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EFFECTS OF LONG-TERM LOW-LEVEL EXPOSURE TO RADIATION
AS OBSERVED IN ACRYLIC SCINTILLATOR

Cause and prevention of radiation disease in uranium calorimeters

Yves Sirois*) and Richard Wigmans**)
CERN, Geneva, Switzerland

ABSTRACT

The acrylic scintillator which was used for several years as the active medium in the Axial Field Spectrometer uranium calorimeter at the CERN Intersecting Storage Rings was found to be severely damaged. The observed light output has decreased on the average by a factor of 2, and the attenuation length by a factor of 3, causing a severe degradation of the energy resolution of the system, for the detection of both electromagnetic and hadronic showers. It could be shown that the effects are due to the radiation induced by uranium decay. The fact that the integrated dose obtained from this process (50 Gy) is 2 orders of magnitude smaller than what was currently believed to be a safe level, strongly suggests that the dose rate is a dominating factor in these radiation damage problems. It could be shown that the radiation resistivity is improved by at least an order of magnitude if contact with oxygen is avoided.

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*) McGill University, Montreal, Canada

**) On leave of absence from NIKHEF, Amsterdam, the Netherlands.

1. INTRODUCTION

Readout techniques based on scintillation light are widely applied in calorimeter systems serving as particle detectors in high energy physics. In particular the most voluminous detectors, where the active medium often covers a surface of many thousands of square metres, make use of scintillator sheets for this purpose. Uranium is being considered more and more as the absorber medium, since it offers some unique advantages with respect to other materials: the improved energy resolution achievable for hadronic showers (fission compensation of unseen energy components); its high Z-value, making compact devices possible; and the availability of an internal calibration signal. Owing to the slow nuclear disintegration of the uranium, this latter aspect is especially important when scintillator is used as the active medium, since calibration problems are amongst the major ones to be solved if light provides the measured information.

The energy resolution of a calorimeter is usually expressed as

$$\sigma/E = cE^{-1/2} \quad (1).$$

This formula implies that only statistical effects are assumed to play a role (shower development, sampling fluctuations, photon statistics, etc.), the value of the constant c being much smaller for hadronic showers in uranium than in other materials. However, at high energies the resolution will be limited by systematic effects, and if these turn out to be large with respect to the value of σ/E obtained from eq. (1), the use of uranium loses one of its main advantages.

This paper will show an example of this, obtained from practical experience. It was found that radiation damage, caused by uranium decay, affects the scintillator to such an extent that after only a few years of operation a dramatic increase of the achievable energy resolution was observed, even at energies of a few GeV.

Section 2 gives a brief description of the calorimeter modules and of the equipment that was used to measure the properties of the optical system. Section 3 deals with the measurement results that led to the conclusion that uranium decay was responsible for the observed deterioration. In Section 4 the explanation of the observed radiation damage phenomena is discussed. This section also contains the results of

measurements that were performed to test the validity of this explanation, and to improve the situation. Conclusions are presented in Section 5.

2. APPARATUS AND EXPERIMENTAL METHODS

2.1 The calorimeter modules

The Axial Field Spectrometer (AFS) calorimeter [1] is a modular device. It contains two types of modules: the so-called uranium stacks and the copper catchers. Both consist of metal plates, interleaved with 2.5 mm thick scintillator plates. In the case of the copper catchers, the copper plates are 5 mm thick. The uranium stacks are subdivided into two sections. The first, the electromagnetic section, is 6 radiation lengths deep and contains 2 mm thick uranium plates. In the hadronic section, 3.8 absorption lengths deep, the metal is depleted uranium (3 mm thick) or copper (5 mm thick), alternated in the ratio 2:1.

The scintillator plates are of the acrylic type^{*)}. The basic matrix is polymethyl methacrylate (PMMA), to which 1% of the scintillating agent PBD-butyl is added. In order to increase the (UV) light yield, the PMMA is mixed with 10% of naphthalene.

