EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

NP Internal Report 75-12
6 October 1975

SCINTILLATOR DEVELOPMENTS AT CERN*)

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G E N E V A
1975

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*) This development was done in collaboration with the following firms: Röhm, G.M.B.H., Germany; Peterlite S.A., France; and Polivar, S.p.A., Italy. Dr. Kretz of Röhm made several important suggestions for the development of the new plastic scintillator.

Large quantities of scintillating material are needed for total absorption counters (calorimeters) in the present high-energy experiments. The use of commercially available plastic scintillators would be extremely expensive; liquid scintillators are cheap but the mechanical construction of the counters is more complicated.

In order to avoid these constraints, we have developed a new, inexpensive plastic scintillator which will be used in the SPS experiment NA3.

In Section 1 of this report the performances of the new scintillator are described, while Section 2 deals with the production of standard scintillators at CERN.

1. A NEW PLASTIC SCINTILLATOR: DOPED PLEXIGLAS "PLEXIPOP"

The basic idea for the development of a new scintillator was to find a plastic material having good optical and mechanical properties and without ageing effects, and to try to make it scintillate by adding suitable chemicals.

Such a material should also be commercially available in large amounts and at low cost.

The requirements on the performances of a scintillator to be used in high-energy experiments can be listed as follows.

a) Light output (L)

For special use in calorimeters there is no need to have as much light output per particle as in the classical scintillators since one measures showers involving many particles rather than single particles. Therefore for such applications a light output L ≈ 10-30% of the normal scintillators should be adequate.

For normal applications in counters where full efficiency is required for a single particle, a scintillator with light output of the order of 30-40% can still be of interest.

b) Attenuation length (λ)

The optical transparency must be good since long and thin sheets are generally used and the light propagates by internal total reflection. The observed attenuation length λ, which is determined by the bulk absorption and the surface reflectivity, should not be worse than for the best commercial scintillators (i.e. $\lambda \gtrsim 2$ m).

c) Decay time (τ)

The decay time should be short ($\tau \lesssim 5$ nsec) as in a classical scintillator if the counter is used for a fast trigger. For usual calorimeters where

only pulse-height analysis is required, a longer decay time ($\tau \approx 20$-30 nsec) can be tolerated. The calorimeter planned for the experiment NA3, however, has to be used in the trigger and therefore the requirement of short decay time is essential.

Having the a,b,c requirements in mind, we have chosen polymethylmethacrylate (PMMA), commercially known as plexiglas, as the base material. It is well known[1] that PMMA, not being an aromatic compound, cannot give as high a light yield as polystyrene (PST) or polyvinyltoluene (PVT); however, its availability in a great variety of shapes and dimensions with very good optical and mechanical properties is attractive enough to use it for a plastic scintillator. One of the important advantages of plexiglas is the stability against ageing effects.

The fluorescent materials to be added to plexiglas were selected according to their known performances and availability.

Para-terphenyl (TP), naphthalene, PPO, and butyl-PBD were used as scintillating agents, POPOP and TPB as wavelength shifters*).

Many samples containing different combinations of scintillating agents and wavelength shifters, prepared for us by Röhm, G.M.B.H., Germany, Peterlite S.A., France, and Polivar, S.p.A., Italy, were measured.

1.1 Measuring technique

1.1.1 Light output (L)

Taking all the materials to be tested, we prepared samples of $200 \times 100 \times 10$ mm^3 wrapped in aluminized mylar and black Scotch tape. Each plate was glued, together with a reference plate of NE 110 with the same dimensions and wrapping, onto a light-guide of 200 mm width, which was viewed by a 56 DVP photomultiplier as shown in Fig. 1a. The pulse-height spectrum of cosmic rays was recorded in a multichannel pulse-height analyser which was gated by a 100×100 mm^2 trigger counter, covering first the sample plate, and then the reference plate. The pulse-height spectra are brought to overlap with the help of an attenuator in the pulse-height recording channel (see Fig. 1b). This method has the advantage of avoiding changes in optical contact, switching of high voltage, etc., and gives reproducible results. All yields will be quoted in percent of NE 110. An example is shown in Fig. 2.

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*) The actual cost of these chemicals for small quantities are:

TP:	360 SF/kg
Naphthalene:	75 SF/kg
PPO:	1150 SF/kg
Butyl-PBD:	1070 SF/kg
POPOP:	300 SF/100 g
TPB:	340 SF/100 g.

