A STUDY OF LIQUID SCINTILLATOR AND FIBER MATERIALS FOR THE USE IN A FIBER CALORIMETER

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ABSTRACT

This reports an investigation into the performance of selected scintillation oils and fiber materials to test their applicability in high energy, liquid scintillator calorimetery. Two scintillating oils, Bicron BC-517 and an oil mixed for the MACRO experiment, and two fiber materials, Teflon and GlassClad PS-252, were tested for the following properties: light yield, attenuation length and internal reflection angle. The results of these tests indicated that the scintillation oils and the fiber materials had an overall good performance with lower energies and would meet the requirements of liquid scintillator detection at SSC energies.

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1. INTRODUCTION

1.1 General Background

With the Superconducting Super Collider (SSC) less than a decade away, scientists and engineers are already striving to advance in technology in the fields of superconductivity, computers, data acquisition and detector development to support experiments being planned for this facility. R&D for detection devices is one of the fields of research being studied at Texas A&M. Currently, most high energy accelerators use magnetic spectrometry to detect high energy particles. Recent research in calorimetric techniques suggest that a calorimeter (total energy absorbing detector) could out perform magnetic spectrometry at the higher energies expected at the SSC. While many of the calorimetric techniques work well at the energies currently available, more R&D is needed for SSC energies. High energy physicists at Texas A&M are now researching liquid scintillators to design a scintillating fiber calorimeter[1].

Fiber calorimetry is a relatively new area of research in detection instruments. The calorimeter is made by taking very thin scintillating fibers and embedding them 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 disadvantage, we are proposing to replace the solid plastic scintillating fibers with hollow tubes filled with liquid scintillating material, which is known to be much more radiation resistant than solid plastic scintillator. The geometry of the fiber calorimeter does appear to be superior to most other designs. When incorporated with the ideal scintillator, the fiber calorimeter could become the detector of the future[1].

1.2 Principles of Calorimetry

A calorimeter is a devise used to measure the total energy of an incident, high-energy particle as shown in Figure 1. The way that a calorimeter detects and measures a particle's energy is a two step process: absorption and detection. The incident particle interacts with a large detector mass. This mass absorbs the initial particle and, in turn, generates secondary particles; these particles then interact with the detector mass to produce tertiary particles; and this process continues until all of the incident energy is in the form of many elementary particles[2]. These elementary particles are than detected by the medium of the calorimeter (such as scintillator).

One type of calorimeter that Texas A&M is interested in researching is a liquid scintillator fiber calorimeter or "spaghetti" calorimeter as shown in Figure 2. The detection medium of the "spaghetti" calorimeter is a group of scintillating fibers arranged in a hexagonal shape. A scintillating fiber is a long hollow tube of $\sim$ 1 mm diameter. The fiber is coated on the inside with a material known to give a high internal reflection angle.

When a light wave traveling in an optically dense medium (large refractive index) comes in contact with another medium of a lower refractive index, some of the total light is reflected back into the dense medium and some of the light is transmitted into the less dense medium. In the case of the fiber scintillator, the dense medium is the liquid scintillator, and the fiber material is the less dense medium. The angle between the light ray and the boundary of the two mediums is denoted as θ. At the *critical angle*, θ_c, all of the light will be reflected and none transmitted. So, for all light that falls upon this boundary at an angle less than the critical angle θ_c, the light will be completely reflected as shown in Figure 3.

This phenomena is called total internal reflection. This angle can be calculated using Snell's Law and the indicies of refraction:

$$\sin(\frac{\pi}{2} - \theta_c) = \frac{n_1}{N_2} \quad (n_1 < N_2).$$

where n_1 is the refractive index of the scintillation oil, N_2 is the refractive index of the fiber material, and θ_c is the angle between the two mediums measured in radians. As the difference between n_1 and N_2 increases, the internal reflection angle increases. This is very important to us, because the amount of light output for a detector is directly proportional to the reflection angle.

The coated fiber is then filled with a liquid scintillator. When an ionizing particle interacts with the liquid scintillator, the scintillator emits light proportional to the energy lost in transit. The photons are then propagated down the inside of the fiber to a photomultiplier tube, PMT, detects the number of transmitted photons.

The primary research necessary is finding the ideal materials to construct this calorimeter. The main components of the detector itself are the scintillating oil, the fiber material, the photomultiplier tubes and the converter. In particular, a detector must have a good energy resolution (which is related to the light output), good light collection, high radiation resistivity and a reasonable cost[3].

Energy Resolution For a typical large scale calorimeter, the energy resolution ($\frac{\sigma}{E}$) necessary for an electromagnetic response is $\frac{0.15}{\sqrt{E}}$ or better[3]. At energies on the order of 4 GeV (SSC energies), the energy resolution is about 7.5%. Since σ equals the square root of the number of particles sampled[4], and the energy, E, equals the number of particles, the energy resolution equals the inverse of the square root of the number of particles sampled:

$$\frac{\sigma}{E} = \frac{0.15}{\sqrt{E}} = \frac{1}{\sqrt{N_{Pe}}} \quad .$$

For 4 GeV of energy, an electromagnetic detector with an energy resolution of $\frac{0.15}{\sqrt{E}}$ or better would have a light output of 177 photoelectrons. A calorimeter detecting energies at the 4 GeV level needs the light output to be on the order of 177 photoelectrons.

Light Collection In a scintillator detector light loss can occur in two different ways: 1) through transmission or absorption at the boundary and 2) through absorption by the scintillator. Since the total light output is inversely proportional to the square of the resolution, a scintillating detector must have a high light output.

The absorption at the boundary is determined by the quotient of the refractive indicies of the scintillator and the fiber material. For large differences in indicies, the reflection angle (TIR) between the two mediums increases. This will in turn allow more light to be collected by the scintillator calorimeter. For high light output, it is necessary therefore, to have a high TIR between the scintillator and the fiber material.

For large detectors, like those employed at particle accelerators, the absorption of light by the scintillator is important, because the path length of the light is on the order of a few meters. The *attenuation length* is defined as the length after which the light intensity is reduced by a factor of e[4.]:

$$E = E_0 e^{\frac{-x}{\lambda_A}} \quad .$$

where E is the energy, E_0 is the initial energy, x is the path length and λ_A is the attenuation length. For accelerator detectors, the attenuation length must be ~ 2 m.

Radiation Hardness Since the SSC is extremely radioactive, the calorimeter must be resistive to high dosages of radiation ($\geq 10^6$ rad/year)[5]. Many materials are known to break down after dosages on this order of magnitude, so the components of the calorimeter must be hardened against radiation.

1.3 Purpose

The purpose of this paper is to report on tests of properties of selected fiber materials and scintillation oils for their use in a liquid scintillating fiber calorimeter at the Superconducting Super Collider (SSC). The particular properties of interest are: 1) internal reflection angle (TIR), 2) light yield and 3) attenuation length. From these properties we can calculate the energy resolution of a calorimeter at 4 GeV with the components tested.

1.4 Research Plan

In this report we will examine the testing of two scintillating oils, Bicron BC-517[6] and a scintillation oil mixed for the MACRO experiment at the Gran Sasso Laboratory[7], and of two different fiber materials, Teflon[8] and GlassClad PS-252[9].

First, we will describe our test cell, a liquid scintillator detector. This description will include the properties and construction of the detector, the electronic set-up, and the μ-telescope (muon-telescope).

Second, we will detail the testing of the scintillation oil and fiber materials. The specific properties we are interested in testing is the index of refraction and the number of photoelectrons versus distance from the PMT. The test of the refractive index of the two fiber materials was done directly using a laser, a clear rectangular box, paraffin oil of index 1.482[10] and aluminum slides coated with the fiber material. The testing procedure for the photoelectrons and attenuation length is a bit more complicated. This required scanning our test detector with a μ-telescope at varying distances from the PMT and for different oil heights. We made three different tests using the following combinations: 1) Bicron oil and Teflon, 2) Bicron oil and GlassClad and 3) MACRO oil and GlassClad.

Third, we will analyze our data. From this analysis we will obtain the absorption constant specific to each oil, the total light output of each system and the reflection constant of each oil. We will also show how light output varies as a function of: 1) distance from PMT, 2) height of oil and 3) combination of scintillator oil and fiber material.

Fourth, we will explain the basic operation of a computer simulation program that we wrote to aid in the analysis of data. The computer simulation program is ray tracer designed to propagate light through a detector of similar design as the test detector. We will discuss briefly the general features of the simulation, the free parameters and how well the simulation compares to the data. We will then discuss possible problems with the simulation program.

2. DESIGN OF LIQUID SCINTILLATOR DETECTOR

2.1 Detector Properties and Construction

The outer shell of the detector consisted of a rectangular slab of PVC ($48'' \times 4.5'' \times 1.0''$) with a center core ($46'' \times 2.0'' \times 1.0''$) removed from it as shown in Figure 5. Then 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 were 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 entire inside of the detector was coated with an adhesive Teflon.

We coated aluminum strips ($48'' \times 2''$) with both Teflon and GlassClad. It was necessary to raise each strip to the height of the bottom of the window. To do this, we create eight small platforms of equal heights and glued them at even spacings on the bottom of the detector.

Plastic tubes were connected to the two holes cut into the detector. The lower of these tubes was used to fill the detector with scintillation oil, the other was used to allow air to escape from the detector. The height of the oil is measured from the test strip to the air oil interface. We monitored the height by viewing the oil level through one of the windows and measuring the height with a height gauge.

After the height of the oil was set, we placed a photomultiplier tube (PMT) onto the window with the test strip flush against it. After the PMT was in place, we taped all areas of the detector that could be exposed to light (light leak testing) 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 any external light source. After the detector was completely light leak tested, it was ready for cosmic ray testing.

A photomultiplier tube, or PMT, is an instrument that collects light and converts light to an electric current through the photoelectric effect. It consists of a photocathode coated with alkali metals, where electrons are liberated by the photoelectric effect. When a photon strikes the window surface, the electrons emitted travel through a chain of secondary-emission electrodes (dynodes) at successively larger potentials. The dynodes amplify the signal by a factor of about 10^7[2]. A PMT records all of the light output from the scintillating material by converting the light into electrons via the photoelectric effect. The resulting signal is amplified by a factor of 10^7 so that the signal is large enough to be recorded.

The term *photoelectron* is the unit used to refer to the light output of a system. When a photon hits the surface of the PMT it liberates an electron through the photoelectric effect. The total number of electrons produced is directly proportional to the number of photons striking the surface of the PMT.

2.2 Electronics

The photoelectrons, after passing through a series of dynodes, form a current. This current can be analyzed with various electronics. Before we discuss the actual electronic setup, we would like to list the components used and briefly explain some of the components functions.

TABLE 1

ELECTRONICS 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

Discriminator A discriminator is a device that responds only to input signals above a certain threshold value. Low voltages coming from the PMT (i.e. background noise) will not register in the discriminator. If a signal above the threshold value enters the discriminator, a logic signal is issued from the discriminator. Discriminators are typically used for triggering (sending a signal to other electronic devices when an event occurs). In our experiment the threshold value was set at 30 mV and the discriminator was used to trigger the QVT.

QVT A QVT multichannel analyzer works by integrating the input charge over the gate time. This charge is equal to the number of photons to the total charge of the electrons liberated at the surface of the PMT when photons strike the surface. The amount of charge of the signal is digitized. The QVT then takes this digitized number and increments a memory channel whose address is proportional to the digitalized value[4]. All incoming pulses are sorted out by their integrated charge and are stored in a channel respective of the charge of the incoming pulse. The QVT used for our experiment has 256 channels each corresponding to 1 picoCoulomb of charge. From the spectrum of charge produced by the incoming spectrum, we can calculate the average charge produced by an event, and thus the average light output of an event.

Logic Unit The logic unit compares two or more signals to see if they are coincident in time. In our case if, and only if, all signals inputted are coincident in time, will the logic unit output a signal.

All of our experiments are conducted with the high voltage supply set at 2,100 Volts. The voltage supply is then connected to the voltage distribution unit used to power each of the 4 PMTs. One PMT was connected to the detector and the other three were connected to a μ-telescope. We use the voltage distribution unit to lower the out-going voltage to our detector to 1,750 Volts and to 1,625 Volts for our μ-telescope. The reason for the voltage difference is that higher voltages increase the gain of the μ-telescope. Our μ-telescope is composed of three plastic scintillators which have a much higher light output than liquid scintillator. So, we have the telescope at the lowest voltage setting possible with our setup.