The scintillator plates are read out on two sides by wavelength shifters (WLS) made of Plexiglas to which 80 mg/l BBQ (shifting agent) is added. These convert the light from ultraviolet to green. The copper catchers are read out by two WLS plates only. In the uranium stacks a tower structure is realized. The scintillator plates are read out by six independent WLS plates on both sides. Moreover, both sections are read out separately, so that 24 channels per stack are available (see fig. 1). More details about the modules, and the calorimeter performance are given in ref. [1].

^{*)} Manufactured by Altulor, Paris, France

2.2 Optical measurements

Measurements of the properties of the optical components were performed with the set-up shown schematically in fig. 2. Electrons from β -decay of ^{106}Ru are used to create scintillation light in a well-defined area of $1 \times 1 \text{ cm}^2$, of the scintillator plate. As in the calorimeter modules, this plate is coupled by a WLS bar to a photomultiplier (PM). The β -electrons are selected by the two small scintillator counters that sandwich the scintillator plate. A coincidence between the small counters triggers the reading of the PM signal. The source-trigger-counter system can be moved in the x- and y-directions to measure the optical properties of the scintillator plate. Moreover, the WLS features can be studied by moving the scintillator plate + trigger system, as a whole, in the z-direction. Stepping motors perform these movements in a remotely controlled way. In order to make sure that only light created in the scintillator plate and travelling by internal reflection to the WLS is detected, the rest of the WLS plate is covered with black foil.

For a proper measurement of the attenuation length of the scintillator it is important to eliminate solid-angle effects that disturb the measurements on plates of finite dimensions. This was achieved by polishing the sides perpendicular to the WLS and covering them with aluminized Mylar foil, and by avoiding reflection from the top side with black tape.

2.3 Calibration with cosmic muons

Since disassembling a calorimeter module is a major operation, we also developed a method by which the optical properties of the scintillator could be determined without having to open the stacks. The method is based on the analysis of the light-sharing amongst the various channels, observed when a minimum ionizing particle traverses a tower. This light-sharing is, apart from geometrical factors, determined by the optical properties of the scintillator material. The measurements were performed with cosmic muons using the set-up shown in fig. 3. A system of trigger counters selects muons traversing one of the six towers of a uranium stack. A suitable combination of trigger counters allows similar tests for the copper

catchers. The system was calibrated with the radioactivity of the uranium. The calibration of the copper catchers was achieved in a similar way with the aid of a 10 mCi ^{137}Cs line-source contained in a central stainless steel rod that assures the mechanical stability of the stack. The gain of the PMs is adjusted in such a way that in the absence of a muon trigger all analog-to-digital converters (ADCs) give the same reading in a 10 μs gate.

A Monte Carlo program was developed to study the relations between the attenuation length in the scintillator and the magnitude of the quantities measured with this device. Figure 4 shows some examples of sensitive quantities, indicating that in this way a precision of about 1 cm can be obtained for the measurement of the attenuation length. The validity of these results was checked by explicit measurements of the scintillator attenuation length, using the set-up described in the previous paragraph.

3. EXPERIMENTAL RESULTS

The present investigation was triggered by the fact that the energy resolution of the calorimeter stacks was found to be considerably worse after four years of operation at the Intersecting Storage Rings (ISR). Tests performed at the Super Proton Synchrotron (SPS) with electron and pion beams in the energy range 10-300 GeV revealed that the energy resolution σ/E had increased from 0.16/ $\sqrt{E}$ to 0.22/ $\sqrt{E}$ for electrons and from 0.35/ $\sqrt{E}$ to 0.52/ $\sqrt{E}$ for hadrons. These results are completely due to a degradation of the optical system. The optical quality of the scintillator/WLS system affects the energy resolution in the following ways:

- 1) Attenuation of the scintillator light on its way to the PM leads to a reduced number of photoelectrons per GeV deposited energy, and hence to an increase of the value of $\sigma/E \cdot \sqrt{E}$.
- 2) For a given number of scintillation photons produced, attenuation of the scintillation light in the scintillator plates leads to a signal, the amplitude of which depends on the distance from the light source(s) to the WLS plates. Therefore the signal for a given

article that enters the stacks perpendicularly depends on the impact point and the details of the shower development. In the tests mentioned before, the beam always hit the stack at the same point (the centre of a tower); only the latter effect contributes to the resolution. The scale for judging the importance of light attenuation in the scintillator is set by two relations:

- a) The ratio between the attenuation length λ_{att} and the typical distance that a photon has to travel before reaching a WLS. The distance from the stack centre to the closest WLS amounts to 10 cm. If λ_{att} is of the order of this distance, the effects on the resolution may be dramatic. If, however, the value of λ_{att} is larger than, say, 30 cm, the effects are very small because of the exponential character of light attenuation. This is illustrated in fig. 5.
 - b) The ratio between λ_{att} and the lateral shower dimensions, since the latter set the scale for the fluctuations in individual shower development. If the lateral shower dimensions are of the order of the attenuation length the contribution will be important. If they are only a few percent of λ_{att} , as in the case of electromagnetic showers, the contribution of this effect to the resolution will be small, provided of course that the particles always enter at the same point.
- 3) Light attenuation in the WLS contributes to the resolution because of the fluctuations in the depth at which the shower starts developing. Also here, the spread in the amplitude of the signals is determined by the relation between λ_{att}^{WLS} on the one side and the radiation/absorption length on the other. Moreover, there is an energy dependence, since the convolution of the light attenuation curve and the longitudinal shower profile determines the effect.

Because of these considerations, we decided to open a uranium stack and determine explicitly the optical properties of scintillator and WLS plates. The results are given in figs 6 and 7. The light attenuation curves for the scintillator (fig. 6) were measured with the precautions described in subsection 2.2. They show a perfect exponential behaviour except in the first centimetre from the WLS. This phenomenon can be

explained by the collection of light emitted under angles with the scintillator surface that are smaller than the angle of total reflection [2]. The horizontal scale gives the perpendicular distance to the WLS. In order to obtain the value of λ_{att} , this distance has to be replaced by the average distance that a photon has to travel from this point before it reaches the WLS, taking into account that the probability of its being detected decreases with the angle to the WLS surface. This latter aspect has been measured explicitly [2]. A least-squares fit which takes these effects into account yields the following values for λ_{att} :

for an unused scintillator plate:	$\lambda_{att} = 34.1 \pm 0.5 \text{ cm}$
for a used plate from the e.m. section:	$\lambda_{att} = 11.3 \pm 0.5 \text{ cm}$
for a used plate from the hadronic section:	$\lambda_{att} = 15.2 \pm 0.5 \text{ cm}.$

The first value is in perfect agreement with values measured four years earlier, directly after purchase. The other values indicate a severe deterioration, quantifying the yellow character of the plates.

Figure 7 shows the attenuation curves for WLS plates. Here no special effort was undertaken to measure a value for λ_{att} . The curves show the response to a photon absorbed at a certain distance from the PM. Deviations from a purely exponential behaviour are due to reflection at the far (open) end of the WLS and to the special light-guide geometry close to the PM. No difference was observed between used and unused WLS plates. Figure 8 shows the response of the optical system to a photon as a function of the distance to the WLS, combining the signals from all PMs, for 34.1 and 11.3 cm attenuation length in the scintillator. It turns out that for a photon in the stack centre the signal has decreased by a factor of 2.3.

Monte Carlo calculations show that the observed deterioration of the energy resolution has to be ascribed to effect 1 for electrons and to effects 1 + 2 for hadrons.

The course of the increased light attenuation

As an explanation of the observed deterioration of the scintillator, several possibilities were considered:

- i) Radiation damage induced by ^{238}U decay;
- ii) Radiation damage due to ISR operation;
- iii) Chemical ageing.

The first hypothesis was initially rejected because the accumulated dose is very low compared with what was believed to be a safe level. Schönbacher and Witzeling [3] measured the effect of ionizing radiation on acrylic scintillator and concluded that the attenuation length changes by less than 10% for a dose of 1000 Gy*). The dose from uranium decay was determined in three ways.