1.1.2 Attenuation length (λ)

Two methods have been applied and checked against each other, always using scintillator sheets of 2000 × 200 × 10 mm^3 glued to a light-guide of 1300 × 200 × 10 mm^3 and the same 56 DVP as for the L measurements:

i) cosmic-ray spectra as in *(1.1.1)* but with the trigger counter being displaced in steps of 25 cm;

ii) anode current produced by a β radioactive source, displaced along the counter.

Both methods gave identical results, but we preferred the current method in the later measurements since it is so much faster. The far end of the sample scintillator was either blackened to avoid reflections, and the attenuation curve fitted to the expression $L(x)/L_0 = e^{-x/\lambda}$; or optically matched to a mirror and λ extracted by fitting to the expression $L(x)/L_0 = \cosh\left[(\ell - x)/\lambda\right]$, where ℓ is the length of the scintillator and x the distance from the light-guide. The mirror method has been preferred in the end since it gives more light. This is also the technique foreseen for the calorimeter in the experiment NA3.

The measurement of λ was also made by inserting an optical filter, between the light-guide and the photomultiplier, which cuts out the light for wavelengths less than 4350 Å. The use of a filter is expected to improve the uniformity because the optical absorption of a plastic material decreases with increasing wavelength[2].

1.1.3 Decay time (τ)

In order to determine the decay time, we have used the standard technique of measuring the delay of the arrival time of the photoelectron with respect to the trigger signal, in such conditions (diaphragm on the photocathode) that the average number of photoelectrons was less than one.

1.2 Results

1.2.1 Two-component systems

We first studied two-component systems as used in normal scintillators, with p-terphenyl (TP) or PBD as scintillating agent and POPOP as wavelength shifter. The combination TP = 0.8% and POPOP = 0.1% gave L ≃ 10%. The combination PBD = 1% and POPOP = 0.1% gave L ≃ 8%. This light yield can be sufficient for many applications, e.g. in electron shower counters, but further investigation was carried out, aiming to reach a higher yield.

When trying the combination naphthalene-POPOP, a marked increase in light yield was noticed (L = 18% for naphthalene = 0.8% and POPOP = 0.1%). However, the decay time turned out to be quite long, τ ≃ 20 nsec, which is unacceptable for fast trigger applications. It is known[3] that pure naphthalene crystals are slow scintillators (τ = 80 nsec), but the decay time becomes shorter (τ ≃ 30 nsec) when adding small amounts of a fast scintillator.

1.2.2 Three-component systems

In order to improve the decay time of the naphthalene-POPOP combination, a three-component system was studied by adding a second fast scintillating agent. The motivation for this is given by the known mechanism of non-radiative energy transfer from the solvent to naphthalene and then to a second fluorescent solute, e.g. as discussed by Birks[4] for liquid scintillators. Unfortunately the combination p-terphenyl + naphthalene does not work[4]. Dr. Kretz of Röhm, G.M.B.H., who has been working on the subject earlier, suggested the use of butyl-PBD instead of TP.

A large series of samples of the three-component system naphthalene-PBD-POPOP in various concentrations were measured for a systematic optimization.

This study has indeed led to a satisfying scintillator, again with a fast decay time, $\tau \approx 5$ nsec (see Fig. 3b). The measured parameters of different combinations are compiled in Table 1, where the results for the commercial scintillator NE 110 are also quoted for comparison.

Table 1

Parameters of the "Plexipop" scintillator (naphthalene-PBD-POPOP)

Type	Naphthalene (%)	PBD (%)	POPOP (%)	L (%)	λ *) (m)	τ (nsec)
I	1	1	0.01	21	2.0 (2.8)	5
IIa	3	1	0.01	30	1.3 (1.7)	6
IIb	1	3	0.01	32	1.5 (2.3)	5
IIc	3	3	0.01	34	1.2 (1.7)	
NE 110				100	2.0 (2.7)	4

In Table 1 the light yield is quoted in % of NE 110. The errors on L, λ, and τ, as estimated from the reproducibility of the results, are about ±10%.

The λ values in brackets are for the use of an optical filter which cuts the light for wavelengths < 4350 Å; this improves the uniformity considerably, reducing however the light output L as measured close to the light guide by $\sim$ 30%.

The effect of varying the wavelength shifter (POPOP) concentration was studied for fixed naphthalene = 3% and PBD = 1% concentrations. The results on the light output and attenuation length are reported in Fig. 4.