The term 'telescope' refers to a system of detectors arranged in such a way as to allow only particles traveling through the entire system of detectors to trigger the QVT. Each of the detectors was typically connected to a discriminator to block out low amplitude noise. The signals from the discriminator travel to a coincident logic unit. When all three signals from the discriminators coincide in time, a particle has traveled through the system of detectors. The system of detectors, the discriminators and the logic unit together constitute the telescope. In our case, when the detector detects an event, it sends a signal to the gate of the QVT, thus triggering the QVT. As the telescope is moveable, we are able to pinpoint when and where an event occurs.

A *μ-telescope* detects when a muon passes through the telescope system. We are testing with cosmic rays which are predominately μ mesons with an energy in the range of a few GeV. We can easily set up our telescope system to detect these muons, since it is unlikely for lower energy cosmic ray particles to travel through the telescope. Muons in this energy range produce an energy loss of 1.95 $\frac{MeV}{g/cm^2}$[11] when passing through the scintillator. This energy loss is often called the "minimum ionizing energy loss" due to the slope of the $\frac{dE}{dx}$ curve as a function of energy in the range of muon energies. For a liquid scintillator with a density of 1.032 g/cm^3[11], the ionizing energy is 0.2012 $\frac{MeV}{mm\ of\ oil}$.

The output signal from our detector went into an attenuator. The attenuator reduced the amplitude of the signal by a factor of 2 for every 6 dB. It was sometimes necessary to do this because sometimes the total charge delivered can exceed the input scale of the QVT. If this occurs, all signals over the full scale value will be entered into the last channel of the QVT anyway. After attenuation, the signal travels through 128 ft of cable, which delays the signal by 170 ns. The signal was then passed through a capacitor which offsets the DC signal. This eliminated any fluctuations in the DC signal which could interfere with the data. The signal finally entered the q-input of the QVT, and, if the gate was "open," the QVT analyzed the signal. The electrical diagram of this is shown in Figure 6. The way the QVT analyzed events was by first measuring the energy of the signal and secondly, by incrementing the count of the channel corresponding to that energy. After the data run was complete, the number of counts in each channel was be printed out and analyzed.

3. TESTING

3.1 Refractive Index

The refractive index of the scintillation oil and of the fiber material is instrumental in calculating the total internal reflection angle (TIR). Since the propagation of the photons along the length of the detector is dependent on the TIR, it is necessary to know the refractive index of the scintillation oil and of the fiber material. In a fiber scintillator the percentage of light that falls within the TIR is:

$$Percentage = \frac{1}{4\pi}\int_{-TIR}^{TIR} d\phi \int_{\frac{\pi}{2}-TIR}^{\frac{\pi}{2}+2TIR} \sin\theta d\theta,$$

$$Percentage = (\frac{TIR}{2\pi})(\sin(2TIR) + \sin(TIR)).$$

The refractive index of each of the scintillation oils was known to be 1.48, the same as the refractive index of paraffin oil. The refractive index of Teflon was also known to be about 1.33[12]. The unknown index of refraction was that of the GlassClad. To determine the index of refraction for the GlassClad, we had to construct an index of refraction measuring device.

The device consists of a clear plastic holding tank ($8'' \times 4'' \times 4''$) filled with paraffin oil. Aluminum strips coated with various fiber materials are laid on the bottom of the tank. A laser beam is propagated into the oil and onto the test strips. The angle between the test strips and the laser beam is varied until total reflection as shown in Figure 7. This phenomenon is observable because: 1) the beam becomes noticeably brighter in the oil, and 2) there is no observable scattering on the surface of the test strips.

The test was first conducted using a Teflon coated aluminum strip. The test showed that the Teflon strip had a TIR of $26° \pm 1°$ and an index of refraction of

1.330 ± 0.011. This was consistent with the predicted refractive index. The next step was to find the refractive index of the GlassClad. We prepared many strips varying the amounts of coating, the etching of the aluminum strips, the curing process, three different types of GlassClad, the concentration of the GlassClad and the methods of application. The reason for producing so many different strips was that we wanted to find the method of coating the aluminum strips that gave us the smoothest coatings, was the easiest to apply and possibly could produce a method for coating the inside of a 1 mm fiber scintillator.

All of the coatings had the same refractive index and TIR. The TIR measured was $17° \pm 1°$ and the index of refraction was thus calculated to be 1.415 ± 0.008. This angle was a little lower than desired, but still reasonable for detector studies.

The percentage of light collected by a liquid scintillator using the GlassClad material is $\sim 4.0\%$. The percentage of light collected by a liquid scintillator using a Teflon coating is $\sim 8.9\%$.

In our experiment as the boundary between the scintillation oil and the fiber material is not perfect, some of the light will be transmitted into the fiber material. For the purpose of clarity I would like to point out that my definition of the TIR (total internally reflecting angle) is the maximum angle between the incident photon and the boundary between the mediums where the photon is almost totally reflected. The amount of light reflected is not 100% because the boundary between the two mediums is not perfect. In most texts the reflection angle is drawn between the incident ray and the normal, but this is not the case in my calculations.

3.2 Calibrating the QVT

As mentioned earlier, the channel numbers in the QVT correspond to the integrated charge of the PMT and this charge corresponds to the number of photoelectrons entering the multiplying procedure of the PMT during an event. The average number of photons that hit the PMT equals a constant multiplied by the average channel number in the QVT. This number is constant with the PMT-dynode combination. To find the number of photons, it is necessary to calculate the value for this constant.

To find this constant, we let the PMT of our detector trigger itself. What this means is that we let the test detector trigger the QVT when a minimum signal is present at the PMT anode. Then, we calculated the average channel number making any correction for attenuation or amplification. We calculated this constant to be $3.752 \pm 1.138 \frac{pC}{Pe}$ at 14 dB. To find the number of photoelectrons, all that we need to do is divide the average channel number measured during a test run by this constant.

3.3 Light Output

The procedures described within this section constituted the bulk of our experiment. For our initial setup, we used a Teflon coated strip and 2 mm of Bicron scintillation oil. We set the μ-telescope at a distance of 10 cm from the PMT. We began taking data, adjusting the attenuation to get an optimal distribution of channels in the QVT.

These measurements were repeated moving the μ-telescope to successively 35 cm, 60 cm, 85 cm and 110 cm from the PMT. Where data was received with a good channel distribution, we changed the height of oil (4 mm, 3 mm, 2 mm, 1 mm) and remeasured the average channel distribution for the varying distances from the PMT. When all of these measurements were completed with the Teflon-

Bicron oil combination, we removed the Teflon strip and placed a strip coated with GlassClad and refilled the counter with the Bicron oil. We remeasured the average channel number at the five different distances and the four different heights. When we completed these measurements, we replaced the Bicron oil with the MACRO oil. We started to take new measurements with the GlassClad-MACRO system, but we ran out of time. The only measurements that we have obtained are those at the six, four and three millimeter oil heights with the μ-telescope scanned across the length of the detector.

The data runs were lengthy (from eight hours to two days), and initially there were many systematic errors that resulted in bad data. This is why we have a limited amount of data at this time.

To find the average number of photoelectrons for each data run, we wrote a computer program (*Avg.for*). This program inputs the entire data for a run. The data is in the form of number of counts at a given channel number for 256 channel numbers. *Avg* reads in the data and, for a given pedestal value and attenuation setting, outputs the number of photoelectrons produced and the root mean square deviation for this average. So, for each data run, we can calculate the average photoelectron and compare these results.

4. ANALYSIS OF DATA

4.1 Systematic Errors in Data

Light Leaks This proved to be the most common problem encountered in the data taking. Light leaks occur when external light is detected by the PMT, which results in a higher light output than an actual reading. To prevent light leaks, the anode signal from the PMT is analyzed with an oscilloscope. If there are light leaks, the number of pulses will increase. To repair light leaks we must view the anode signal and tape every part of the detector that could be exposed to external light sources. Once the number of pulses has decreased to a minimum (this is a judgement call based on months of experience), the detector is said to be leak tight.

Oil Leaks in the Detector The hole through which the fill tube was connected started leaking oil. This leak resulted in a lowering of the oil level inside the PMT and after a short time in the break down of the tape used to cover the light leaks, which in turn reexposed the detector to external light. This oil leak was repaired by removing the tubes, glueing the old holes in the detector and redrilling and tapping new holes for the oil fill tubes. Another oil leak developed at one of the screw holes for the bottom of the detector. A seal was attempted using RTV, but this did not completely solve the problem. This hole still leaks, but over the time spans of the data runs, an unappreciable amount.

Contaminated Oil One set of data (Bicron-Teflon at the 2 mm oil level) had an extremely low light output. When we changed the oil, the light output at that level improved greatly. This oil had been removed from the detector, transfered to several containers, and was reused in the detector. Our conclusion was that the external handling caused some contamination to the oil.

Faulty High Voltage Supply The *Fluke* High Voltage Supply began putting out Voltages over 2500 Volts. Upon examining the Voltage Supply, we noticed that the Voltage Supply had a faulty reference resistor. We replaced that Voltage Supply unit with the *ORTEC* Voltage Supply.

GlassClad – Bicron System As the light output measured in this system was not consistent, no analysis is available for this system. The exact cause of the bad data is unknown.

4.2 Analysis of Pulse Height Distribution

As mentioned earlier, the amplitude of a signal from the PMT is digitized and stored in a channel number. This channel number is directly proportional to the number of photons that strike a photon during an event. From the distribution, we can calculate the average number of photoelectrons (Channel number). If we compare these distributions, we can notice three natural tendencies:

1. As the μ-telescope is moved farther away from the PMT, the average channel number decreases as shown in Figure 8. This decrease is caused by two things: A) the mean path length is increasing (which means more light is being absorbed by the scintillator), and B) the number of bounces necessary to reach the PMT of the average photon increases, thus increasing the chance for the light to be absorbed at the coating-oil interface.
2. As the oil level is reduced, the average channel number decreases as shown Figure 9. This is because a muon loses 0.2 $\frac{MeV}{mm\ of\ oil}$. So the energy loss is proportional to the oil level. Since the energy loss is proportional to the

number of photons produced, the average channel number should decrease.

3. The average channel number varied with each scintillator-fiber material system as shown in Figure 10. This can be attributed to different absorption lengths of the oil, different reflection constants at the two mediums interfaces and because Teflon has a higher light collection due to the larger TIR.

TABLE 2

LIGHT OUTPUT OF TEFLON-BICRON SYSTEM

Oil Level (mm)	Distance (cm)	Light Output (Pe)	Standard Deviation
4	10	44.076	18.572
	35	19.902	9.368
	60	12.574	5.278
	85	8.712	5.051
	110	5.802	3.927
3	10	23.097	9.340
	35	11.719	6.136
	60	8.081	4.653
	85	4.526	2.887
	110	3.150	2.146
2	10	11.502	5.938
	35	5.024	3.273
	60	3.314	2.253
	85	2.163	1.432
	110	1.945	1.306
1	10	7.408	4.497
	35	3.103	2.219
	60	2.408	1.873
	85	1.785	1.262
	110	1.621	1.079

TABLE 3

LIGHT OUTPUT OF GLASSCLAD-MACRO SYSTEM

Oil Level (mm)	Distance (cm)	Light Output (Pe)	Standard Deviation
6	10	30.841	13.135
	23	17.631	11.450
	35	10.724	5.311
	60	7.135	3.872
	85	4.770	2.444
4	10	13.834	7.494
	35	3.905	3.089
	60	2.715	2.093
	85	2.060	1.580
	110	1.940	1.428
3	10	10.360	7.084
	35	2.397	1.975
	60	2.022	1.598
	85	1.701	1.125
	110	1.618	1.013

4.3 Attenuation Length of Each System

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. To put this in mathematical terms:

$$E = E_0 e^{\frac{x}{\lambda_A}} \quad .$$

where E is the final energy, E_0 is the initial energy, λ_A is the attenuation length, and x is the distance the photon travels.

We initially believed that the attenuation length, λ_A, was independent of the height of the scintillation oil and was only characteristic of a scintillation oil-fiber material system. However, our data appears to indicate that the attenuation length does change with height of the scintillation oil.

As indicated earlier in this report, the number of photons detected by a PMT at a certain distance away is related this way:

$$E = E_0 e^{\frac{x}{(\lambda_A)}} \quad .$$

An alternate way of expressing this equation is:

$$\lambda_A = \frac{\Delta x}{\ln(\frac{E_x}{E_{x+\Delta x}})} \quad .$$

In the analysis of the attenuation length, we used the distances of 60 cm, 85 cm, and 110 cm, because the data between these points appeared to be linear. See Figures 11 and 13. We used a linear regression program that is built into a calculator (HP-28S) to fit these three points and then calculated the error through propagation of error. The attenuation length is the inverse of the slope of the line generated graphed on a distance from PMT vs. natural log of the number of photoelectrons.