- 1) A computation based on the characteristics of the decay schemes of the nuclides involved in the decay chain of ^{238}U , and the stopping power of the materials present in the stack. The ^{238}U decays in 14 steps (8 α -decay and 6 β -decay processes) to ^{206}Pb . Of these, only the sequence $^{238}\text{U} \rightarrow ^{234}\text{Th} \rightarrow ^{234\text{m}}\text{Pa} \rightarrow ^{234}\text{U}$ is relevant for radiation damage. The ^{234}U has a half-life of 20,000 years; therefore it takes a long time before the processes following the decay of this nuclide contribute at a significant level to the radiation emitted by the plates, provided that these did not contain ^{234}U at the time of production. We checked this by measuring the spectrum of the γ -rays from the plates. Some of the nuclides following the decay of ^{234}U (e.g. ^{214}Pb) have dominating γ 's in their decay schemes (branching ratios up to 48%). These γ -rays were not observed. On the other hand, we did observe γ -rays from the decay of $^{234\text{m}}\text{Pa}$ (preceding ^{234}U) with branching ratios as low as 10^{-5} . The result of the radiation dose calculation, averaged over the uranium stack, is 10 Gy/y. The main contribution to the dose comes from β 's and γ 's from $^{234\text{m}}\text{Pa} \rightarrow ^{234}\text{U}$ decay.
- 2) A comparison between the calorimeter signals from the uranium 'noise' and from a hadron shower fully contained in a stack. It was found [4] that the signal from uranium decay in one tower, sampled during 10 μs , is as large as the signal induced by a 3 GeV stopping pion. This result leads in a straightforward way to a radiation dose estimate of 12 Gy/y.

*) 1 Gray (Gy) = 1 J/kg = 100 rad

- 3) Plato [5] has measured the dose rate produced by natural uranium as a function of depth. Using his data we find 15 Gy/y for our stacks, where all α -particles are stopped by a 60 μm thick layer of paper between the uranium and scintillator plates.

Summarizing, we conclude that the integrated dose from ^{238}U decay absorbed by the scintillator plates four years after the production of the stacks is of the order of 50 Gy, i.e. a factor of 20 below what was claimed to be a level at which no changes of the optical properties occur [3].

To test the hypothesis that the degradation of the optical quality was due to ISR operation, i.e. radiation damage that might have occurred during stacking and from beam losses, we compared the quality of 10 uranium stacks that had been placed in very different positions. Substantial differences had to be expected, for example between the stacks in the beam plane and the stacks 2 m away from this plane, or between stacks inside and outside the intersecting rings. No such differences were observed. To measure the optical quality we used the cosmic-muon calibration method (see subsection 2.3). It turned out that the observed differences between stacks are perfectly correlated with their age (see fig. 9).

This clearly indicates an internal cause for the observed degradations. The fact that unused scintillator was not affected means that, if chemical ageing were to be the explanation, the damaging processes would somehow have to be catalysed by the presence of uranium and/or copper, which is also a major component of the stacks. Therefore, our attention was focused on the copper catchers, which contain no uranium. This led to a big surprise. A comparison of the results from cosmic muon calibrations performed on the same stacks with a time difference of about two years revealed that during this period the ratio of the signals from the ^{137}Cs source and from the cosmic muons had decreased by about 30% (fig. 10). Moreover, the width of the ^{137}Cs signal distribution had significantly increased during this same period. This strongly indicates local damage to the scintillator plate around the position of the source. This was confirmed when we opened a copper catcher. The scintillation plates clearly showed a yellow circle around the central rod containing the ^{137}Cs source. Figure 11 shows the results of measurements that were

performed to quantify the damage. A scintillator plate was scanned along the y-direction in the setup described in subsection 2.2 at a fixed distance from the WLS plate. The light output strongly dips around the position of the source. The affected region has a radius of about 8 cm. At a distance of 8.5 cm from the WLS plate the signal drops by 35% in the centre compared with the unaffected regions near the edges of the plate.

