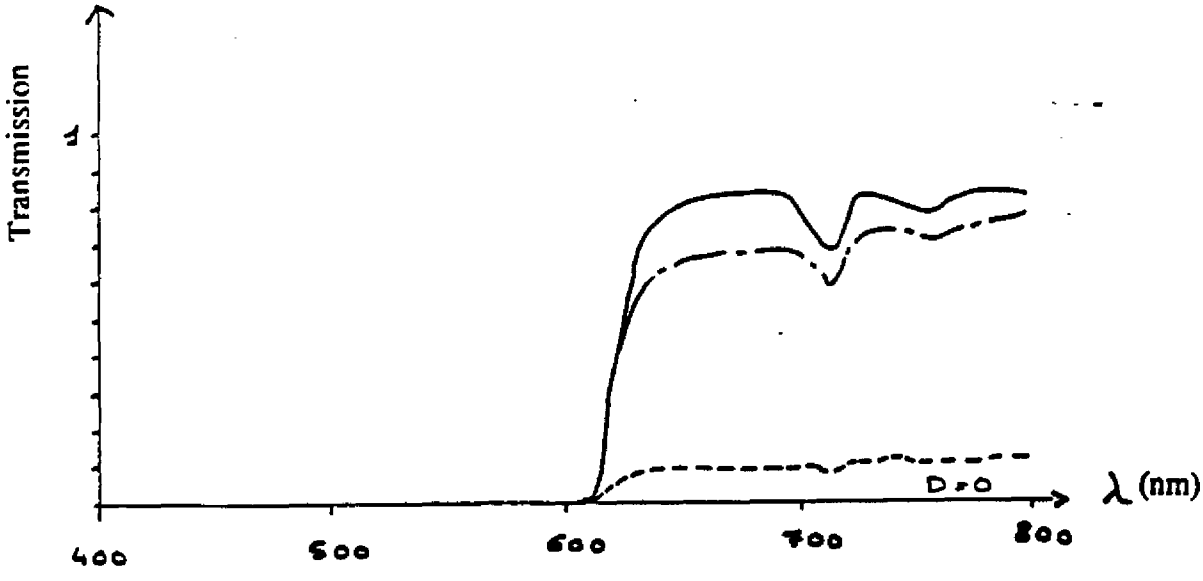
b - Kuraray SCSN-81

Figure 7 ter.

Transmission curves after 5.7 Mrad at 9 krad/h (D).



c - Kuraray SCSN-81-Y8



d. Kuraray SCSN-81-Y7-R3

Figure 7 ter. (continued)