The results were curious. The measured attenuation length appeared to increase as the oil level decreased. The following table indicates the attenuation lengths measured for each system with their respective deviations:

TABLE 4

ATTENUATION LENGTH

System	Oil Level (mm)	Attenuation Length (cm)	Standard Deviation
Teflon	4	64.599	9.414
&	3	53.022	7.106
Bicron	2	91.743	23.793
Oil	1	90.580	46.220
GlassClad	6	61.73	
&	4	148.810	66.719
MACRO	3	224.215	143.498
Oil			

For each of the systems measured, the attenuation length increased for lower oil levels. This increase in attenuation length for low oil levels could occur because at low oil levels, the PMT is at the one photoelectron. The light output levels out at one photoelectron; so, the attenuation length, which is dependent on the quotient of the light output of two different distances, would naturally increase as the light outputs approach each other.

The attenuation length of the Teflon-Bicron system at 4 mm oil level is $64.599 \pm 9.414\ cm$. This length decreased for the 3 mm oil level. The decrease in the attenuation length at this level is probably due to an increase in the average number of times photons contact a boundary. At the 2 mm and 1 mm oil level, the attenuation length increases. This is probably because the light output at these oil levels is at the one photoelectron level. The only attenuation lengths that are calculatable to any reasonable degree of accuracy are the 3 mm and 4 mm oil levels of the Teflon-Bicron system. The attenuation length at these oil levels are on the order of 50-75 cm.

The GlassClad-MACRO system reduced to the one photoelectron level very rapidly for oil levels 4 mm and lower. The attenuation length measured at the 4 mm oil level was about 1.5 meters. This attenuation length may be higher than the actual attenuation length, because the data at these points are close to the one photoelectron. Because of this reduction to the one photoelectron level, we took another reading at the 6 mm oil level. The result of this new data run resulted in an attenuation length of 61.73 m. This is consiistent with the Teflon's attenuation length.

4.4 Total Light Output for Each System

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. The distance this standard is 0 cm from the PMT. To calculate the number of photoelectrons at 0 cm we use the same linear regression program that is built into the HP-28S calculator. See Figures 11 and 13. The number of photoelectrons at 0 cm is e raised to the y-intercept.

TABLE 5

LIGHT OUTPUT

System	Oil Level (mm)	Light Output at 0 cm (PE/mm of oil)	Standard Deviation
Teflon	4	8.010	1.167
&	3	8.056	1.080
Bicron	2	2.040	0.529
Oil	1	3.494	1.783
GlassClad	6	3.147	
&	4	0.980	0.439
MACRO	3	0.647	0.414
Oil			

The data shows that for the Teflon-Bicron system at the 4 mm and 3 mm oil level, the light output at 0 cm is about 8 photoelectrons per mm of oil. For the 2 mm and 1 mm oil level, the light output at 0 cm decreased to about 2 and 3.5 photoelectrons respectively. This inconsistency may be due to the fact that the light output at these oil levels were at the one photoelectron level.

For the GlassClad-MACRO system, the light output at 0 cm was on the order of 3 photoelectron for the 6 mm reading. The 4 and 3 mm readings had a light output close to 1 photoelectron. This could be because the light output at the two oil levels measured were at the one photoelectron level.

5. COMPUTER SIMULATION PROGRAM

5.1 General Features

The computer simulation program *Simulation.for* design is to analyze the data and attempt to predict:

1. The acceptability of the data produced by each run.
2. The approximate reflection constant of the fiber material (what percent of light is reflected each bounce).
3. The attenuation length of the scintillation oil.

To complete this task, *Simulation.for* generates random muons that interact with scintillation oil to generate photons. These photons propagate down the interior of a detector to a PMT.

The exact specifications of *Simulation.for* are as follows:

Initial Parameters	1.	Width of Detector (10 cm)
	2.	Number of Photons Produce per mm of Oil (10000)
	3.	TIR of Water (42.435°)
	4.	TIR of Teflon (26.000°)
	5.	TIR of GlassClad (17.000°)
Variable Parameters	1.	Height of Oil
	2.	Distance from PMT
Predicted Parameters	1.	Absorption Length of Oil
	2.	Percent Reflected from Teflon Surface
	3.	Percent Reflected from GlassClad Surface

With these entered, *Simulation.for* automatically does the following:

Random Variables
1. Height in the Scintillator
2. Distance of Event from the Left Side of the Detector
3. Direction of the Photon

Ray Tracing
1. Calculates the Angle of a Photon Incident on any of the Four Surfaces (Water, Coating, or the two Teflon Sides).

   A. If the angle is less than the TIR,
   the program allows the ray to bounce.

   B. If the angle is greater than the TIR,
   the program checks Fresnal's equations
   to see if the photon is reflected.
2. Checks to see if any light is absorbed by the scintillator.
3. Checks the reflection constant for each bounce.
4. Counts all photons that are detected by the PMT.

Finally, *Simulation.for* outputs the following data:

1. Number of Photons Detected (Light Output)
2. Percent of Photons Detected
3. Standard Deviation

One needs only to compare the simulated data to the actual data to find the absorption length of the scintillation oil and the reflection constants of the fiber materials. The method we used to compare the simulated data to the experimental data is:

1. Set the light output of the simulated data at 60 cm from PMT and 4 mm oil height to the measured light output at that same point and adjust the other simulated light output accordingly.

2. Adjust the absorption length and the reflection constants to get approximately the same attenuation length for the 4 mm oil level. The comparisons are all done visually

5.2 Results of Simulation

$\underline{Teflon - Bicron}$ The simulated light output fit remarkably well to the measured output at the 4 mm oil level. The 3 mm, 2 mm and 1 mm oil levels did not compare as nicely, but were certainly within the limits of the standard deviation. See Figure 12.

The apparent absorption length of the Bicron BC-517 Scintillation Oil is predicted to be 1.0 meter. This is approximately a factor of ten less than the advertised attenuation length. The predicted percent of light reflected from the Teflon Surface after each bounce is 97.0%.

$\underline{GlassClad - MACRO}$ This system was a little easier to simulate since the MACRO oil has been well tested and the absorption length is known to be $\geq 10.0m$[8]. The visual comparison of the simulated data to the measured output was not as precise as that of the *Teflon-Bicron* system. The measured light output had a sharper increase in light output at distances close to the PMT than the simulation program could obtain. The actual light output measured at the lower oil levels did not agree with the data obtained by the simulation program. The reflection constant calculated for the GlassClad by the simulation program is 98.0%. See Figure 14. Because the data for the 6 mm reading was just taken, the simulation for this oil level has not been completed.

6 CONCLUSION

6.1 Results of Measurement and Simulation

For the *Teflon-Bicron* system, the attenuation length measured for the oil levels of 4 mm and 3 mm is between 0.645 ± 0.094 - 0.530 ± 0.071 meters, and the light output at 0 cm from the PMT is $\sim 8.01 \pm 1.10$ photoelectrons per mm of oil. The attenuation lengths increased and the light output per mm of oil decreased for the 2 mm and 1 mm oil levels. This could be attributed to the fact that the light output at these levels are around one photoelectron. According to the simulation program, the Bicron BC-517 oil has an absorption length of 1.0 m and the Teflon surface reflects 97.0% of the light at angles less than the TIR angle of 26°.

For the *GlassClad-MACRO* system, the attenuation length measured was 1.488 ± 0.667 meters for the 4 mm oil level and 2.242 ± 1.435meters for the 3 mm oil level. The light output at 0 cm measured for these oil levels was 0.980 ± 0.439 Pe/mm of oil for the 4 mm oil level and 0.647 ± 0.414 Pe/mm of oil. These results could be inaccurate because both of the oil levels have light output on the one photoelectron level. Because of this, we took an extra data run at the 6 mm oil level. The results of this run show the attenuation length was ~ 61.73 m and the light output at 0 cm was ~ 3.15 photoelectrons. The simulation program indicates that the reflection constant of the GlassClad is 98.0%. The absorption length of the MACRO oil is known to be 10.0 meters. The TIR of the GlassClad is 17° and the refractive index is 1.415.

6.2 Suitability for Use in Calorimeter Construction

The minimum attenuation length necessary for a calorimeter is about 2 m. Both systems, the *Teflon-Bicron* and the *GlassClad-MACRO*, have attenuation lengths which are close enough to warrant further investigation.

The number of photoelectrons necessary for a reasonable electromagnetic resolution at 4 GeV was previously calculated to be 177 photoelectrons. The energy loss of a muon traveling through scintillator was calculated to be $0.2012 \frac{MeV}{mm\ of\ oil}$. Converting the number of photoelectrons at 4 GeV to the number of photoelectrons liberated when a muon passes through a mm of oil, we obtain 0.009 photoelectrons per mm of oil. Both detectors produced many more photoelectrons than this, indicating that both materials could possibly be suited for use in a calorimeter.

6.3 Further Items to Study

It will be necessary to obtain clearer data from both GlassClad systems. The data from the GlassClad-Bicron system was inconsistent. The light output for this system should be remeasured to see if there was a systematic error in this data that caused the inconsistent data. Also, one should run some tests on a Teflon-MACRO system to see how the light output compares with the other three systems.

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 varies with high radiation dosages.

REFERENCES

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2. D. Perkins, "Introduction to High Energy Physics, 3^{rd} Edition" Menlo Park: Addison-Wesley Publishing Company, Inc., 1987.
3. M. Gilchriese, "Detector Research and Development for Experiments at the Superconducting Super Collider," Collider Physics: Current Status and Future Prospects, Nashville, October, 1987.
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6. Bicron Oil BC-517L is a product of Bicron Corporation.
7. MACRO Oil, *This custom scintillating oil mixture is being used in a large underground cosmic ray experiment at the Gran Sasso Laboratory, L' Aquila, Italy. The composition of this mixture is 6% Pseudocumene, 93% Mineral Oil, 0.9% PPO, and 0.1% Bis-MSB.*
8. Teflon is a Reg. TM of E.I. DuPont Co.
9. GlassClad PS-252 Petrarch FF is a product of Petrarch Systems Silanes & Silicones.
10. Paraffin Oil 0-122 is a product of Fisher Scientific.
11. "Review of Particle Properties," Physics Letters B204, April, 1988.
12. R. Weast, "Handbook of Chemistry and Physics," Chemical Rubber Co., Cleveland, 1970.

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Figure (14) Graph of the simulated light output for the GlassClad-Bicron system.