Clearly, in this case the effects are caused by radiation damage. Since we have a line source, the radiation dose absorbed by the scintillator decreases with the distance from the source. The average integrated dose absorbed by the affected region can be estimated as follows: the source is contained in a hollow stainless-steel cylinder. The thickness of the cylinder wall is 2 mm, which is sufficient to stop all β 's from ^{137}Cs decay, so only the 0.66 MeV γ 's contribute to the damage. The age of the opened stack was 4.6 years. The total energy released in this period by the 10 mCi source amounts to

$$3.7 \times 10^8 \times 1.4 \times 10^8 \times 0.661 \times 1.6 \times 10^{-13} = 5800 \text{ J} ,$$

of which 5% is observed by the scintillator, and the rest by the copper plates. The mass of the affected region is 5 kg, which leads to an average dose in the affected region of 60 Gy, corresponding to 13 Gy/y, about the same value as was found for the uranium stacks. This is to be expected since the source strength chosen was such as to make the calibration signals about equally large for both types of stacks. The average attenuation length of the scintillator traversed by light produced in the centre (λ_{eff}) can be determined from the drop in light yield with respect to the edges where λ_{att} is still 35 cm (fig. 11). Taking into account that the average distance that the light has to travel before reaching the WLS is longer than the 8.5 cm at which the scan was performed (detailed calculations yield 10.6 cm), we find

$$e^{-10.6/\lambda_{\text{eff}}} = 0.65 e^{-10.6/35} \rightarrow \lambda_{\text{eff}} = 14.4 \text{ cm} .$$

So both the average dose and the average magnitude of the effect are in agreement with the results observed for a uniform exposure of scintillator to ^{238}U plates and, therefore, the conclusion should be that radiation damage induced by ^{238}U decay causes the deterioration of the optical

system. The question is, however: How is it possible that very modest dose levels of a few tens of Gy can create such catastrophic effects, whilst no effect at all was observed after exposure of the same material to 1000 Gy [3]? This question will be dealt with in the next section.

4. THE EXPLANATION OF THE OBSERVED PHENOMENA AND HOW TO AVOID THEM

In this section we will explain how the radiation damage effects that severely deteriorated the optical performance of our acrylic scintillator could escape detection at integrated radiation doses that are 20 times larger. We will also show how these effects could have been avoided. First, we will summarize the facts:

- the acrylic scintillator became completely yellow after exposure to ~ 50 Gy from ^{238}U decay;
- no deterioration at all was observed after an accelerated exposure of the same material to 1000 Gy at the ISR beam dump;
- WLS plates exposed to roughly the same doses in the uranium stacks did not show any degradation of their optical properties;
- after about four months, the damaged scintillator plates did not show any sign of recovery.

The scintillator plates have the following chemical composition:

- 89% polymethyl methacrylate (PMMA), the plastic material;
- 1% PBD-butyl, the scintillating agent;
- 10% naphthalene, added to improve the light yield.

Figure 6 shows a remarkable phenomenon. In spite of the fact that the attenuation characteristics are very different for the exposed and the unused scintillator plates, measurements close to the WLS plates yield the same signal. In other words, the light production by ionizing particles seems unaffected, but the losses between the impact point and the WLS detector have changed considerably. This means that it is the basic matrix (PMMA) that is damaged. Instead of being transparent to the UV light produced by the scintillating agent, it absorbs this light and re-emits in the yellow part of the spectrum, which of course cannot be converted by the WLS (which emits in green).

We investigated the sensitivity of the scintillator and WLS plates to UV light from an external source. A circular area with a radius of 7 cm was exposed to a 300 W Osram UV lamp at a distance of 25 cm. On the scintillator plates this circle became yellow after some time. Figure 12a shows the resulting light output as a function of y from a scan through the centre of the exposed circle, after 2, 5, and 13.5 hours of exposure. The effects are very large; the resulting effective attenuation lengths (see Section 3) are given in fig. 12b. No effects were observed for the WLS plates, which contain, however, a UV absorbing chemical in order to be less sensitive to Cherenkov light [1]. Since particle detection via the production of UV light is the working principle of this device, one may conclude from these results that it is potentially self-destructive. The question is, however, to what extent this is the case.