————	Before irradiation
- - - - - -	D + 7
— - —	D + 11
—— - -	D + 44

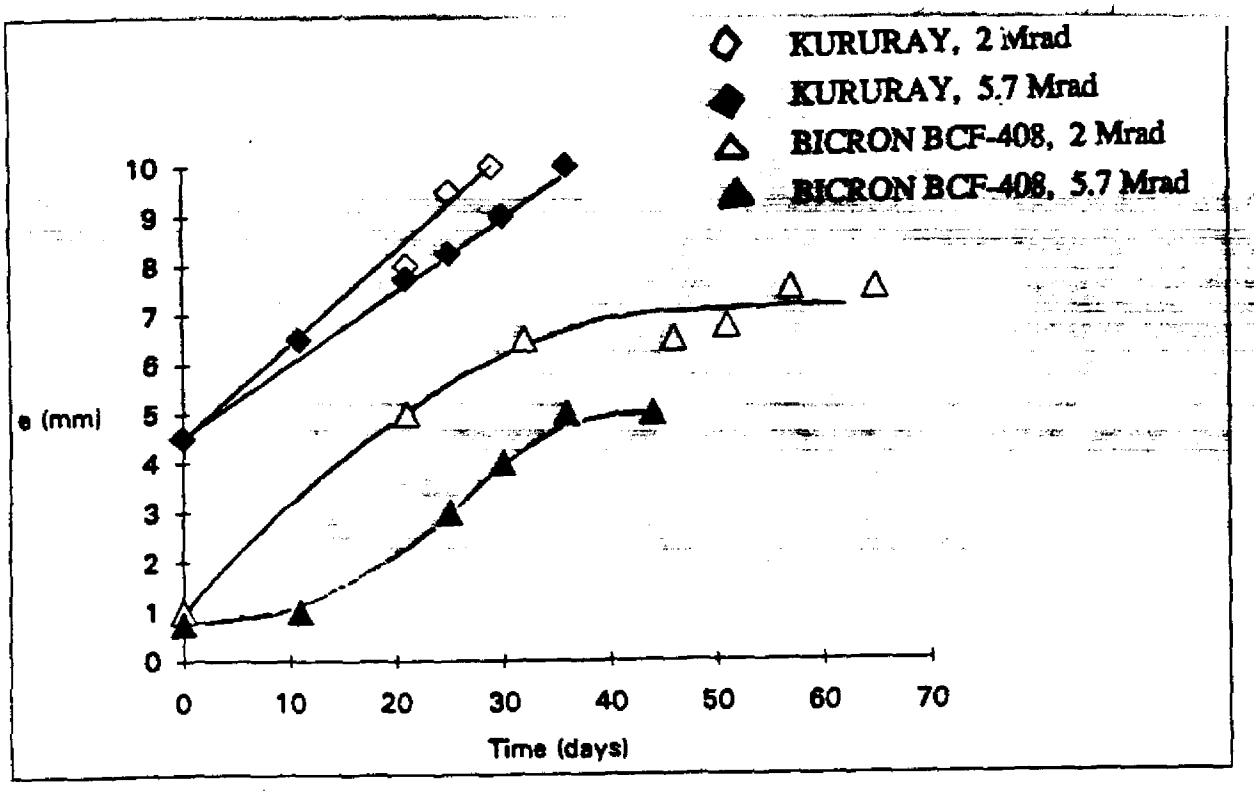


Figure 10.

Variation of the thickness of the visible peripheral annealed zone as a function of time after irradiation. The full area of the bar corresponds to e=10 mm for KURURAY and e=12.5 mm for BICRON.