FIGURE 1

Hadronic Calorimeter

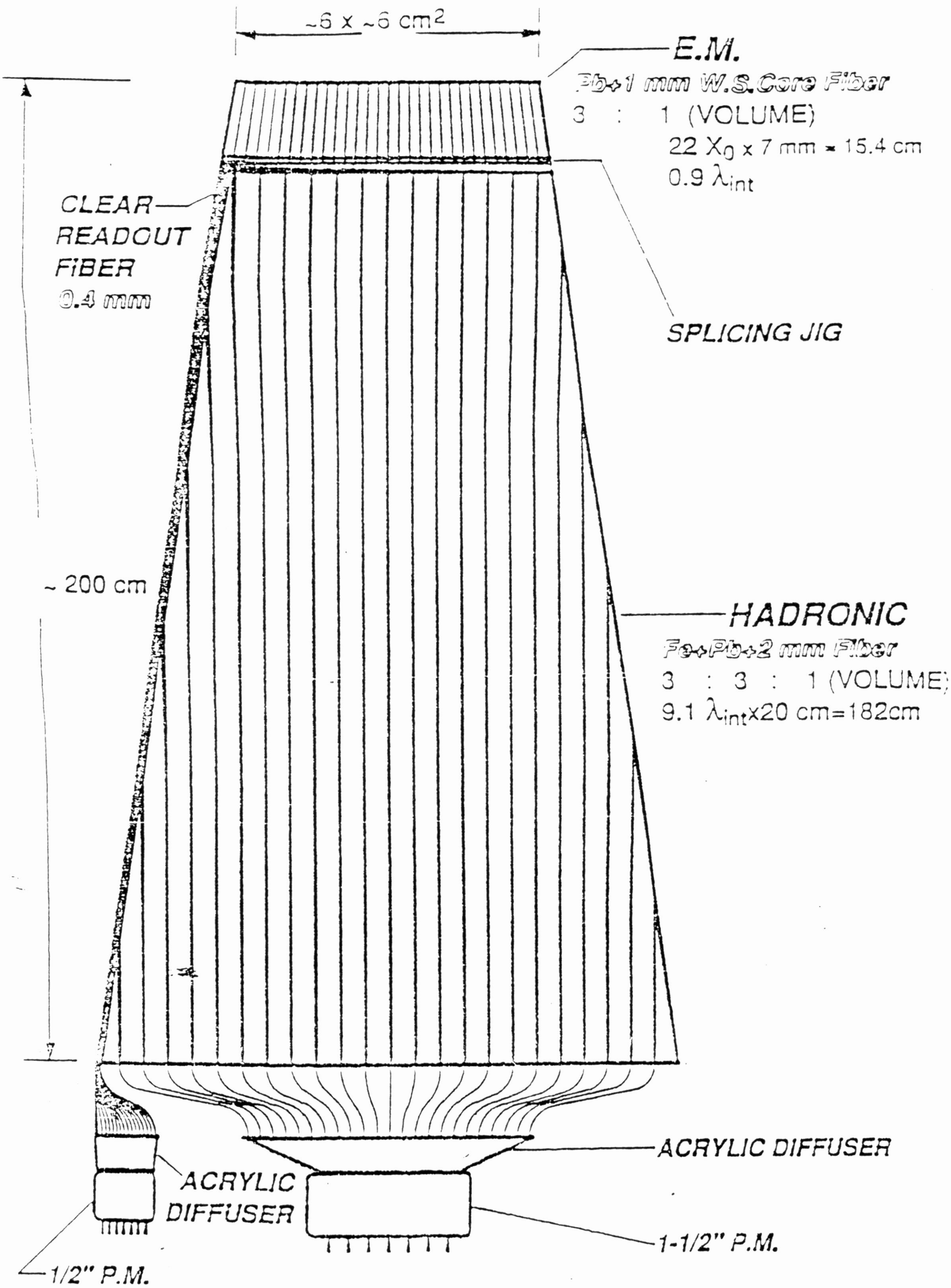


FIGURE 2

Fiber Scintillator Detector

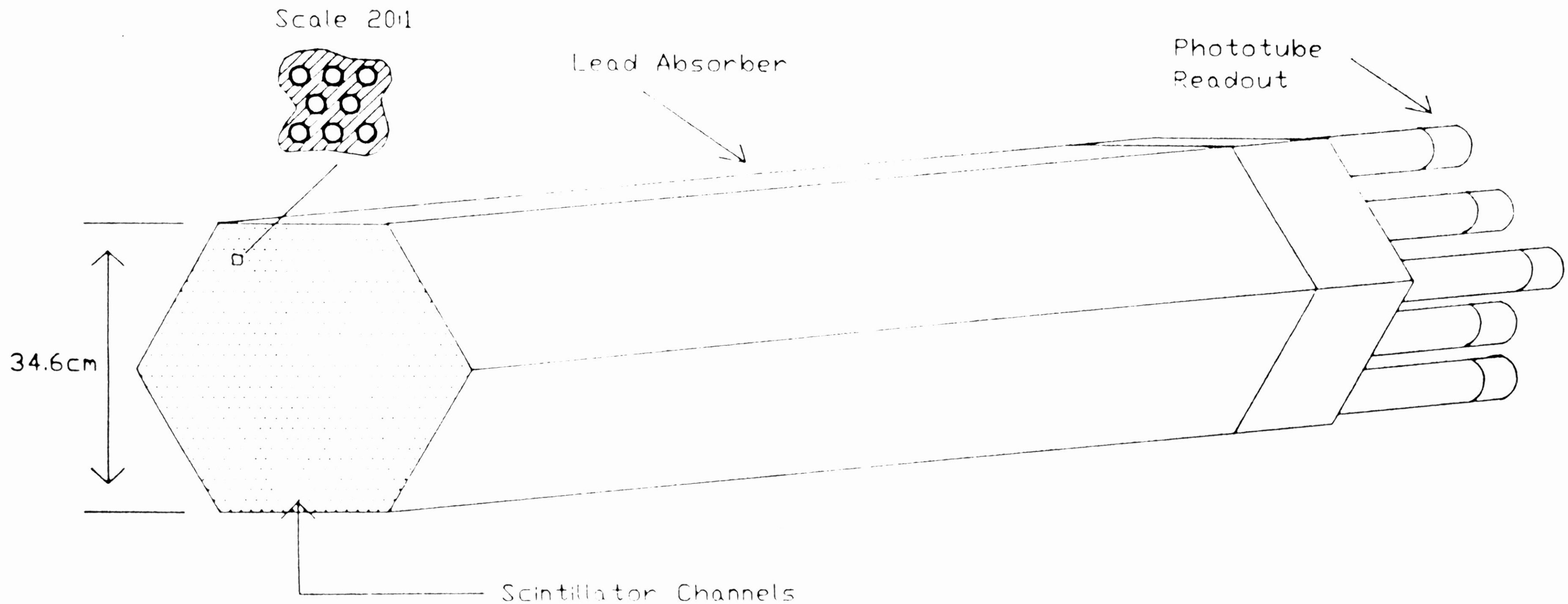
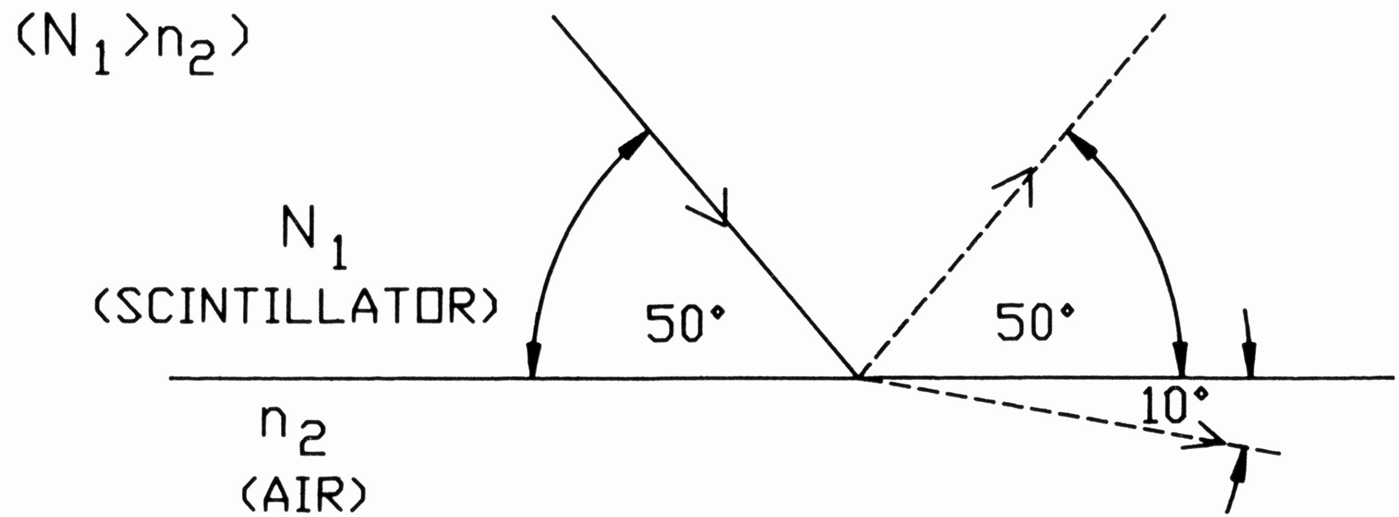