The use of a different scintillating agent, PPO instead of PBD, and of a different wavelength shifter, TPB instead of POPOP, was also investigated. The

*) The λ values of Table 1 are obtained by setting the mirror reflectivity = 1; a more realistic value is probably 0.9, for which all the values of λ must be increased by $\sim$ 10%.

combination naphthalene = 3%, PPO = 1%, and POPOP = 0.01% gave L = 29% and λ = 1.4 m; these values are similar to those corresponding to the three-component system with PBD = 1% (see Table 1) but PPO is more expensive than PBD. The combination naphthalene = 3%, PBD = 1%, and TPB = 0.01% gave L = 24% and λ = 1.5 m. Therefore, the use of TPB instead of POPOP as wavelength shifter reduces the light yield L by $\sim$ 25% without significantly improving λ. This same reduction of the light yield when using TPB instead of POPOP was also observed when comparing the two-component systems TP-POPOP and TP-TPB and can be explained by the difference of photocathode efficiency for the wavelengths corresponding to the maxima of the emission spectra of POPOP and TPB.

The best three-component Plexipop scintillator, both with respect to quality and cost is therefore the combination naphthalene-PBD-POPOP.

From Table 1 and Fig. 4 the following conclusions can be drawn.

1.2.3 Light output (L)

i) L versus POPOP concentration

The dependence of L on the POPOP percentage for fixed naphthalene and PBD concentration (see Fig. 4a) shows a rather typical behaviour[5] with a slow increase and a broad maximum around 0.02-0.03%. For our tests of optimization of the naphthalene and PBD concentration we have chosen, somewhat arbitrarily, a POPOP percentage of 0.01%. The optimum, however, appears to be between 0.02% and 0.03%; this would increase the L values of Table 1 by $\sim$ 5%.

ii) L versus naphthalene and PBD concentration

As seen in Table 1, the yield increases with PBD and naphthalene content in much the same way; however, PBD is expensive while naphthalene is cheap. In large scintillators, what counts is not just L but the combined effect of L and λ, which determines the amount of light emerging from a great depth. Therefore L must be optimized as a function of λ.

1.2.4 Attenuation length (λ)

i) λ versus POPOP concentration

Figure 4b shows that λ does not change with POPOP concentration between 0.1% and 0.003%; therefore one can freely choose the POPOP percentage within these limits to achieve maximum yield, as discussed above.

ii) λ versus naphthalene and PBD concentration

As seen in Table 1, the best transparency (λ = 2 m) is achieved for the lowest concentration of scintillating agents, i.e. for type I. Its λ is as good as for the best commercial scintillator, NE 110, and shows the same

improvement by using an optical filter. By increasing the naphthalene and PBD concentrations the transparency becomes poorer; λ seems more sensitive to naphthalene than to PBD. The gain in light output for class II mixtures is therefore only useful if the scintillators are not too long, i.e. 2 m. Numerical example: for a 2 m long sheet, the light yield L from the *far end* is as high for type I Plexipop as for type IIb, even though the latter produces 1.5 more light too close to the light-guide. Uniformity curves measured with the mirror method (with and without filter) are shown in Fig. 5 for Plexipop types I and IIa, and also for NE 110 for comparison.

1.2.5 Decay time (τ)

The addition of the fast scintillating agent PBD to the naphthalene-POPOP combination results in a substantial decrease of the decay time, making the three-component system suitable for a fast trigger.

1.3 Conclusions

The Plexipop scintillator has obvious advantages with respect to commercial scintillators as far as cost is concerned*). While the results reported above allow a choice to be made of the type of Plexipop which is more suitable for a given application, the following general remarks can be made.

i) The two-component Plexipop with a fast scintillating agent (TP or PBD) and wavelength shifter (POPOP), is fast, has good transparency ($\lambda \simeq 2$ m), but low light output, L ≃ 5-10%.

ii) The two-component Plexipop containing naphthalene and POPOP is cheap, transparent, and also reasonably efficient (L ≃ 18%), but slow. It is therefore of interest for applications in calorimeters not used in a fast trigger where only pulse-height analysis is required.

iii) The three-component Plexipop of type I (see Table 1) is attractive for rather general use because of the rather high light output (L = 20-25%), high transparency, and short decay time. These features make the Plexipop type I suitable for applications in the calorimeters which are used for a fast trigger. This type of Plexipop will probably be used in the electron-γ calorimeter of the SPS experiment NA3.

iv) The most efficient Plexipop scintillators have L ≈ 35% and attenuation length λ = 1.2-1.5 m. Plexipop type IIa is of special interest among the other combinations listed in Table 1, because it offers a high yield at low cost. This kind of plastic scintillator is, however, not suited for making

*) Preliminary estimates indicate $\sim$ 300 SF/m^2 for type I for sheets of 10 mm thickness. The extra cost with respect to pure plexiglas is essentially determined by the PBD.

long counters because of the substantial attenuation; rather, it is of interest for medium-size counters or calorimeters.