Dose-rate effects are a well-known phenomenon in radiation damage problems. Much experience has been gained from studies needed for nuclear power-plant safety. For organic materials, one frequently finds that accelerated tests tend to underestimate the effects. It was found, for example, that the effects may differ by an order of magnitude if the dose rate changes by 2 orders of magnitude [6]. As an explanation for these phenomena, one often refers to the role played by oxygen. Oxygen may diffuse from the surrounding atmosphere into the irradiated object. Ionization of the molecular oxygen may lead to the formation of free radicals, which are chemically very aggressive and easily induce the breaking of a polymer chain. This diffusion is a slow process. Therefore, at high dose rates the 'burning' of the oxygen will be faster than the supply of fresh molecules by diffusion; hence the impact of the total absorbed dose will be less than in the case of a long irradiation at low dose rate. The radiation resistance tests for our scintillator were performed at the ISR beam dump. A very large fraction of the 1000 Gy accumulated during these tests was absorbed during beam dumps, so that the effective irradiation period was very short --a fraction of a second-- and the dose rate correspondingly huge. The dose rate in a uranium stack amounts to 2 milligray/hour, which is many orders of magnitude lower than in the mentioned tests.

In order to get an insight into the dose-rate dependence of the radiation damage effects and to check the validity of the explanation given for them, we performed a series of tests at a dose rate much closer to the experimental value, namely around 0.1 Gy/h. For this purpose, we used a 7 mCi ^{90}Sr β -source. The scintillator plates were exposed in a closed box, the distance from the source being 93 mm. The box could be filled with air, or flushed by nitrogen or oxygen. Before installing the source, the scintillator plates were left in the box for two days in order to create an equilibrium situation with the surrounding gas. Each irradiation took about three weeks, small corrections in exposure time were applied to compensate for the decay of the source. During this period, 115 Gy were absorbed in the centre of the plate, 91 Gy at a distance of 5 cm from the centre; and 41 Gy were absorbed in the centre of a second plate placed 3 mm behind the first one. These numbers were determined with LiF counters, based on thermoluminescent effects induced by ionizing radiation. The radiation damage effects were determined in the same way as for the plates from the copper stacks. The light yield was measured by scanning with a collimated β -source along the y-axis of the plate, through the centre of exposure. The results are given in fig. 13. The signal is clearly reduced in the central region in the case of an exposure in air or oxygen. No effect at all (< 10% of the effect in air) is observed in the case of a nitrogen environment. The effects in oxygen are much larger than in air. These results clearly emphasize the crucial role played by the oxygen present in the air.

We determined the effective attenuation length in the centre of the plate in the same way as for the plates from the copper stacks. This was also done for plates that had received a lower integrated dose (41 Gy). Figure 14 summarizes the results. The effective attenuation length is given as a function of the total absorbed dose, for different dose rates. It turns out that there is still a dose-rate effect between the 0.1 and 0.002 Gy/h cases, but the ^{90}Sr test results give a much better estimate of the radiation sensitivity than do the ISR beam-dump tests. The differences observed between exposures in air and oxygen indicate that even at a low rate of 0.1 Gy/h, the availability of oxygen in the sample is a limiting factor, thus leading to a dose-rate dependence of the effects.

Specialized studies [7] have revealed that the combination of UV light and molecular oxygen is especially favourable for the formation of free radicals, through excitation of singlet oxygen $^1\text{O}_2$. Most likely this photochemical process (induced by the UV light produced by PBD-butyl) is the mechanism that causes the properties of our scintillator to deteriorate. This would then also explain why no degradation of the WLS is observed. The fraction of UV photons produced by the scintillator and reaching the WLS is negligibly small. Tests with the UV lamp performed on scintillator in an inert atmosphere also show a reduced sensitivity of the PMMA to UV light.

In any case, it is clear that the radiation resistance, and hence the lifetime of the detector, can be drastically improved by at least an order of magnitude if the device is operated in an inert atmosphere, and that is what we are planning to do in the immediate future.

5. CONCLUSIONS

The acrylic scintillator that was used as active medium in a uranium calorimeter was found to have severely deteriorated after a couple of years. It could be shown that the radiation emitted by ^{238}U decay is responsible for this phenomenon. The total absorbed dose (a few tens of Gy) is orders of magnitude below what was believed to be a safe level from accelerated tests at the ISR beam dump. This discrepancy is due to dose rate and environmental effects. It turned out that a much better way to measure the radiation resistance is possible with a β -source at dose rates of ~ 0.1 Gy/h. The results of these measurements also revealed the details of the mechanism responsible for the deterioration: the combination of ultraviolet light and oxygen diffused inside the plastic favours the creation of free radicals that break up the polymer structure of the basic material, i.e. the PMMA, which becomes yellow, resulting in a strongly increased attenuation for scintillation light. This mechanism leads to dose-rate effects, since the diffusion of molecular oxygen into the scintillator is a limiting factor; it also explains why no damage was observed in the wavelength shifter plates, which have suffered from the same absorbed doses at similar rates. If one avoids contact with oxygen, the lifetime of the detector may increase by at least an order of magnitude.

