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LARGE AREA LIQUID SCINTILLATION DETECTOR SLAB*

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Summary

A low-cost detector 18' x 2' x 5" has been developed for an underground cosmic ray neutrino experiment. The liquid employed is a high-clarity mineral oil-based mixture, and light is quided to the ends of the detector by total internal reflection at the surface of the Lucite container. Signals from 2 five-inch photomultipliers at each end give energy and event location for single penetrating particles, with relatively good discrimination against natural radioactivity by virtue of the substantial thickness. Data are presented on the response function of the tank, energy resolution, rates and thresholds. A number of modifications that have been tried are also described.

Introduction

The detector to be described was developed to meet the requirements of a class of experiments in neutrino physics for which large sensitive area is of paramount importance. An array of 60 such detectors aggregating about 180 square meters is presently operating at a deep underground site in South Africa. Most of the array has been operating continuously for nearly two years. The constraints imposed by the particular experiments for which these detectors were designed may be tabulated briefly:

1) Desired area of several square meters per individual detector.
2) Low cost housing and scintillant.
3) High degree of optical clarity in the detector medium. About 4 photomultiplier tubes per detector, to permit fourfold coincidence circuitry for suppressing tube noise.
4) Thickness to ensure that penetrating charged relativistic particles will deposit an amount of energy well in excess of radioactive decay energies.
5) Response function such that pulse height variation for events at center and end of tank does not exceed a factor of five or six.
6) Geometrical arrangement to permit determination of location of event in the detector.
7) Length not to exceed limits set by capabilities of mine hoists.
8) Eventual design to include provision for calibration and monitoring of each individual detector.
9) Vertical dimension relatively small so that several detectors may be stacked vertically one above the other in a deep underground site.

Experience of the Case group for a number of years with a liquid scintillator[1] consisting of 90% pure mineral oil, 10% Shell TS-28 solvent, and appropriate amounts of PPO scintillating compound and POPOP wavelength shifter indicated the suitability of such a liquid for the present detectors. This liquid features good luminescent efficiency, extremely high optical clarity, low cost, and excellent freedom from tendencies to attack materials used to fabricate containers. First design attempts using containers surfaced with high reflectivity white paint were singularly unsuccessful. However the technique of using plastic containers with totally reflecting walls, developed by the neutrino group at CERN,[2] was found to enable construction of detectors of quite substantial size having remarkably good characteristics. In the course of developing the present tanks studies were made of the properties of detectors 5' x 5' x 6" with white painted walls, followed by plastic-walled units with dimensions 5' x 4' x 5", 2' x 12' x 5", and 2' x 18' x 5", the configuration finally adopted for the large area hodoscope array.

Figure 1 shows the construction of the plastic tank. It is fabricated from pieces of 3/8 inch thick ultra-violet transmitting Lucite joined by cement, with additional strength imparted by running a filet along each corner with 1/8 inch Lucite rod coated with cement. Since the largest available sheet Lucite stock is 12' long, the sides and bottom are pieced together using a butt joint backed by a 2" wide strip cemented over the joint. The top is cemented all along the tank except for three sections which may be lifted off for cleaning, filling, and other operations. Bulging of the tank walls due to the hydrostatic pressure of the fluid is controlled by a pattern

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of spacers made of 3/4 inch diameter Lucite rods with 1/8 inch diameter steel studs which clamp the side walls tightly against the ends of the spacers It was found that the cement joints at the ends of the spacers were prone to crack in the wake of shock waves from blasting operations in the mine, so that it bacame necessary to cement small plastic caps over the ends of the steel studs to seal these spacer assemblies. In later versions of the tanks these caps were affixed during manufacture. Very few seam leaks have developed in the tanks in nearly two years of operations, and in every case it has been possible to repair the leaks by smoothing the outside surface, cleaning thoroughly with alcohol, and quickly cementing on a strip of Lucite.

As noted by the CERN group, some further improvement in the performance of these detectors can be effected by placing a layer of aluminum foil around the Lucite container to aid in collecting light which is not trapped by total internal reflection. However it was found that white painted surfaces are equally effective, so that the final configuration adopted utilizes a close fitting box made of 1/8 inch thick masonite with inside surfaces painted white to serve as a light tight housing and backup reflector. It was also deemed desirable to install spacers between the tank and the plank running under it so that a small quantity of liquid collecting under the tank will not spoil the conditions for total reflection at the bottom surface. Considerable care is necessary to apply opaque tape to these masonite boxes to render them truly light tight, so that a more expensive sheet steel housing is used on later tanks. However, it was subsequently found to be possible to wrap the masonite boxes with black polyethylene tarpulins in such a way that they are completely light tight even under conditions of bright ambient illumination.

The photomultiplier tubes used are Dumont type KM 2548 five inch tubes with the dropping chains wired directly onto the base of the glass envelope and the entire assembly with connectors potted in a compact unit. Figure 2 shows the dropping chain circuit diagram. The photomultiplier tubes are optically coupled to the ends of the Lucite box with Dow Corning C-2-0057 compound in a mechanical assembly using three 8-pound tension springs.