2. PRODUCTION OF "CLASSICAL" SCINTILLATORS AT CERN

(W. Kienzle, and L. Maitre, C. Brégy and M. Sartorio from the West Workshop)

High yield plastic scintillator is generally produced by dissolving certain scintillating chemicals in *aromatic* base materials such as polyvinyltoluene (PVT) or polystyrene (PST)*).

The first (PVT) is used by Nuclear Enterprises (and has some mechanical disadvantages), the second has been used at CERN by the CERN-Bologna Collaboration in their scintillator production during 1974. We have made use of the new installation of the West Workshop; the following modifications of the equipment and production procedure were made:

i) new forms to obtain standard sheets of 10 mm thickness (1250 × 800 mm^2 area);

ii) distillation of the raw material, at the Battelle Institute (Geneva);

iii) modified polymerization cycle;

iv) new scintillating agent (butyl-PBD instead of p-terphenyl).

The product obtained in our recent test runs (August 1975) is equivalent to NE 110 in light output (L = 100%).

Aims:

i) Use a mixture of PST and PVT rather than pure PST, in order to avoid possible ageing effects and further improve the transparency.

ii) Complete the development work by the end of 1975, and start series production with a capacity of $\sim$ 500 m^2/year.

Production capacity:

Approximately 20 sheets of 1250 × 800 × 10 mm per cycle of two weeks, i.e. $\sim$ 500 m^2 of scintillator per year using the present installation. The feasibility of making thinner sheets (5 mm) will be tried soon.

Cost:

Estimated at $\lesssim$ 1/3 of NE 110 (if the base material is bought already distilled).

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*) For details see BIRKS, "Scintillator Counters".

Acknowledgements

This technical development was made within the framework of the preparation of the SPS experiment NA3. We are grateful to all our colleagues at CERN, and those of CEN (Saclay) Collège de France, Ecole Polytechnique (Paris), and the Laboratoire d'Accélérateur Linéaire (Orsay) for many useful discussions. We thank our technicians, J. Catin, J. Hill, R. Lorenzi, as well as Mrs. Trottberger for continuous technical help.

We are grateful to our Summer Student, Sven Wilhelmsson, for his efficient help during the Plexipop development.

REFERENCES

1) J.B. Birks, The theory and practice of scintillation counting (Pergamon Press, London, 1964), p. 327.

2) See J.B. Birks, for a measurement of the optical absorption coefficient as a function of wavelength for a commercial plastic scintillator, op. cit., p. 338.

3) *Ibid.*, pp. 245 and 304.

4) *Ibid.*, p. 279.

5) *Ibid.*, p. 293.

