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**REPORT ON THE PERFORMANCE OF THE MACRO
OIL-GLASSCLAD COATING DETECTOR SYSTEM**

by

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Figure (3) Electronics layout of the detector system.

1. INTRODUCTION

1.1 General Background

With the Superconducting Super Collider (SSC) less than a decade away, a race is underway to find the ideal detector system for the giant collider. One such area that seems promising is fiber calorimetry.

Fiber calorimetry is a fairly new area of research in detector instruments. The calorimeter is composed of very thin scintillating fibers embedded in lead in a hexagonal geometry. Originally, the fiber calorimeter was designed for use with plastic scintillators. however, these plastic fibers are very sensitive to damage by high doses of radiation. To overcome this, we are proposing to replace the solid plastic scintillating fibers with hollow tubes filled with liquid scintillating material, which is much more radiation resistant than solid plastic scintillator^[1].

1.2 Principles of Calorimetry

A calorimeter is a device used to measure the total energy of an incident, high-energy particle. A calorimeter detects and measures a particle's energy in a two step process: absorption and detection. The incident particle interacts with a detector mass. It, in turn, absorbs the initial particle and generates secondary and tertiary particles^[2], until all the incident energy is in the form of elementary particles. These particles are then detected by the scintillating material.

Other factors to be considered in the design of the calorimeter are the refractive indices of the media. In the case of the fiber scintillator, one of the medium is the liquid scintillator, and the fiber material is the other. The angle between the light ray and the boundary of the two media is denoted as θ . See figure 1. At the *critical angle*, θ_c , we have total internal reflection (TIR). Using Snell's Law and the indices of refraction:

$$\sin(\frac{\pi}{2} - \theta_c) = \cos(\theta_c) = \frac{n_1}{n_2} \quad (n_1 < n_2).$$

FIGURE 1

REFLECTION/TRANSMISSION

TOTAL INTERNAL REFLECTION

attenuation length. For accelerator detectors, the attenuation length must be ~ 2 m.

1.3 Purpose

The purpose of this paper is to report on the properties of the MACRO Oil and GlassClad coating system, as they pertain to the requirements for SSC calorimetry. The particular properties of interest are: 1) light yield, 2) attenuation length, 3) wavelength dependence of the light output, and 4) energy resolution of the system.

1.4 Research Plan

In this report we will examine the testing of a scintillation oil mixed for the MACRO experiment at the Gran Sasso Laboratory^[5], and a fiber material, GlassClad PS-252^[6]. In addition, we will study the effects of color filters on the light yield and attenuation length. A description of the data collection process will be given, followed by the tabulated results. Some final comments will be offered on the conclusions that can be drawn from the data interpretation.

2. THE LIQUID SCINTILLATOR DETECTOR

2.1 Detector Description

The outer shell of the detector consists of a rectangular slab of PVC ($48'' \times 4.5'' \times 1.0''$) with a hollow center core ($46'' \times 4.0'' \times 1.0''$). A rectangular window was cut at both ends of the detector, and affixed to each end is a clear plastic window. Connected to both the top and the bottom of the detector are two aluminum plates ($48'' \times 4.5'' \times .025''$). Two $3/8$ inch diameter holes, one $1/4$ inch higher than the other, were cut on each side of the detector for filling and removing scintillation oil. To collect all available light, the sides of the detector were coated with an adhesive Teflon^[7], and there is also a metal strip coated with the GlassClad fiber material glued to the bottom of the detector.

Connected to the clear plastic window at one of the ends is a photomultiplier tube (PMT), an instrument that collects and converts photons to electrons through the photoelectric effect. The total number of electrons produced is directly proportional to the number of photons striking the surface of the PMT. See figure 2. After the PMT was in place, all areas of the detector that could be exposed to light (light leak testing) were taped with black electrical tape. This is to insure that all of the light detected by the PMT is light emitted from the scintillator and not from some external light source.

The term *photoelectron* is the unit used to refer to the light output of the system.

2.2 Electronics

The PMT transform these photoelectrons into a current, which can be analyzed with various electronic devices. See figure 3.

TABLE 1ELECTRONICS IN EXPERIMENT

Component	Model Number	Manufacturer
System Bin	401A	ORTEC
High Voltage Supply	556	ORTEC
Power Supply	415B	Fluke
QVT Multichannel Analyzer	3001	LeCROY
Printer Interface	3157	LeCROY
Digital Printer	DPP-Q7	DATEL
4-Fold Logic Unit	365AL	LeCROY
Quad Discriminator	821	LeCROY
Photomultiplier Amplifier	612AM	LeCROY
Oscilloscope	485	Tektronix
BCD Scaler	1880B	Jorway
Voltage Distribution Unit		Harvard

FIGURE 2
SKETCH OF LIQUID SCINTILLATOR DETECTOR

FIGURE 3
ELECTRONICS LOGIC

3. DATA COLLECTION

3.1 Calibrating the QVT

The QVT is a multichannel analyzer which integrates the input charge over the gate time. The charge is proportional to the energy of the photon that strikes the PMT surface. The QVT then digitizes the charge and stores the digitized number in the appropriate channel number. In this experiment, the data was stored in four different 256-channel QVT memory sections.