Detector Response Function F(z) and Event Position Determination

The detector response function F(z), i.e. the relative signal amplitude for a single photomultiplier tube as a function of the location of the event z in the tank, is shown in Figure 3. It is seen that the variation in pulse amplitude is remarkably small considering the extreme length of the tank, and yet it is possible to capitalize on the departure from flatness of the response function to deduce the positions of individual events. In Figure 4 there is plotted the quantity $R(z) \equiv F(z)/F(L-z)$. If this ratio R(z) is identified with the ratio of the average signal from the pair of photomultiplier tubes at one end of the tank to the average signal from the pair at the other end, it is seen that the value of this ratio uniquely determines the event position z. Although the Landau distribution for energy deposited in the tank by penetrating particles is quite broad, the fluctuations, fortunately, have the same direction and magnitude for each of the four photomultiplier tube signals for a given event. Thus the ratio R(z) has only fluctuations associated with the processes of light collection and production of photoelectrons. From observations of the constancy of signal amplitudes for the pair of photomultiplier tubes at the same end of a tank, it is believed that observed ratios can be depended on to determine event position to an accuracy of about ± 1 foot.

It is acknowledged that the one dimensional representation of the response function shown in Figure 3 is somewhat of an over simplification. Rigorously the event location should be specified in two dimensions, or even three. However, most measurements have been made using external detectors to steer cosmic ray muons through the tank at various points, so that the determination to date of the tank response function has been somewhat crude. Some supplementary measurements with radioactive sources and pulsed light sources have been carried out, but careful measurements with accelerator particles have not yet been made. Nevertheless it has been possible to show that the one dimensional curve of Figure 3 is quite dependable for z greater than about 18" independent of the vertical coordinate of the event. For events closer to the photomultiplier tube the actual pulse heights will of course be somewhat less than the on-axis values plotted in Figure 3.

Refinements in the Detector Configuration Design

In the array of 60 tanks used in the underground neutrino experiment the only events that are analyzed are those in which signals greater than the threshold value are simultaneously present at all four photomultiplier tubes in a given tank, and the events of greatest interest are those in which signals are simultaneously present in a particular pair of tanks. Thus the "signatures" of the events of interest are sufficiently complex that it is possible to make meaningful rate measurements in the range of a few events per year despite the fact that the array aggregates over 20 tons of scintillating medium and 240 photomultiplier tubes and is situated in an environment where the radioactive background is somewhat high. Measurements indicate that, in spite of the fact that the energies of the events of interest are well above the range of energies associated with radioactive decay, it is still not possible to render the system completely insensitive to background events due to radioactivity.

Most of the background events appear to be due to the chance juxtaposition in time of a gamma ray absorption process near the AB end of the tank and another unrelated one near the CD end. Several measures have been tried to combat these background processes:

1) Adding transparent vertical partitions which permit 15 inch long zones at each end of the tank to be filled with pure non-scintillating mineral oil.
2) Insertion of horizontal light dividers in the liquid at the ends of the tank to optically isolate A from B and C from D.
3) Variation of the separation of the pairs of photomultiplier tubes.
4) Elimination of the white diffuse reflective coating at the end regions of the tank.

Modification 1) obviously eliminates the region where the tank response function becomes very large, with a resulting penalty in the form of loss of sensitive volume and introduction of gaps in the hodoscope array. It is felt that the improvement in performance probably warrants acceptance of this penalty.

Modification 2) renders the tank much less sensitive to events due to simultaneous absorption of gamma rays at the two ends of the tank, though it does not eliminate these background events entirely. In principle one would expect that energetic events in the end regions would be missed as in the case of modification 1), but since the light dividers do not give perfect isolation some events in the end regions are still detected. A combination of both these modifications is probably superior to either alone.

Some isolation of A from B can be accomplished by merely increasing the separation of the tubes. However, as noted below, when light dividers are inserted maximum isolation of A from B is accomplished by decreasing the separation of the tubes, because of the penumbra conditions just beyond the end of the light divider.

Because of the "wave guide-like" nature of these tanks most of the light due to events occurring some distance from a given photomultiplier tube arrives in the form of rays totally reflected from the Lucite-air interface, whereas light from nearby events reaches the photomultiplier tube by paths utilizing the diffuse reflecting surfaces. Thus it is possible to suppress the small signals from gamma rays absorbed near the end of the tank relative to the small signals from penetrating particles at the center or far end of the tank by placing a black drape over the end regions of the Lucite tank.

Tables I, II, and III show representative data obtained when a number of tank configurations are compared. Sample rates are given as well as ratios of rates which indicate the effectiveness of the various modifications which have been tried. Briefly, the results of these measurements with the conjectured physical explanations may be summarized as follows:

When light dividers and black drapes are added to the basic tank the measured factor of reduction in the AB coincidence rate at a representative threshold energy is 28. Gamma rays absorbed near the photomultiplier tubes, in the region where the response function is large, are prevented by the light divider from giving a large signal in both A and B tubes. The light dividers are 15" long aluminum plates with 2" long vertical flanges at the lines of contact with the Lucite walls to reduce light leakage around the edges of the divider.