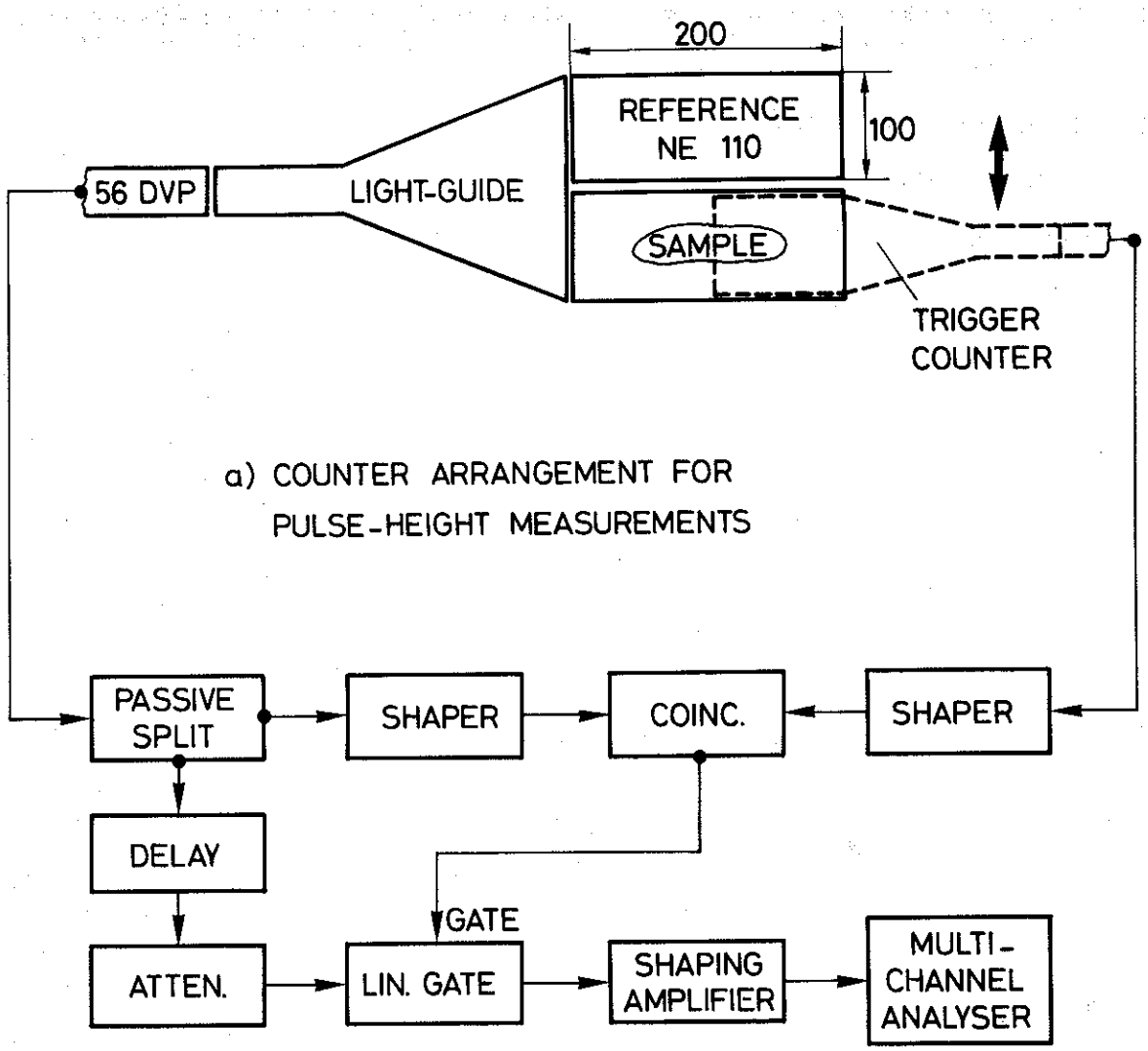
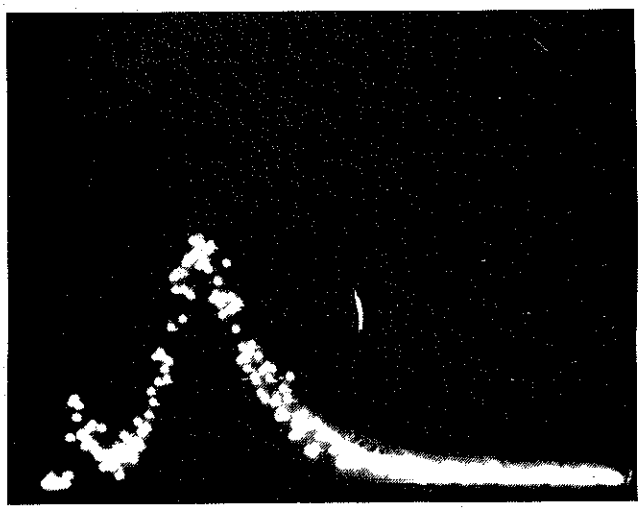


FIG.1: SYSTEM FOR MEASURING
RELATIVE LIGHT OUTPUT



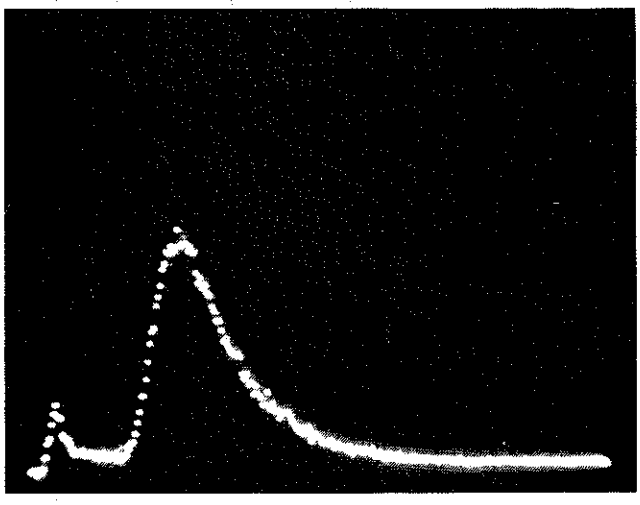
a) PLEXIPOP (1)