In calibrating the QVT, the PMT is allowed to trigger itself, that is, the test detector triggers the QVT when a minimum signal is present at the PMT anode. Then, we calculated the average channel number making any corrections for attenuation or amplification. The calibration yielded $3.752 \pm 1.138 \frac{eC}{p_e}$ at 14 dB. Thus, the number of photoelectrons is determined by the ratio of the average channel number measured during a test run to this constant.

3.2 Light Output Measurements

The procedures described within this section constitutes the bulk of our experiment. For our initial setup, we used a GlassClad coated strip and 3 mm of MACRO scintillation oil. We set the μ -telescope at a distance of 10 cm from the PMT. The telescope refers to a system of three plastic scintillator detectors arranged in such a way as to allow only particles that traverse all three and the liquid scintillator detector to trigger the QVT. After enough data has been collected, it is printed out and analyzed.

These measurements were repeated moving the μ -telescope successively to 23, 35, 50, 65 and 110 cm from the PMT. After the initial run was completed a blue filter was inserted between the detector window and the PMT window, and data was again collected following the scheme described above. Two runs with a yellow filter at 6mm and 8mm, respectively, were also successfully completed. Finally, an additional run with 6mm and no filters was also added to the data.

4. ANALYSIS OF DATA

4.1 Systematic Errors in Data

Light Leaks In contrast to previous experiences with light leaks in this detector, this experiment had very few light leaks (all of them minor) affecting the data collection process.

Oil Leaks in the Detector After repairing an initial oil leak near the PMT window, no appreciable oil leaks were detected. Consequently, the data was not affected by this problem.

4.2 Analysis of Spectra

From the spectra, we can calculate the average number of photoelectrons (channel number) and make the following comments about these distributions:

1. As the μ -telescope is moved farther away from the PMT, the average channel number decreases. This decrease has two causes: 1) more photons are being absorbed by the scintillating oil, and 2) the number of bounces off the fiber coatings necessary to reach the PMT increases, thus increasing the chance for the photons to be absorbed at the coating-oil interface. Furthermore, this decrease does not appear to be the expected linear decrease, but instead, seems to be an exponential decay.
2. As the oil level is reduced, the average channel number decreases. Since a muon loses $0.2 \frac{\text{MeV}}{\text{mm of oil}}$ [8], the energy per muon deposited in the detector decreases with oil level. This decrease appears to be linearly proportional to the oil level (total oil volume), as expected. Therefore, the light output for a given distance from the PMT is proportional to the oil level.
3. The filters affected the light output significantly. Since the yellow filter reduced the light output dramatically (a factor of about 5), we can safely say that most of the photons are not in the yellow-red region of the spectrum. The blue filter reduced the light output by a factor of 2, a further indication that the majority of photons

emitted by the MACRO Oil are in the blue-ultraviolet region, with a significant portion in the blue-green region. This remark must be tempered with the fact that the PMT used in this experiment is more responsive to blue light than to yellow-red light.

4. The number of photoelectrons necessary for an electromagnetic resolution of 7.5% at 4 GeV was previously calculated to be 177 photoelectrons. The energy loss of a muon traveling through the scintillator was known to be $0.2012 \frac{\text{MeV}}{\text{mm of oil}}$. Converting the number of photoelectrons at 4 GeV to the number of photoelectrons liberated when a muon passes through the detector, we obtain the necessary light output for our detector to achieve the minimum 7.5% resolution,

$$N_{Pe} = \frac{E \times 10^{-3} \text{GeV}}{0.0225} \times H,$$

where H is the height of the scintillating oil in mm.

Therefore, for 8 mm of oil, we need 0.07 photoelectrons to achieve the stated resolution. Since even our poorest measurements have achieved at least 1.3 photoelectrons (yellow filter at 6 mm), our detector has an energy resolution considerably better than the minimum necessary for a SSC detector.

TABLE 2
LIGHT OUTPUT OF GLASSCLAD-MACRO SYSTEM

Oil Level (mm)	Distance (cm)	Light Output (PE)	Standard Deviation
8	10	35.000117	16.954
	23	22.340555	12.556
	35	15.991265	9.010
	60	10.422077	6.215
	85	6.918381	4.663
	110	4.904050	3.429
6	10	30.841416	13.135
	23	17.631021	8.932
	35	10.723603	5.311
	60	7.134567	3.872
	85	4.770107	2.891
	110	3.400897	2.265
8 (blue)	10	15.825656	9.231
	23	10.642015	6.712
	35	8.602335	5.619
	60	5.743003	4.041
	85	4.035431	3.041
	110	2.803201	2.413

TABLE 3
LIGHT OUTPUT OF GLASSCLAD-MACRO SYSTEM

Oil Level (mm)	Distance (cm)	Light Output (PE)	Standard Deviation
6 (yellow)	10	2.247013	1.733
	23	1.762906	1.290
	35	1.563105	1.028
	60	1.538333	1.020
	85	1.504513	0.927
	110	1.370483	0.804
8 (yellow)	10	2.162177	1.747
	23	2.062191	1.513
	35	1.951265	1.403
	60	1.846174	1.336
	85	1.711127	1.210
	110	1.623653	1.092

4.3 Attenuation Length

As a photon is propagated down the fiber, it has a chance to be absorbed by either the scintillation oil or by the fiber material. The attenuation length, λ_A , is the distance a photon travels before its energy is reduced by a factor of e , as shown in section 1.2.