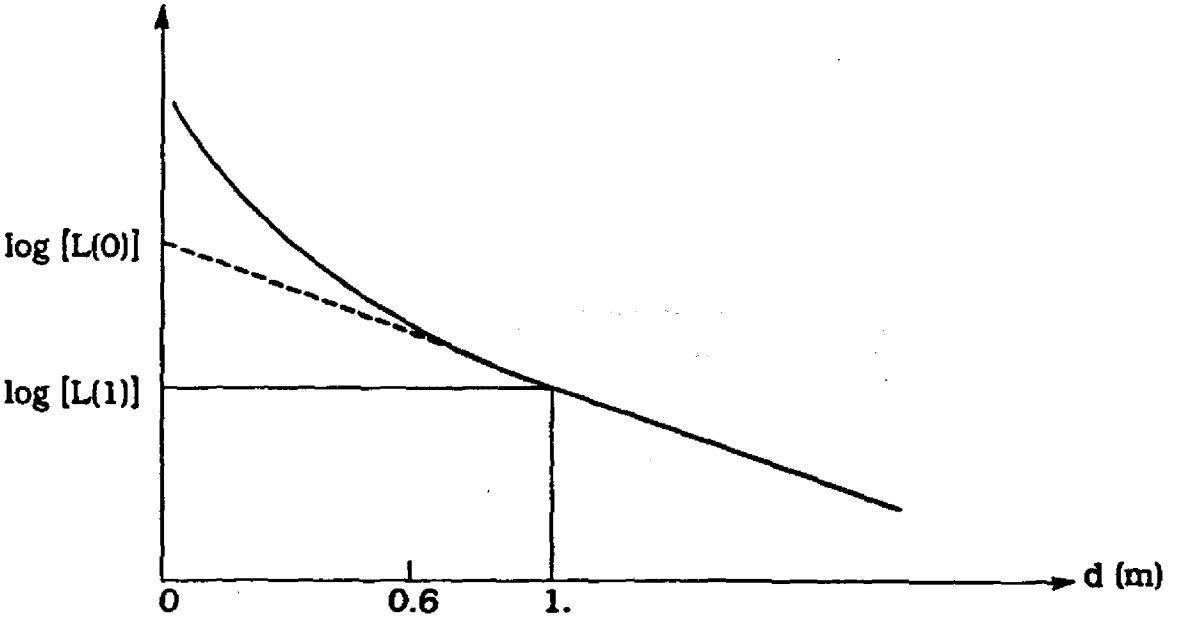


Figure 11.

The quantities derived from the measurement of scintillating fibers.
L(d) is the relative light yield at a distance d (in meters) from the PMT.