1% NAPHTHALENE

1% PBD

0.01% POPOP

L = 21%



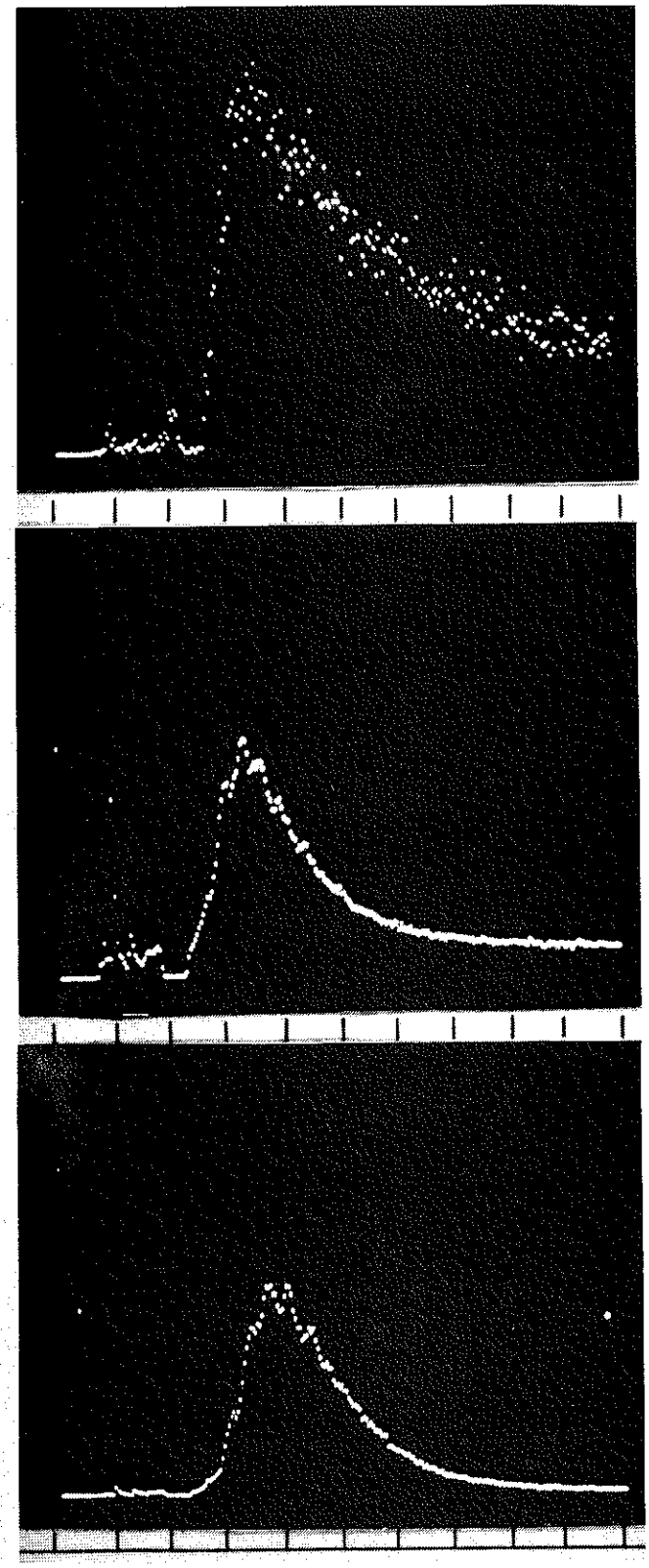
b) SCINTILLATOR

NE 110

(L ≡ 100 %)

FIG. 2: PULSE-HEIGHT SPECTRA:

PLEXIPOP versus SCINTILLATOR



a) TWO COMPONENT PLEXIPOP

0.8% NAPHTHALENE
0.1% POPOP

$\tau \approx 20$ nsec

b) THREE-COMPONENT PLEXIPOP

1% NAPHTHALENE
1% PBD
0.1% POPOP

$\tau \approx 5$ nsec

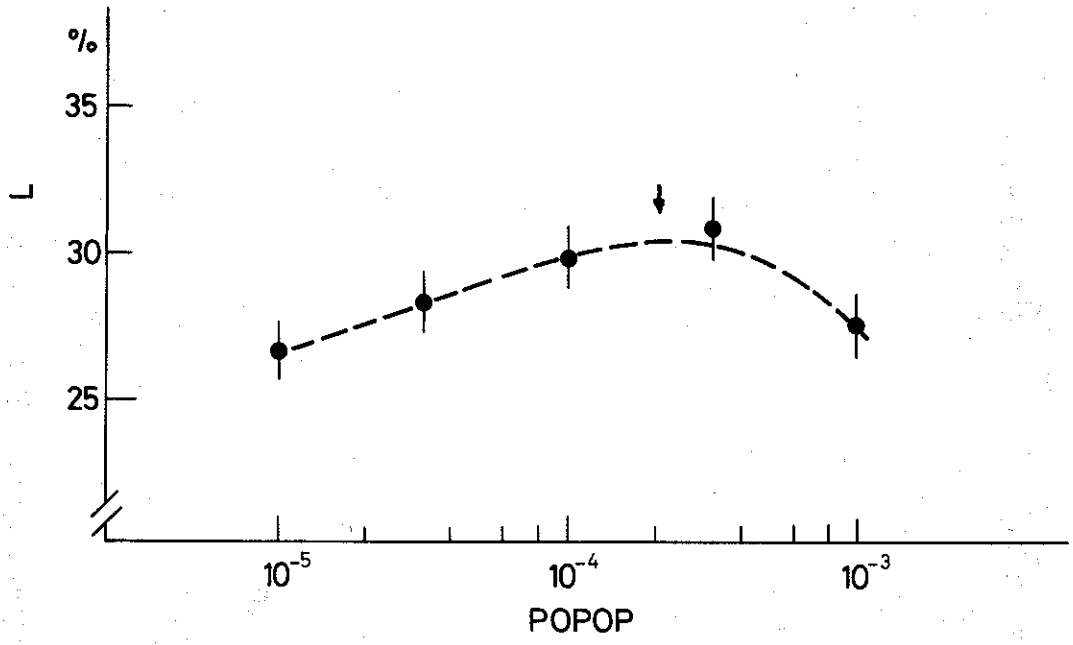
c) NE 110

$\tau \approx 4$ nsec

time (4 nsec / DIVISION)