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REFERENCES

- [1] T. Akesson et al., Properties of a fine sampling uranium-copper scintillator hadron calorimeter, preprint CERN/EP 85-
- [2] D. Darabara, NA34 Internal Note No. 85-CERN (1984), unpublished.
- [3] H. Schönbacher and W. Witzeling, Nucl. Instrum. Methods 165 (1979) 517.
- [4] O. Botner et al., IEEE Trans. Nucl. Sci., NS-29 (1982) 373.
- [5] P. Plato, Int. J. Appl. Radiat. & Isot. 30 (1979) 109.
- [6] P. Maier and A. Stolarz, Long-term radiation effects on commercial cable-insulating materials irradiated at CERN, CERN Report 83-08 (1983).
- [7] R.L. Clough, J. Amer. Chem. Soc. 102 (1980) 5242.

Figure Captions

- Fig. 1 Isometric view of one calorimeter module. The enlargement shows the readout of the electromagnetic front section.
- Fig. 2 Layout of the set-up for the optical measurements.
- Fig. 3 Schematic view of the set-up for calibration with cosmic muons.
- Fig. 4 Monte Carlo predictions of the relation between the attenuation length and quantities which can be directly measured in the cosmic-muon calibration. The measured points result from statistics of about 1000 muons per tower, obtained for a four year-old stack:
- a) the effect of a change in attenuation length of the scintillator on the light-sharing between towers;
 - b) the effect of a change in attenuation length of the scintillator on the light-sharing between the two PMs viewing the left and right sides of the tower;
 - c) the effect of a change in attenuation length of the scintillator on the r.m.s. width of the pulse-height distribution.
- Fig. 5 The influence of the attenuation length of the scintillator on the calorimeter resolution. Results of a Monte Carlo calculation taking into account only the effects of fluctuations in the light yield for particles entering the calorimeter at random impact points. The shower development is parametrized. Effects of photon statistics and fluctuations in the lateral shower profile are not taken into account.
- Fig. 6 Light attenuation curves measured for used and unused scintillator.
- Fig. 7 Light attenuation curves measured for used and unused WLS plates.
- Fig. 8 The response of the optical system to a photon, as a function of the position where it is created, for used and unused scintillator.

Fig. 9 Various quantities determined by the optical quality, plotted against the age of the module.

- a) change in the fraction of the μ -signal seen in a tower adjacent to the one traversed by the muon;
- b) change in the width of the distribution $(L-R)/(L+R)$, L and R denoting the two PMs viewing the tower traversed by the a muon;
- c) change in the width of the uranium noise-signal distribution;
- d) the attenuation length of the scintillator as a function of time, determined from the results shown in Fig. 4 (see also Fig. 5).

Fig. 10 Histogram showing the change in performance of 65 individual copper stacks after a period of two years. Change in the width of the ^{137}Cs source-signal distribution (upper part); change in the muon/source-signal ratio (lower part).

Fig. 11 The light yield of a plate from a copper stack (y-scan), measured at a fixed distance from the WLS plate.

Fig. 12a The light yield of a scintillator plate exposed to UV light (during 2, 5, and 13.5 hours), as a function of y, measured at 10 cm from the WLS (central axis scintillator plate).

12b The effective attenuation length of the scintillator as a function of the exposure time.

Fig. 13 The light yield of a scintillator plate, irradiated by ^{90}Sr (115 Gy), as a function of y at 10 cm from the WLS (central axis scintillator plate), for air, nitrogen, and oxygen environments. The curves are drawn to guide the eye.

Fig. 14 The effective attenuation length as a function of total absorbed dose, for different dose rates and various environments. The curves are drawn to guide the eye.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12a

Fig. 12b

Fig. 13

Fig. 14