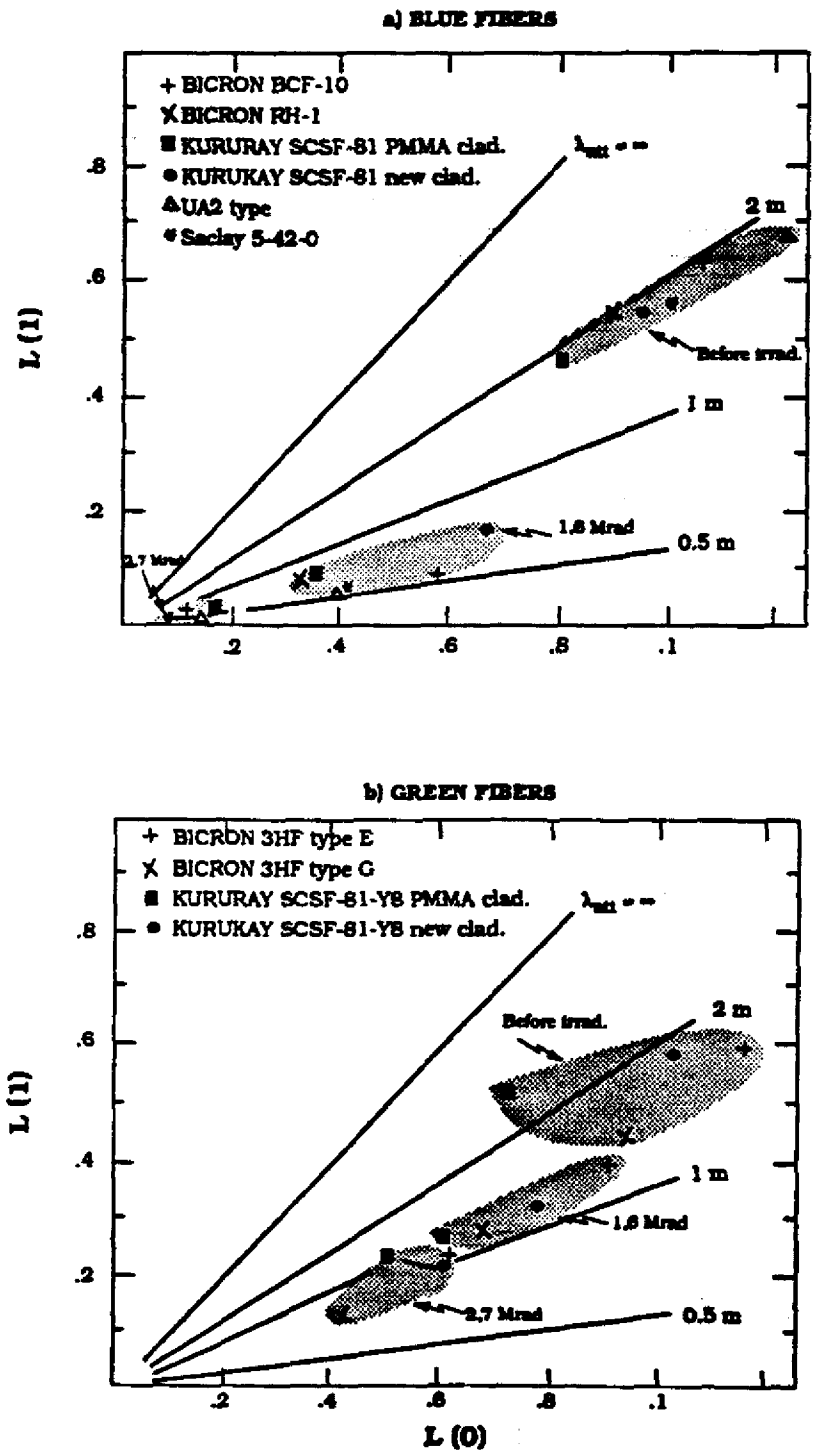


Figure 12.

Relative light yield [L(d)] and attenuation length [λ_{att}] of fibers after various doses of irradiation.

a) Blue fibers. L=1 corresponds to an absolute value of 7.7 photoelectrons.

b) Green fibers. The absolute scale for L is not determined.

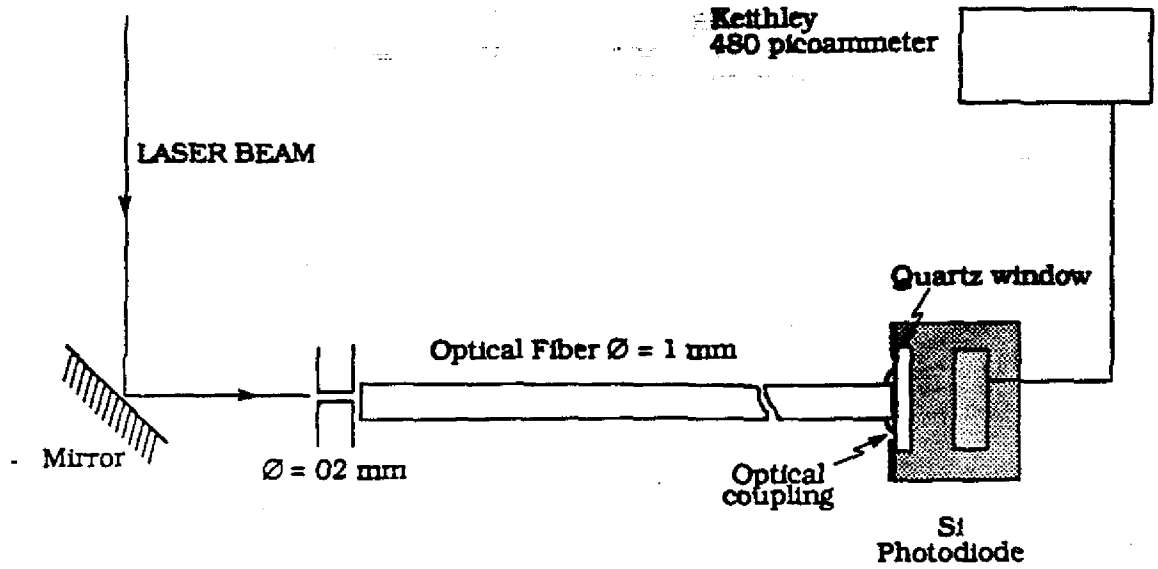


Fig. 13

Set up used in the measurement of the transmission of laser light by clear fibers.