It was initially believed that the attenuation length, λ_A , was independent of the height of the scintillation oil or wavelength of the photons emitted and was only characteristic of a scintillation oil-fiber material system. However, our data appears to indicate that the attenuation length does change somewhat with height of the scintillation oil and color filter selection.

In the analysis of the attenuation length, the data points far away from the PMT were

used (usually starting from 60 cm), because the data between these points appeared to be linear. A least squares fit was applied to analyze these data points and then the error was calculated through propagation of error. From the straight line equation $y = mx + b$, one can calculate the attenuation length using,

$$att.length = \frac{b}{(m \times e)} - \frac{b}{m}.$$

The attenuation length seems to be fairly constant for the first three measurements. Therefore, the attenuation length seems to be independent of oil level or the blue filter, at least in these experimental conditions, anyway. However, the measurements with the yellow filter have unusually long attenuation length, and this length is approximately inversely proportional to the oil level. This behavior may be partially explained by the fact that the lower limit of light output is one photoelectron. Therefore, when the distribution is no more than a couple of photoelectrons throughout the length of the detector, as in this case, the light output vs. distance graphs flattens out! A quick look at the attenuation length equation above shows that the slope then approaches zero and produces very long attenuation lengths. See the attached plots.

4.4 Total Light Output

To measure the total light output for a system, we first need to set a standard distance from the PMT to count the number of photoelectrons. This standard distance is taken to be 0 cm from the PMT. The results are shown below.

TABLE 4
ATTENUATION LENGTH

System	Oil Level (mm)	Attenuation Length (cm)	0 cm Light Output
GlassClad	8	91.9031 ± 1.01191	18.6767 ± 6.73455
&	6	92.3207 ± 0.65513	12.7126 ± 4.12535
MACRO	8(blue)	89.9654 ± 0.59217	11.0808 ± 3.57516
Oil	6(yellow)	408.9315 ± 4.09757	1.6813 ± 0.96353
	8(yellow)	267.2877 ± 1.88522	2.1664 ± 0.79877

5 CONCLUSION

5.1 Results of Measurements

Previous data indicates that the reflection constant of the GlassClad material is 98.0%. The TIR of the GlassClad is 17° and its refractive index is 1.415. The absorption length of the MACRO oil is known to be 10.0 meters, which is a factor of ten larger than our best measurements. This confirms that the absorption length is dependent on the oil level.

As stated before, the light output for a given distance from the PMT is directly proportional to the total oil volume. Preliminary data from a 4 mm oil level reading seems to confirm this prediction.

A curious observation in our data is the apparent nonlinearity of the light output vs. distance graphs, especially for low oil levels. As it can be seen from the graphs, the light output seems to exhibit a broken-line behavior with the break occurring between 23 and 35 cm. As a matter of fact, some of the graphs seem to show a decaying exponential behavior! As the oil level rises, though, the broken line behavior shows a tendency for flattening out, and it is suspected that at even higher oil levels, the flattening will be more apparent, and the linear prediction will be confirmed.

One possible explanation for this unexpected behavior is the possible unevenness of the surface coatings. Since the propagation of the photons depends on reflection off the Teflon side coatings and the GlassClad bottom coating, nonuniform surface coatings may have a significant effect on the TIR angle and on the number of photons reaching the PMT.

5.2 Suitability for Use in Calorimeter Construction

The minimum attenuation length necessary for a calorimeter is about 2 m. The *GlassClad-MACRO*, has attenuation lengths which are close enough to warrant further investigation. The energy resolution and light output of the test detector meet the minimum requirements for SSC energies, and so liquid scintillators may be suited for forward

calorimetry (high energy) detectors, pending further studies.

5.3 Further Items to Study

The next step is to test these components for their sensitivity to radiation. It is necessary to see if any visible damages occur. After this initial inspection, one needs to see if the attenuation length, light output, reflection constant or the absorption length changes under high radiation dosages. Also, one may want to investigate the predicted linearity of the light output vs. distance at high oil levels, a prediction that seems to fail at relatively low oil levels. Further studies with color filters may also be helpful in making a more detailed study of the wavelength of the emitted photons.

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APPENDIX A

LIGHT OUTPUT VS. DISTANCE HISTOGRAMS

APPENDIX B

LIGHT OUTPUT GRAPHS

Energy vs Distance (Macro Oil-Glass Clad Coating)

Energy vs Distance (Macro Oil-Glass Clad Coating)

Energy vs Distance (Macro Oil-Glass Clad Coating)

Energy vs Distance (Macro Oil-Glass Clad Coating)

Energy vs Distance (Macro Oil-Glass Clad Coating)

Light Output vs. Oil Level (Macro Oil-Glass Clad Coating)

Light Output vs. Oil Level (Macro Oil-Glass Clad Coating)

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