FIG. 3: COMPARISON OF DECAY TIMES

a) LIGHT OUTPUT versus POPOP CONCENTRATION



b) ATTENUATION LENGTH versus POPOP CONCENTRATION

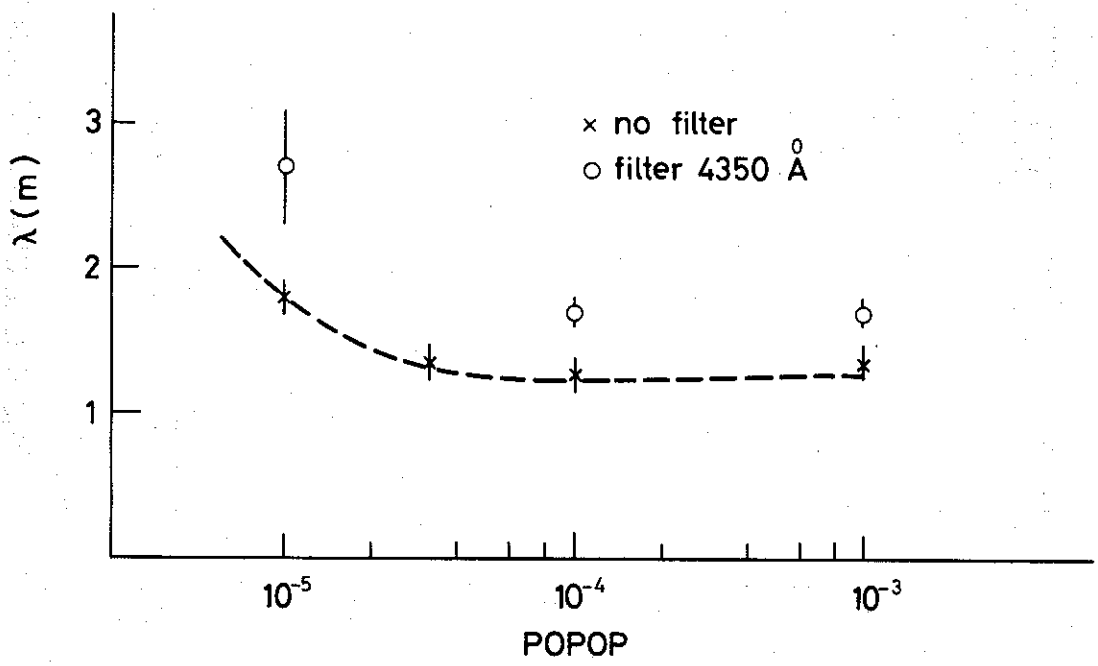


FIG. 4: EFFECT OF THE WAVE-LENGTH SHIFTER (POPOP) FOR PLEXIPOP OF TYPE II

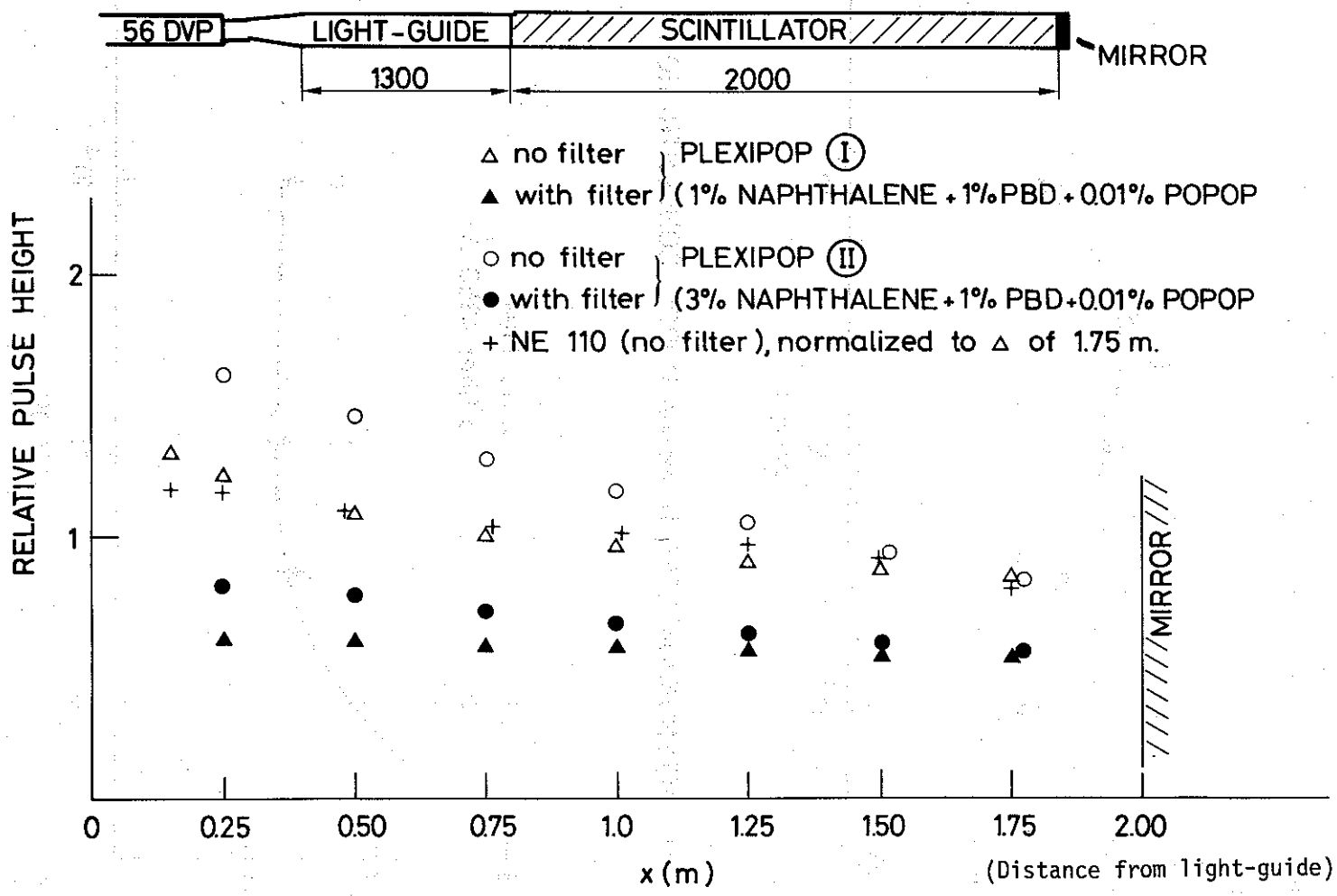


FIG. 5 UNIFORMITY OF LONG SCINTILLATORS (2000 × 200 × 10 mm^3)
WITH MIRROR ON FAR END