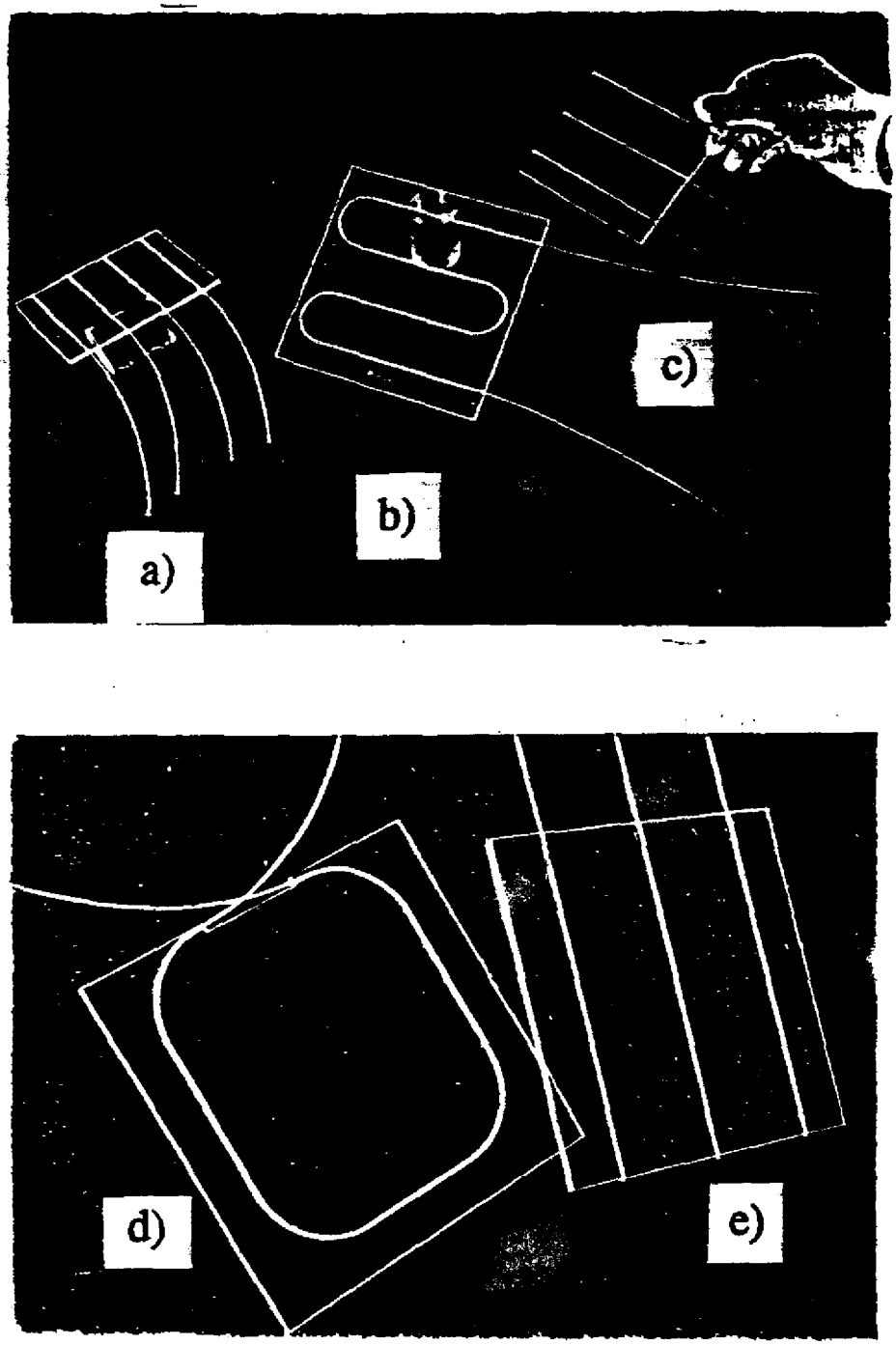


Figure 14.

Various tile/fiber assemblies:

- with straight fibers (a, c, e)
- with bent fibers (b, d) according to Fermilab designs.