FIGURE 3

REFLECTION/TRANSMISSION



TOTAL INTERNAL REFLECTION

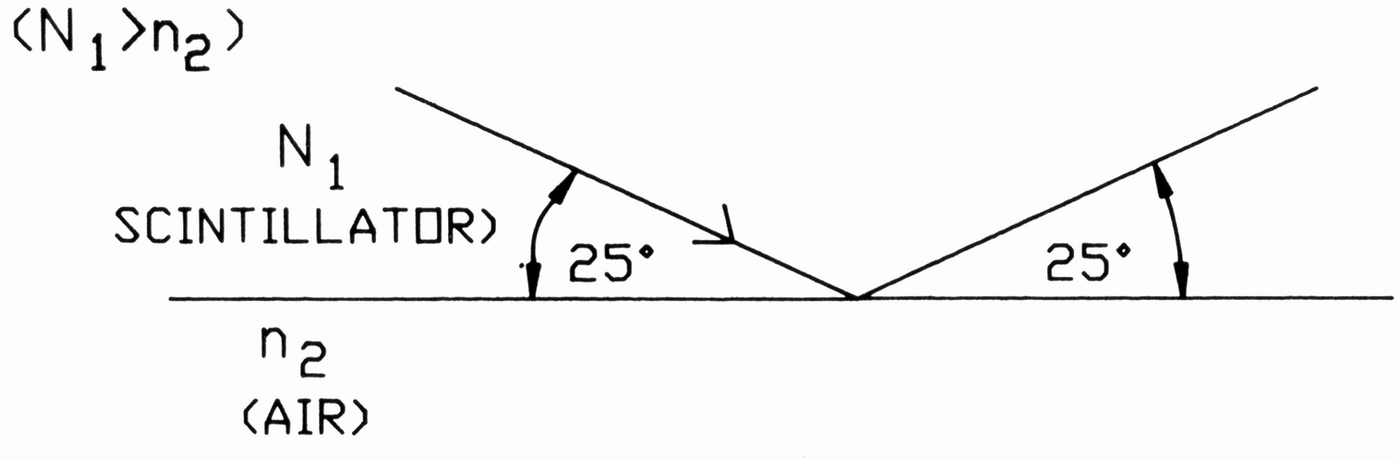


FIGURE 4

TEST CELL FOR LIQUID/COATING

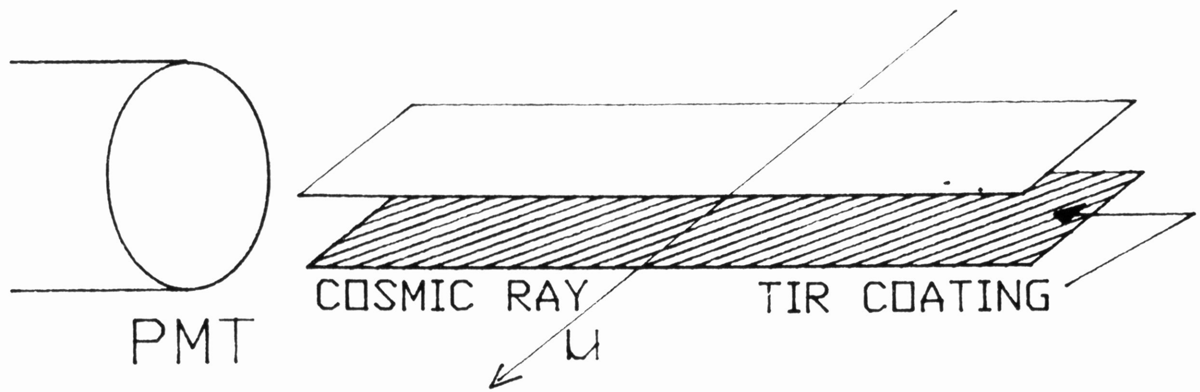


FIGURE 5

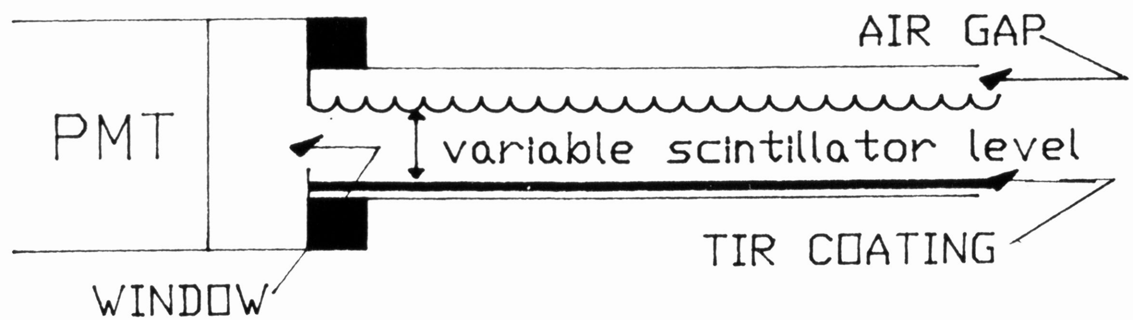


FIGURE 6
ELECTRONICS LOGIC

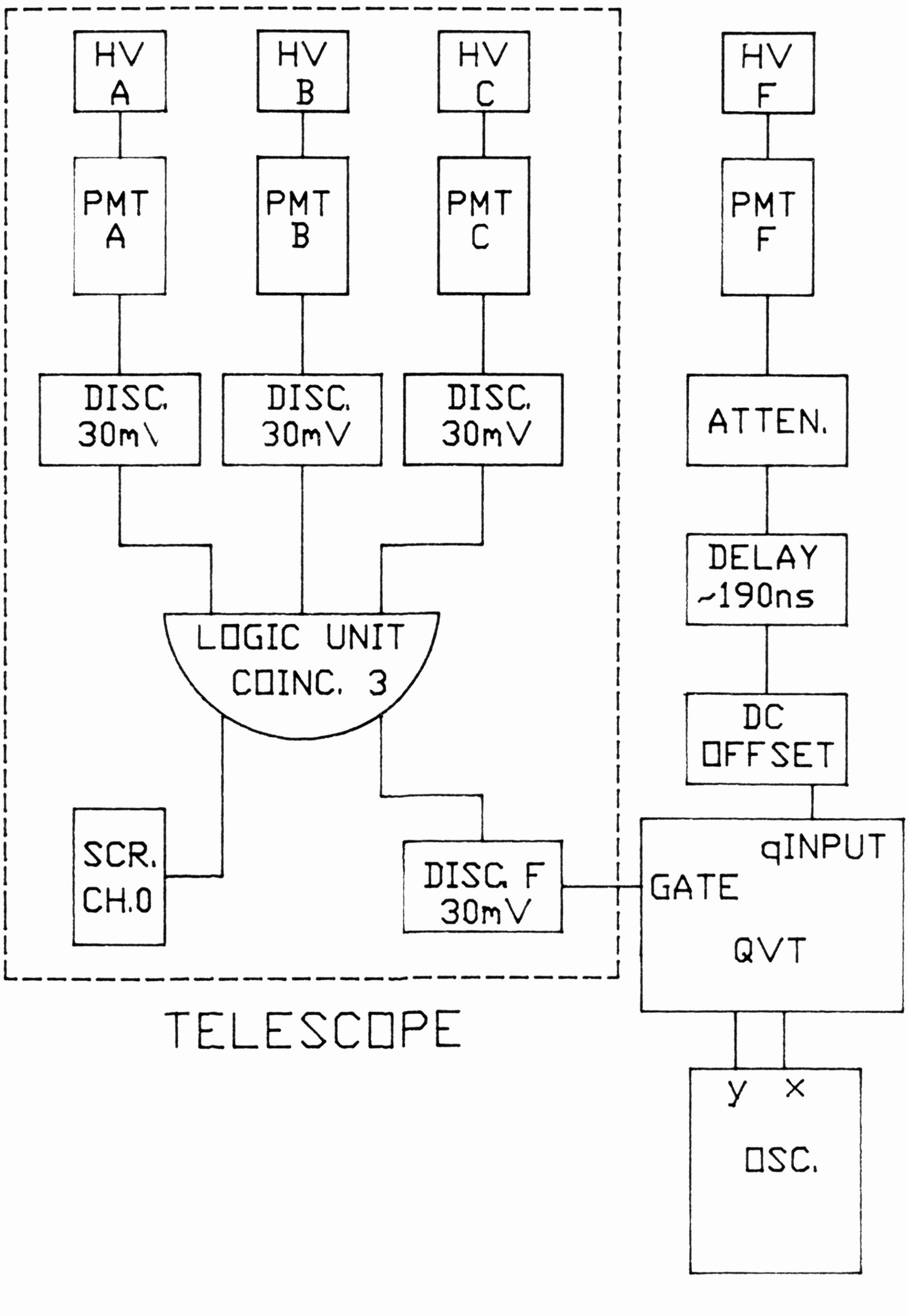


FIGURE 7

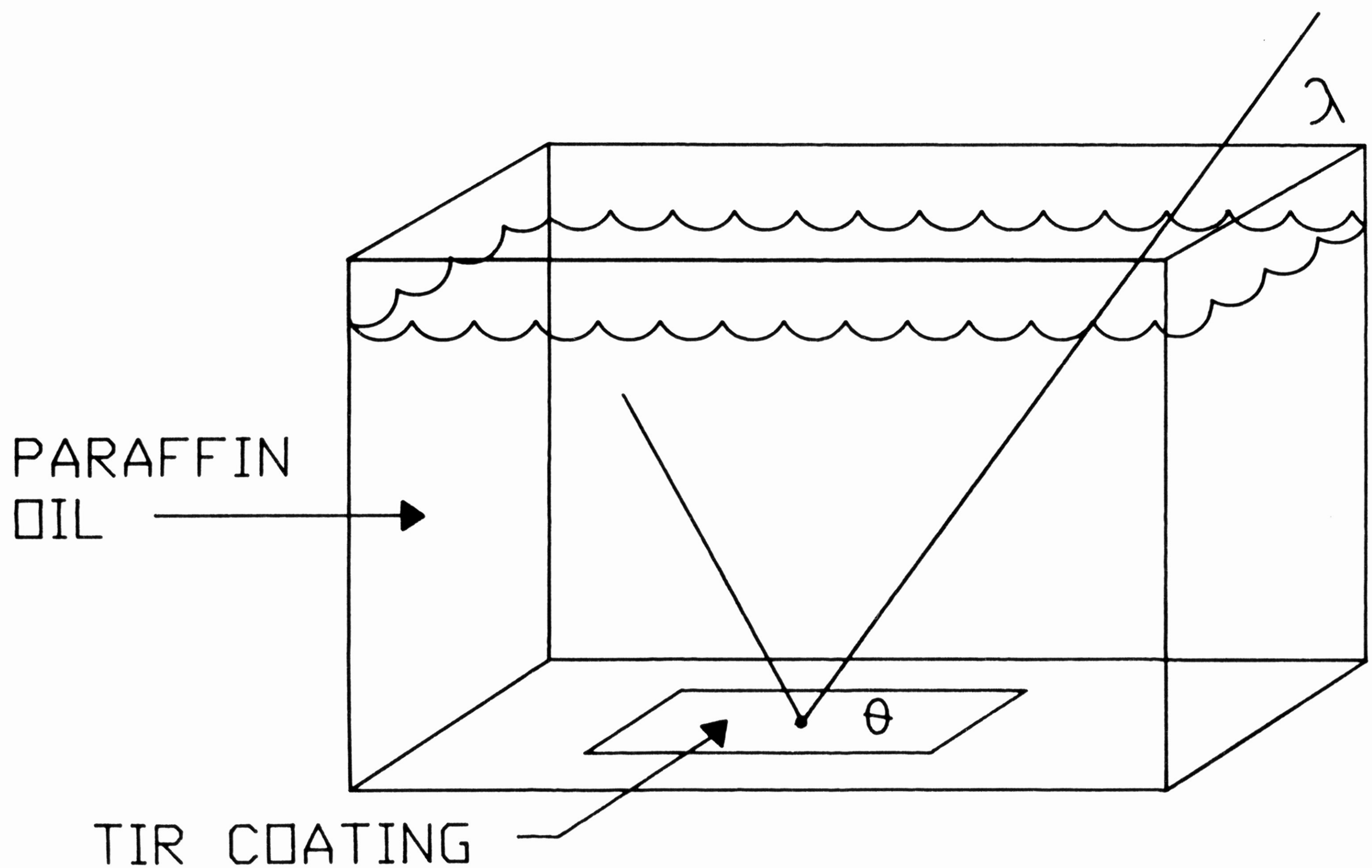
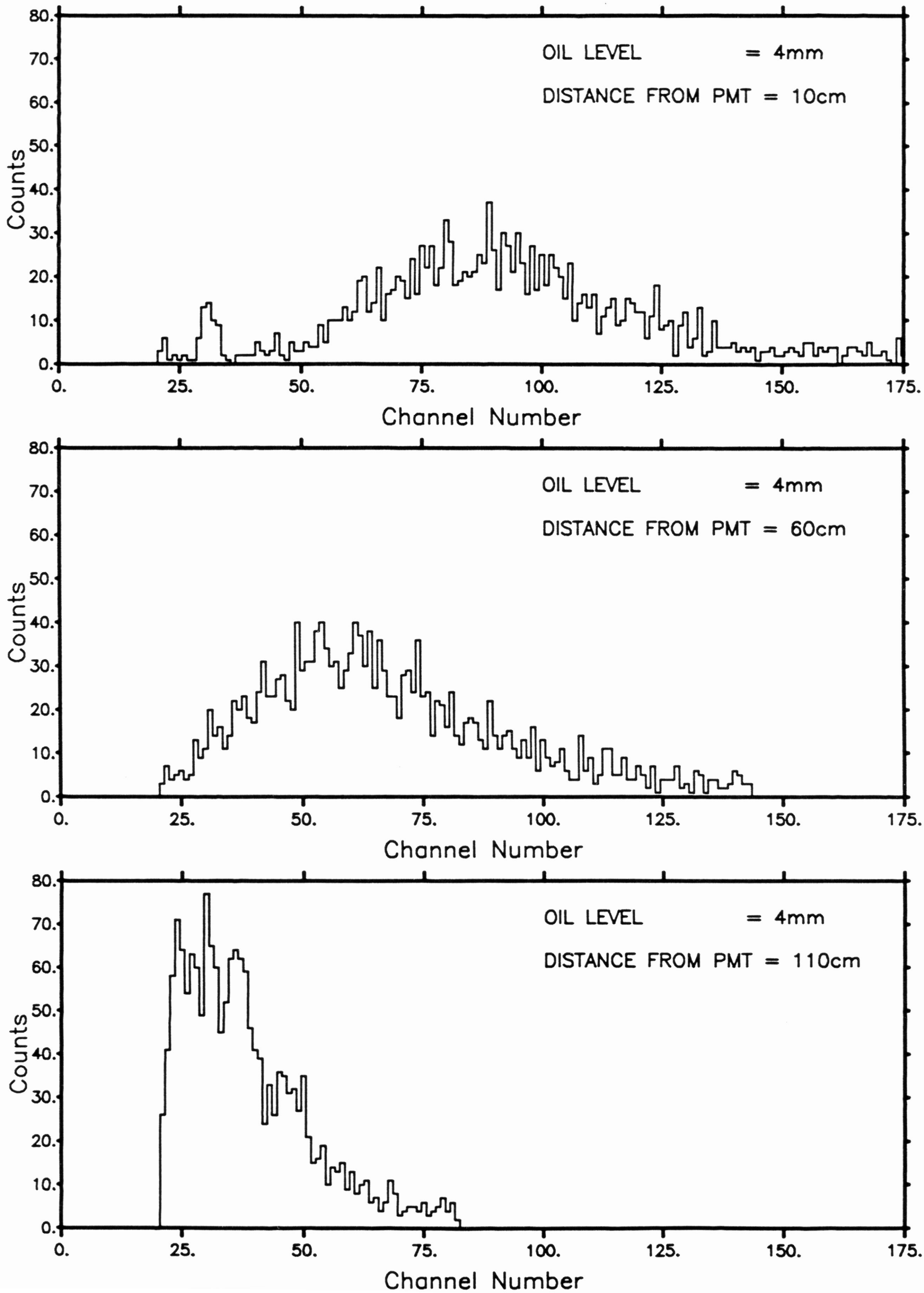
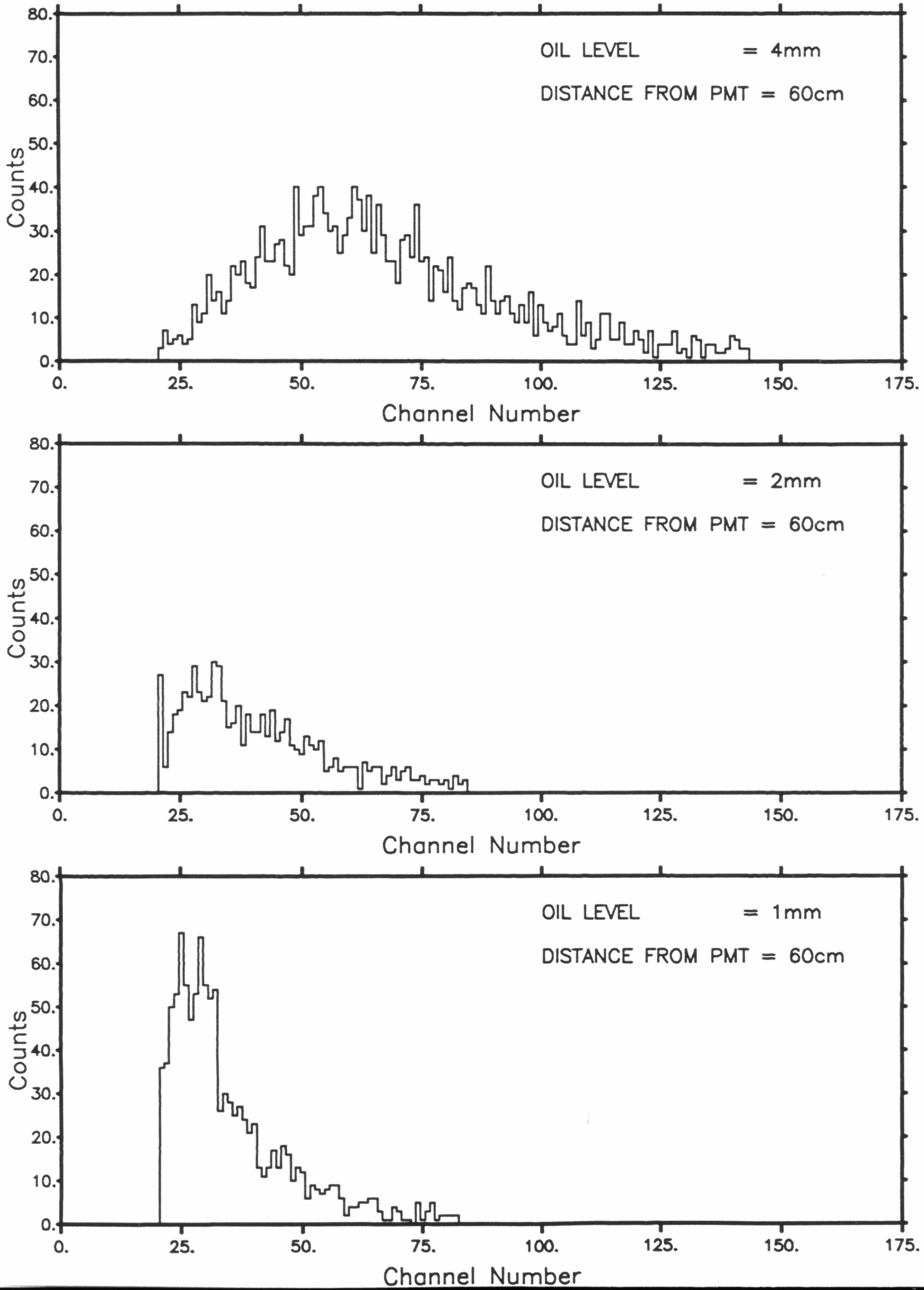


FIGURE 8



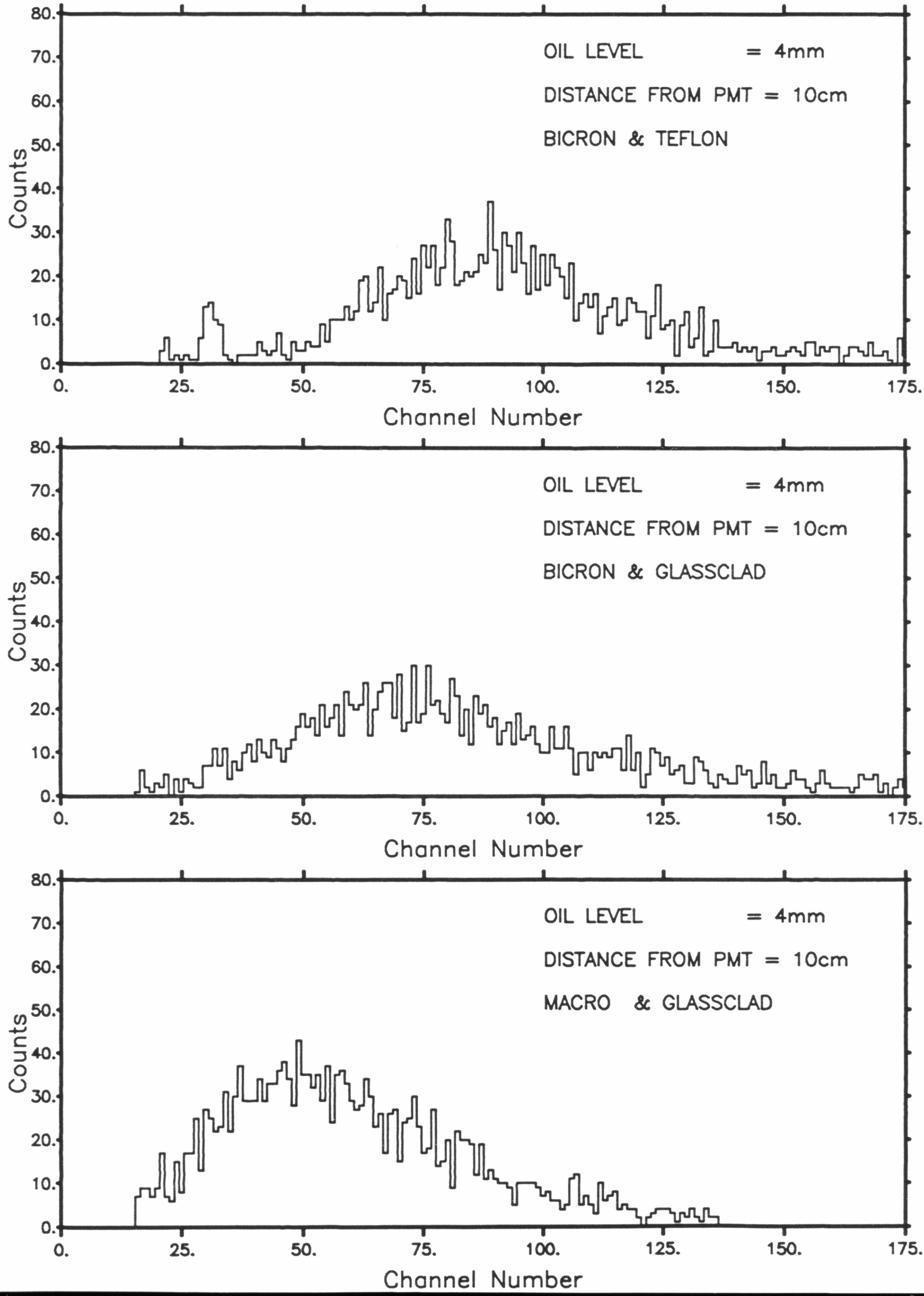
OIL LEVEL = 4mm
DISTANCE FROM PMT = 10cm
Counts
Channel Number
0. 25. 50. 75. 100. 125. 150. 175.
0. 10. 20. 30. 40. 50. 60. 70. 80.
OIL LEVEL = 4mm
DISTANCE FROM PMT = 60cm
Counts
Channel Number
OIL LEVEL = 4mm
DISTANCE FROM PMT = 110cm
Counts
Channel Number

FIGURE 9



OIL LEVEL = 4mm
DISTANCE FROM PMT = 60cm
Counts
Channel Number
OIL LEVEL = 2mm
DISTANCE FROM PMT = 60cm
Counts
Channel Number
OIL LEVEL = 1mm
DISTANCE FROM PMT = 60cm
Counts
Channel Number

,FIGURE 10



OIL LEVEL = 4mm
DISTANCE FROM PMT = 10cm
BICRON & TEFLON
Counts
Channel Number
OIL LEVEL = 4mm
DISTANCE FROM PMT = 10cm
BICRON & GLASSCLAD
Counts
Channel Number
OIL LEVEL = 4mm
DISTANCE FROM PMT = 10cm
MACRO & GLASSCLAD
Counts
Channel Number

FIGURE 11

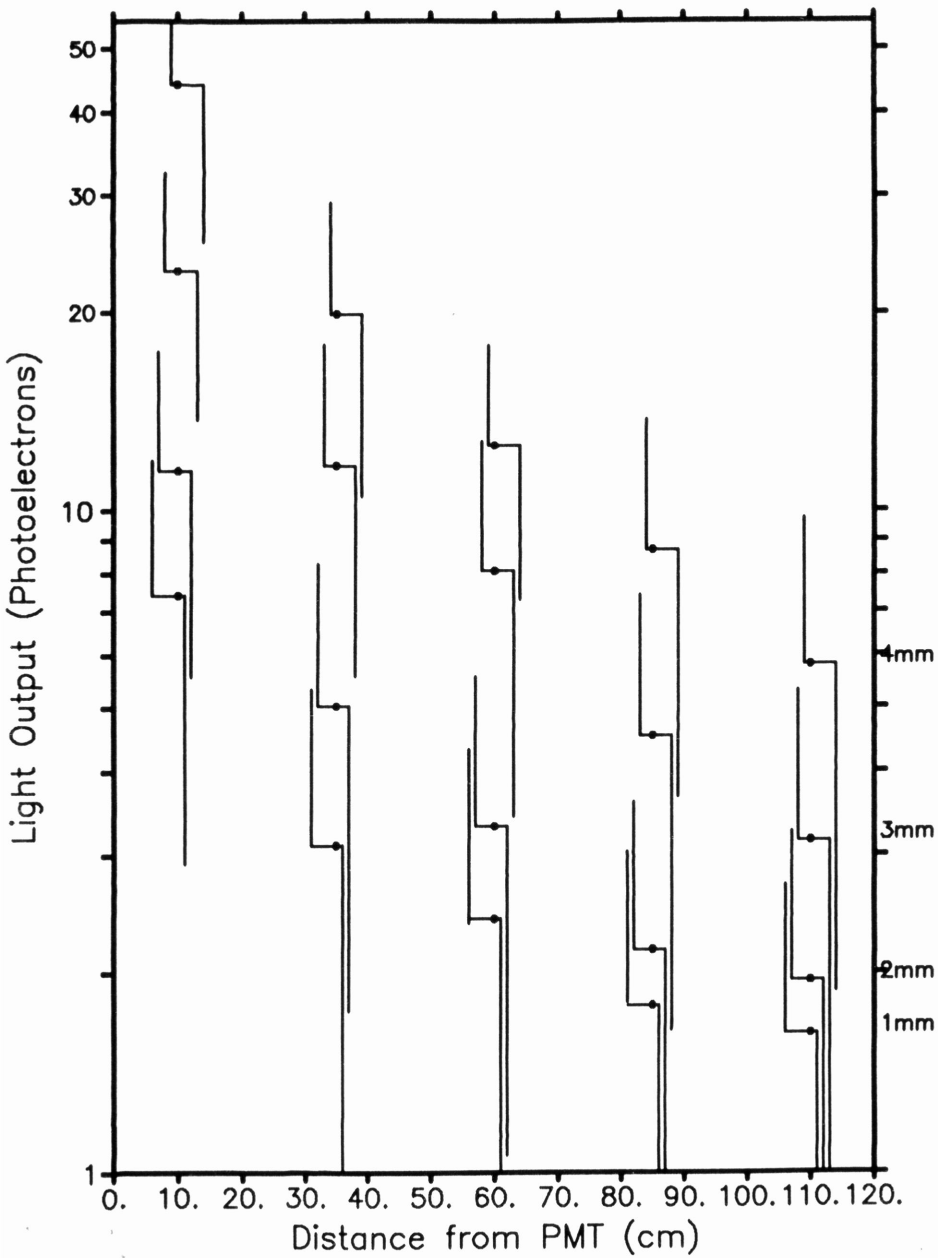


FIGURE 12

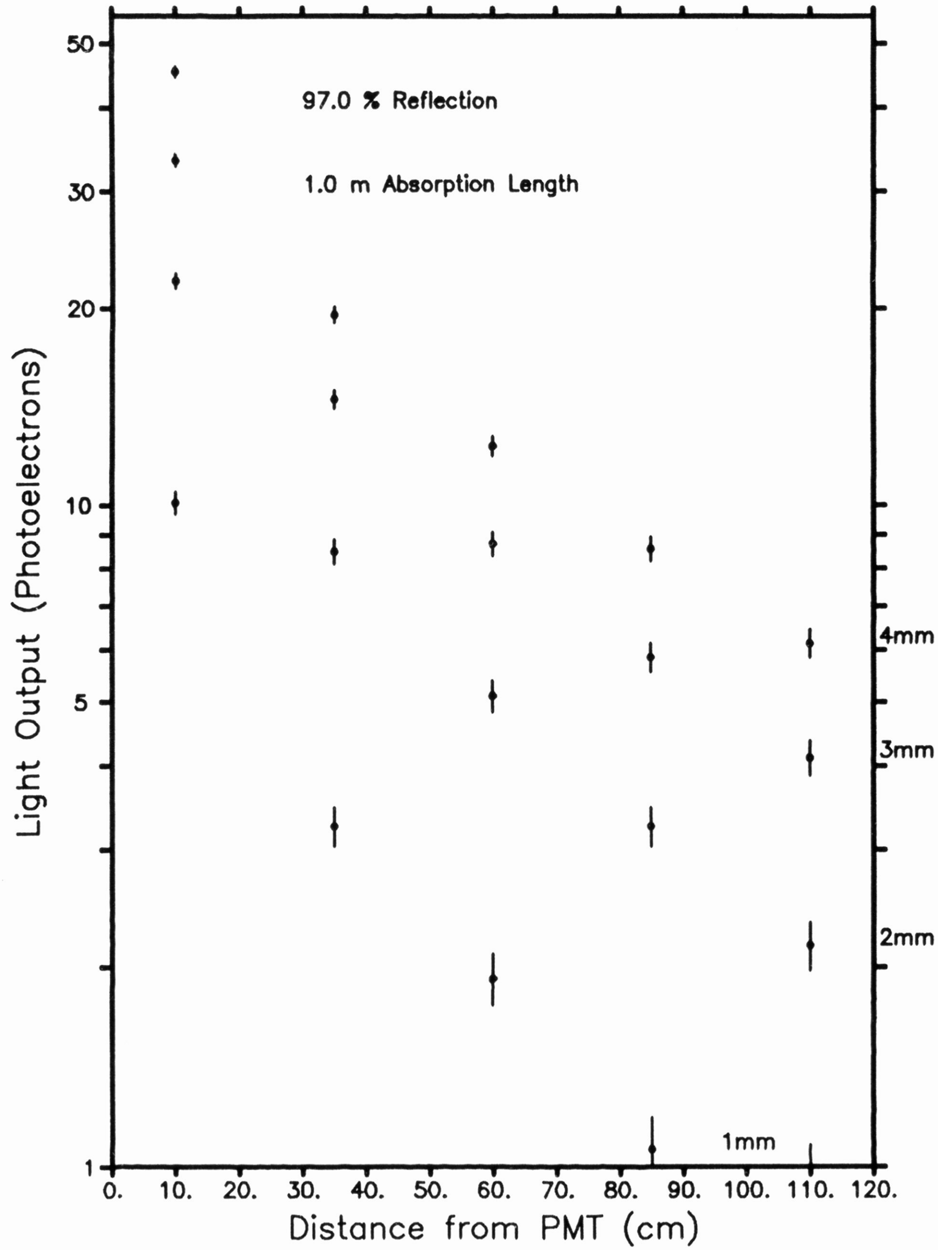


FIGURE 13

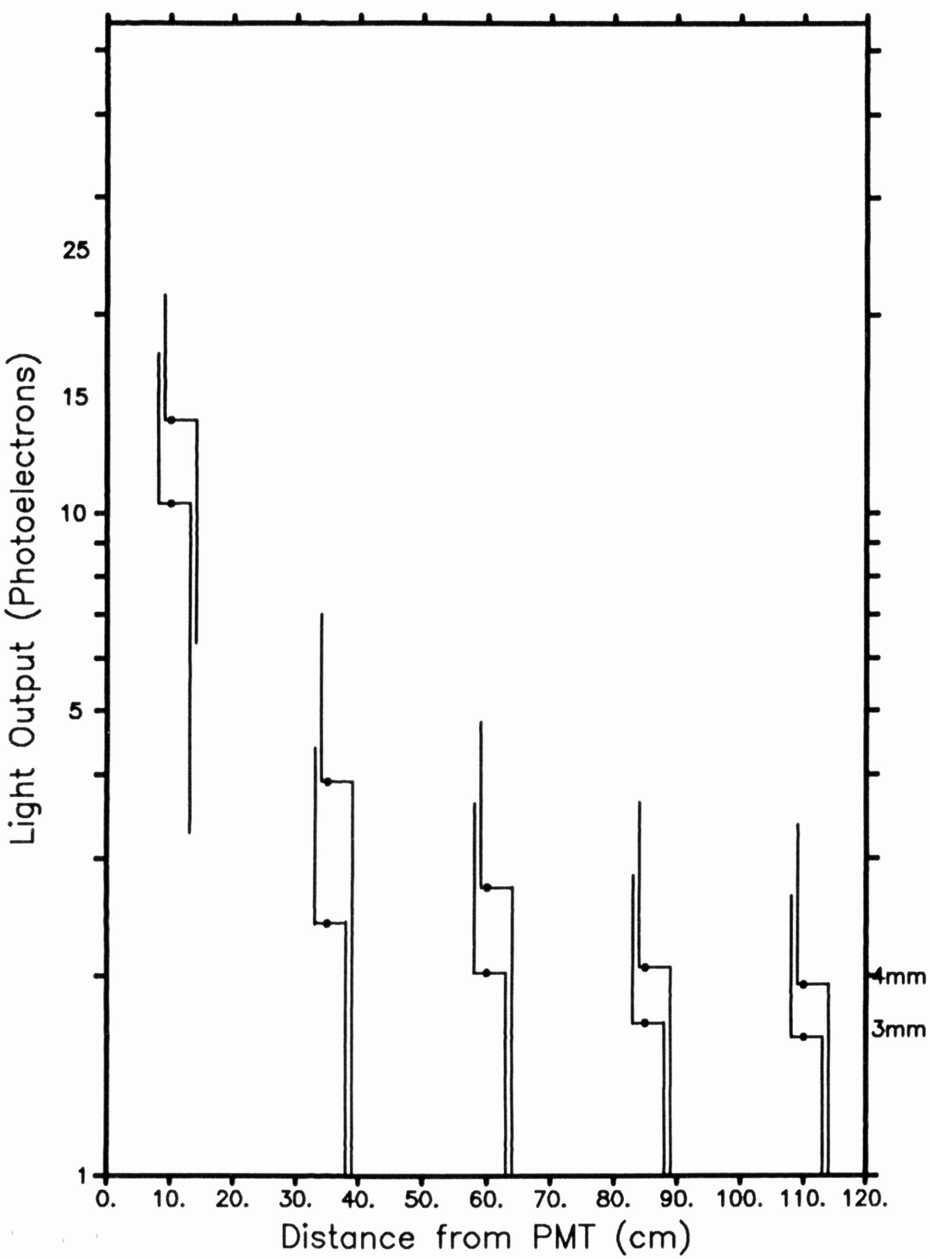
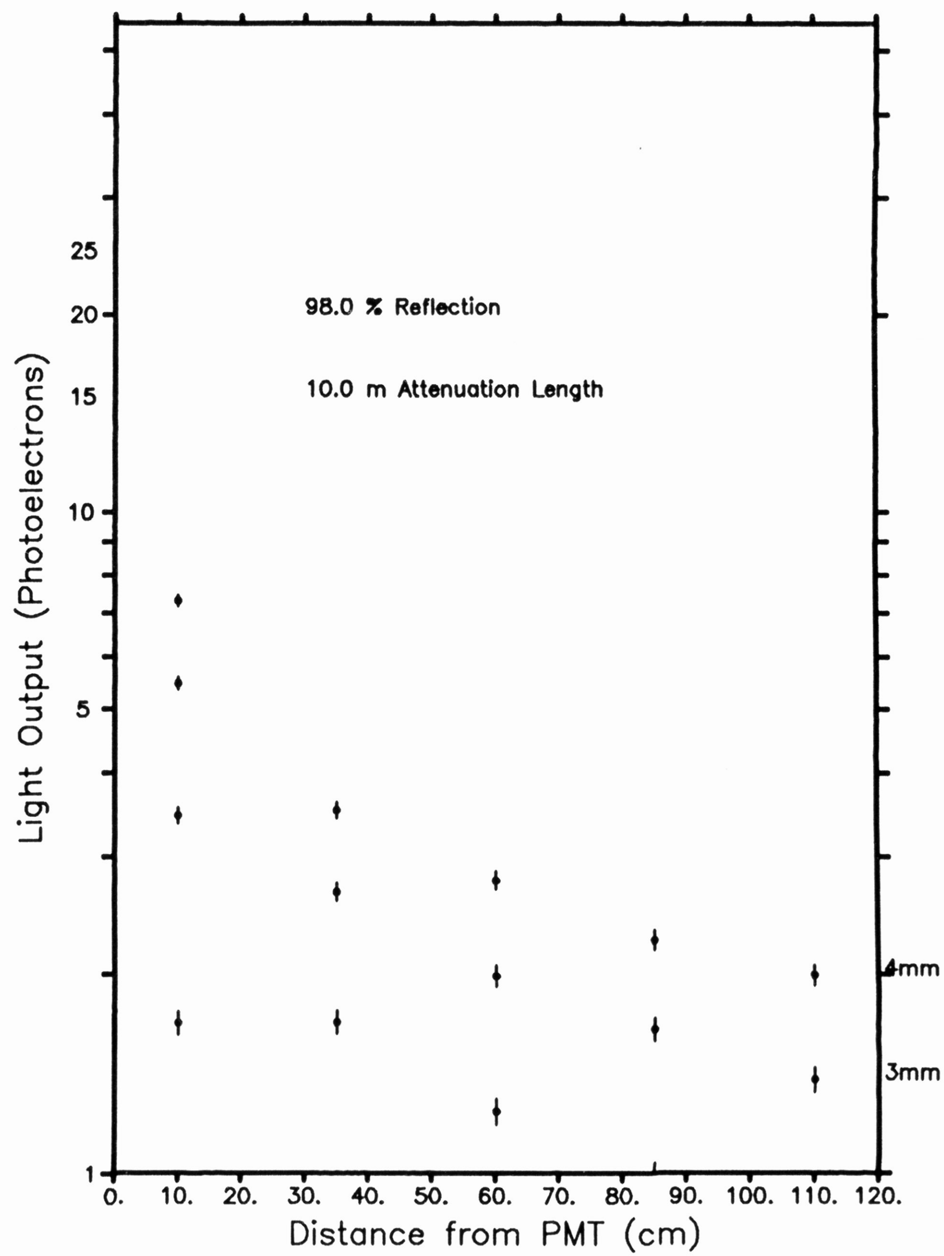


FIGURE 14



APPENDIX A

AVG.FOR

```
      IMPLICIT REAL*8(A-H,O-Z)
      Real*8 x(300),y(300)
      DIMENSION A(300),B(300)
      CHARACTER*20 dafi
      parameter(att_want=1.0d-14)
C
      WRITE(*,*) 'INPUT DATA FILE NAME --->'
      READ(*,101) DAFI
      WRITE(*,*) 'INPUT PEDESTAL VALUE --->'
      READ(*,*) PED
      WRITE(*,*) 'INPUT ATTENUATION ------>'
      READ(*,*) ATT
      write(*,102)dafi
101   format(a20)
102   format(2x,'For data file = ',a20)
C
      if(dabs(att).lt.1.0d-14)att=1.0d-14
      if(dabs(att_want).lt.1.0d-14)att=1.0d-14
      DIV=1.0d-14
      SUM=1.0d-14
      OPEN(UNIT=10,FILE=DAFI,STATUS='OLD',READONLY)
      n=0
      DO 100 I=1,300
        READ(10,*,END=200) X(i),Y(i)
        B(I)=Y(i)
        A(I)=(X(i)-PED)*2**((ATT-att_want)/6.0d00)
        SUM=SUM+A(I)*B(I)
        DIV=DIV+B(I)
        n=n+1
100   CONTINUE
200   AVE=SUM/DIV
      pcpe=3.75287*2.0d00**((14.0d00-att_want)/6.0d00)
      j=att_want
      write(*,199)j
199   format(2x,'FOR ATTENUATION OF ',i2,' DB')
      write(*,*) 'The average channel is --->'
      WRITE(*,*) AVE
      write(*,*) 'The average PE is ------>'
      write(*,*) ave/pcpe
      WRITE(*,*) 'THE TOTAL COUNTS ARE ',DIV
      sqsum=1.0d-14
      do 1001 i=1,n
         sqsum=sqsum+b(i)*((a(i)-ave)/pcpe)**2
         ach=ach+b(i)*(a(i)-ave)**2
1001  continue
      var=1.d00/(div-1.0d00)*sqsum
      avar=1.d00/(div-1.0d00)*ach
      dev=dsqrt(var)
      adev=dsqrt(avar)
      write(*,1002) var
      write(*,1003) dev
      write(*,1004) adev
1002  format(5x,'variation = ',f8.3)
1003  format(5x,'deviation = ',f8.3)
1004  format(5x,'channel dev=',f8.3)
      STOP
      END
```

APPENDIX B

SIMULATION.FOR

```
C  This program is designed to create a simulation of incoming photons with
C  a liquid scintillator.  It is necessary to input:  1) distance of telescope
C  from PMT (in cm), 2) height of oil (in mm), 3) number of photons per mm of
C  oil, 4) reflectivity constants (%), 5) attenuation length of oil (in
C  mm), and 6) TIR of teflon.
C
        real*8 xxx(100000), zee(100000), theta(100000), phi(100000), pi,length,amount
        real*8 dist_from_PMT, height, reftef, refcoat, attenuation, waterTIR,rc,rt
        real*8 per_produced, teflonTIR, coatingTIR,prob_att,per_tot,random,big
        real*8 r(100000),y(100000),z(100000),distance(100000),x(100000),xx,zz
      integer ibounce1(100000),ibounce2(100000),ibounce3(100000),ibounce4(100000)
        integer num_per_mm, num_final,i1,i2,i3,i4,loss_ref,loss_att,num_tot
      character*40 dafi
C
C       parameter (dist_from_PMT=60.d00,height=4.d00,coatingTIR=26.d00)
        parameter (reftef=0.995d00,refcoat=0.95d00,attenuation=8.75d02,length=1.0d02)
        parameter (teflonTIR=26.d00,waterTIR=42.435d00,num_per_mm=10000)
C
        do 1000 coatingTIR=17.d00,26.d00,9.d00
                do 1000 dist_from_PMT=10.d00,110.d00,25.d00
                        do 1000 height=4.d00,1.d00,-1.d00
                                open(11,file='dub1:[altice.scint]dataname.dat',status='old',readonly)
                        read(11,200) dafi
200                             format(a40)
                                open(10,file=dafi,status='new')
                                iseed=265436
                                pi=datan(1.0d00)*4.0d00
                                pi2=datan(1.0d00)*2.0d00
                                numtot=num_per_mm*height
                                num_final=0
                        tefTIR=teflonTIR*pi/180.d00
                                watTIR=waterTIR*pi/180.d00
                                coatTIR=coatingTIR*pi/180.d00
                        loss_ref=0
                                loss_att=0

                        i1=0
                        i2=0
                        i3=0
                        i4=0

C
                                do 500 ibig=1,numtot
                                        distance(ibig)=dist_from_PMT*10.0d00
                                        xxx(ibig)=ran(iseed)*length
                                        zee(ibig)=ran(iseed)*height
                                        theta(ibig)=ran(iseed)*pi
                                        phi(ibig)=ran(iseed)*2.0d00*pi
                                        r(ibig)=1.0d-14
                                ibounce1(ibig)=0
                                ibounce2(ibig)=0
                                ibounce3(ibig)=0
                                ibounce4(ibig)=0
C
C  This is the program that that tests each side and bounces.  Side 1 and
C  side 2 are the teflon coated sides, side 3 is the water, and side 4 is
C  the coating on the bottom.
C
C                                                 SIDE 1
C
1                                         if (phi(ibig).ge.1.0d-14.and.phi(ibig).lt.pi2) then
                                                xx=length-xxx(ibig)
                                                y(ibig)=xx*dtan(phi(ibig))
                                                z(ibig)=zee(ibig)+xx/dtan(theta(ibig))/dcos(phi(ibig))
                                if (y(ibig).gt.distance(ibig)) then
                                                        y(ibig)=distance(ibig)
                                                        z(ibig)=zee(ibig)+y(ibig)/dtan(theta(ibig))/dsin(phi(ibig))
```

```
                  endif
                  if (z(ibig).gt.height) goto 3
                  if (z(ibig).lt.1.0d-14) goto 4
                  r(ibig)=r(ibig)+dabs(y(ibig)/dsin(theta(ibig))/dsin(phi(ibig)))
                  distance(ibig)=distance(ibig)-y(ibig)
                  xxx(ibig)=length
                  zee(ibig)=z(ibig)
                  if (distance(ibig).le.1.0d-03.and.distance(ibig).ge.-1.0d-03) goto
     *          100
C test TIR angle
                  if (pi2-phi(ibig).le.tefTIR) then
                        phi(ibig)=pi-phi(ibig)
                        ibounce1(ibig)=ibounce1(ibig)+1
                        goto 2
                  else
                        goto 500
                endif
                endif
C
C                 SIDE 2
C
2               if (phi(ibig).ge.pi2.and.phi(ibig).lt.pi) then
                  xx=-xxx(ibig)
                  y(ibig)=xx*dtan(phi(ibig))
                  z(ibig)=zee(ibig)+xx/dcos(phi(ibig))/dtan(theta(ibig))
        if (y(ibig).gt.distance(ibig)) then
                        y(ibig)=distance(ibig)
                        z(ibig)=zee(ibig)-y(ibig)/dtan(theta(ibig))/dsin(phi(ibig))
                  endif
                  if (z(ibig).gt.height) goto 3
                  if (z(ibig).lt.1.0d-14) goto 4
                  r(ibig)=r(ibig)+dabs(y(ibig)/dsin(theta(ibig))/dsin(phi(ibig)))
                  distance(ibig)=distance(ibig)-y(ibig)
                  xxx(ibig)=1.0d-14
                  zee(ibig)=z(ibig)
                  if (distance(ibig).le.1.0d-03.and.distance(ibig).ge.-1.0d-03)
     *          goto 100
C test TIR angle
                  if (phi(ibig)-pi2.le.tefTIR) then
                        phi(ibig)=pi-phi(ibig)
                        ibounce2(ibig)=ibounce2(ibig)+1
                        goto 1
                  else
                        goto 500
                endif
                endif
C
                if (phi(ibig).ge.pi) goto 500

C
C                       SIDE 3
C
3               if (theta(ibig).gt.1.0d-14.and.theta(ibig).le.pi2) then
                  zz=height-zee(ibig)
                  y(ibig)=dabs(zz*dtan(theta(ibig))*dsin(phi(ibig)))
                  x(ibig)=xxx(ibig)+zz*dtan(theta(ibig))/dtan(phi(ibig))*
     *          dabs(dsin(phi(ibig)))

        if (y(ibig).gt.distance(ibig)) then
                        y(ibig)=distance(ibig)
                        x(ibig)=xxx(ibig)+y(ibig)/dtan(phi(ibig))
                  endif
                  if (x(ibig).gt.length) goto 1
                  if (x(ibig).lt.1.0d-14) goto 2
                  r(ibig)=r(ibig)+dabs(y(ibig)/dsin(theta(ibig))/dsin(phi(ibig)))
                  distance(ibig)=distance(ibig)-y(ibig)
                  xxx(ibig)=x(ibig)
                  zee(ibig)=height
                  if (distance(ibig).le.1.0d-03.and.distance(ibig).ge.-1.0d-03)
     *          goto 100
C test TIR angle
                  if (pi2-theta(ibig).le.watTIR) then
                        theta(ibig)=pi-theta(ibig)
                        ibounce3(ibig)=ibounce3(ibig)+1
                        goto 4
                  else
                        goto 500
                endif
                endif
```

```
C
C                                SIDE 4
C
4                      if (theta(ibig).gt.pi2.and.theta(ibig).le.pi) then
                            zz=-zee(ibig)
                            y(ibig)=dabs(zz*dtan(theta(ibig))*dsin(phi(ibig)))
                            x(ibig)=xxx(ibig)+zz*dtan(theta(ibig))/dtan(phi(ibig))*
     *                      dabs(dsin(phi(ibig)))
                   if (y(ibig).gt.distance(ibig)) then
                                 y(ibig)=distance(ibig)
                                 x(ibig)=xxx(ibig)+y(ibig)/dtan(phi(ibig))
                            endif
                            if (x(ibig).gt.length) goto 1
                            if (x(ibig).lt.1.0d-14) goto 2
                            r(ibig)=r(ibig)+dabs(y(ibig)/dsin(theta(ibig))/dsin(phi(ibig)))
                            distance(ibig)=distance(ibig)-y(ibig)
                            xxx(ibig)=x(ibig)
                            zee(ibig)=1.0d-14
                            if (distance(ibig).le.1.0d-03.and.distance(ibig).ge.
     *                      -1.0d-03) goto 100
C test TIR angle
                            if (theta(ibig)-pi2.le.coatTIR) then
                                 theta(ibig)=pi-theta(ibig)
                                 ibounce4(ibig)=ibounce4(ibig)+1
                                 goto 3
                            else
                                 goto 500
                       endif
                       endif
C
C
100                    num_final=num_final+1
                       i1=i1+ibounce1(ibig)
                       i2=i2+ibounce2(ibig)
                       i3=i3+ibounce3(ibig)
                       i4=i4+ibounce4(ibig)


                       do 600 i=1,ibounce1(ibig)+ibounce2(ibig)
                            random=ran(iseed)
                            if(reftef.lt.random) then
                            loss_ref=loss_ref+1
                                 goto 500
                            endif
600                    continue
                       do 700 i=1,ibounce4(ibig)
                            random=ran(iseed)
                            if(refcoat.lt.random) then
                            loss_ref=loss_ref+1
                                 goto 500
                            endif
700                    continue

                       prob_att=dexp(-r(ibig)/attenuation)
                       random=ran(iseed)
                       if(prob_att.lt.random) then
                            loss_att=loss_att+1
                       endif

500             continue
                     per_produced=(num_final*1.0d02)/numtot

                num_tot=num_final-loss_ref-loss_att
                per_tot=(num_tot*100.d00)/numtot
                     if (dist_from_PMT.le.10.d00+.01d00.and.dist_from_PMT.ge.10.d00
     *               -.01d00.and.height.le.4.d00+.01d00.and.height.ge.4.d00-.01d00)
     *            then
                            big=per_tot
                     endif
                     amount=per_tot/big*(height/4.0d00)
                     rc=refcoat*100.d00
                     rt=reftef*100.d00

                     write(10,101) coatingTIR
                write(10,*)
                write(10,102) dist_from_PMT
                write(10,103) height
                write(10,104) length/10.
                write(10,*)
```

```
                        write(10,105) num_per_mm
                  write(10,*)
                  write(10,106) rc
                  write(10,107) rt
                  write(10,108) attenuation
                  write(10,*)
            write(10,115) i1
            write(10,116) i2
            write(10,117) i3
            write(10,118) i4
                  write(10,*)
                  write(10,*)
                  write(10,*)
                  write(10,109) num_final
                  write(10,110) per_produced
                        write(10,*)
                        write(10,111) loss_ref
                        write(10,112) loss_att
                  write(10,*)
                  write(10,*)
                  write(10,113) num_tot
                        write(10,114) per_tot
                        write(10,119) amount

1000    continue


101     format(2x,'Simulated data for sample coating with a reflection angle:
     *',f6.2)
102     format(5x,'Distance from PMT                       : ',f7.2,'   cm')
103     format(5x,'Height of Oil                           : ',f7.2,'   mm')
104     format(5x,'Length of Detector                      : ',f7.2,'   cm')
105     format(5x,'(We assume the particle emits ',i5,' photons per mm of oil.)')
106     format(5x,'Percent reflected at coating surface    : ',f6.2,'    %')
107     format(5x,'Percent reflected off Teflon sides      : ',f6.2,'    %')
108     format(5x,'Attenuation Length                      : ',f9.2,' mm')
109     format(5x,'Final number of unhindered photons      : ',i7)
110     format(5x,'Percent from original photons           : ',f6.2,' %')
111     format(5x,'Loss of light due to absorption on sides : ',i5)
112     format(5x,'Loss of light due to attenuation length  : ',i5)
113     format(5x,'Total number of photons making it       : ',i5)
114     format(5x,'Percentage of photons making it         : ',f6.2,' %')
115     format(5x,'Total number of times photon hits Side 1 : ',i5)
116     format(5x,'Total number of times photon hits Side 2 : ',i5)
117     format(5x,'Total number of times photon hits Water  : ',i5)
118     format(5x,'Total number of times photon hits Coating : ',i5)
119     format(5x,'Amount of Light reaching PMT            : ',f6.4)
        stop
        end
```