In table II the basic tank with modifications is compared to new-type tanks wtih non-scintillating end regions. At the threshold energies at which the tanks are normally operated the reduction in singles counting rate is very striking--more than a factor of 100, indicating that throughout the scintillating region the tank response function is sufficiently low that virtually no gamma ray events are able to give photomultiplier tube signals greater than the threshold level. The reduction in singles rates is much less pronounced when the threshold level is reduced, indicating that events are "seen" throughout an appreciable portion of the scintillating region.

The doubles rates are similarly improved in the new-type tanks when the threshold is set at a moderate value--an improvement of a factor of 10. However, it will be noted that the new-type tanks are inferior to the basic tanks with light dividers under low-threshold operating conditions. The explanation for this appears to be that the effect of the light dividers actually extends beyond the physical end of the structure, i.e. that there is a penumbra region created for a considerable distance into the fluid.

Figure 5 shows the background singles spectrum for a new-type tank compared with that for the basic tank with light dividers. The tanks are balanced to give the same signal amplitude for a standard event at midtank. The effect in the region of the "tail" of the differential pulse height distribution is quite striking.

In Table III the basic tank with light dividers is compared to a new-type tank to which light dividers have been added. The performances are now more nearly alike, though the new-type tank still has a higher doubles rate. The residual difference in performance appears to be due partly to the fact that the light divider in the new-type tank is about 5% shorter, and partly due to the somewhat greater photomultiplier tube separation.

It may be noted that isolation of A from B is improved in the basic tank when the photomultiplier tube separation is increased, but that when light dividers are used the penumbra region becomes more extensive as the photomultiplier tube separation is <u>decreased</u>. Thus the optimum separation of the photomultiplier tubes is different depending on whether or not there are light dividers in the tank.

None of the modifications tried thus far have succeeded in reducing the doubles rate at useful threshold energies to the level of the chance coincidence rate.

All tanks in the experimental array now have builtin pulsed light sources permanently mounted on the sides, for periodic automatic monitoring of the system.

Tank calibration at the deep underground site is carried out by making measurements with a standard radioactive source relative to a reference tank on the surface.

Following a suggestion of Dr. M. Reinharz[3] calculations have been carried out to determine analytically the detector response function. A straightforward summation of the 3-dimensional set of virtual sources arising from the total reflection process is made for each event location. The calculations are in good agreement with the large measured mean free path for the scintillation light and with the experimentally determined tank response function. It is believed that such calculations will be helpful in predicting performance of tanks of different site and shape which may be needed in future experiments.

Detector Performance

Certain aspects of the detector performance such as representative rates have already been discussed in previous sections. Figure 6 shows spectra of cosmic ray muons guided through the tank at different distances. These curves give the distribution of signal amplitudes from a single photomultiplier tube gated by a pair of small external detectors at top and bottom connected in coincidence. Thus the spectrum represents mainly events in which a muon traverses the entire 22" height of the fluid, with mean energy deposition of 92 Mev. The breadth of these peaks is doubtless largely due to the intrinsic Landau distribution, but curves such as these and similar ones obtained with a pulsed light source which simulates a rigorously monoenergetic sequence of events give a qualitative indication that the resolution of the tanks is quite good for events of the energy range of interest in the present experiment. Again, careful quantitative determination of energy resolution and number of photoelectrons liverated from the photocathode for representative events have not yet been carried out.

Figures 7 and 8 show representative signals recorded with the array of tanks[4] in the underground neutrino experiment. The recording apparatus is a special purpose chronotron system, one of the two independent recording systems described in accompanying papers. In each case the A, B, C and D signals appear in sequence on the top oscilloscope trace and the two pulses on the other three traces are "locator" pulses which indicate which tank in the hodoscope array has been struck. Figure 7 is the record of an event in which a single particle travelling nearly horizontally traversed two tanks. Note that the particle passed through almost the exact center of the West tank and a distance of 7 feet from the AB end of the East tank. The calculated event energies for the two tanks are 29 and 19 Mev, consistant with the interpretation that a minimum ionizing particle passed through horizontally. Figure 8 is a record of a signal from a pulsed light source placed at the center of this East tank. The equivalent energy is considerably higher than that deposited by a muon.

Appendix

There follows a concise tabulation of a number of pertinent dimensions, parameters, etc. relating to the scintillation detector slabs.

Tanks	
Material	$\frac{3}{8}$" u-v transmitting Lucite
Length (inside)	18 feet
Height (inside)	22 5/8 inches
Thickness (inside)	5 inches
No. of structural spacers	22
Scintillator	
Composition	90% mineral oil, 10% TS-28, PPO, POPOP
Sensitive area	3.07 meters^2=33.0 ft^2
Volume	103 gallons
Weight	743 lb.
Density	0.865 gm/cm^3
Fluid depth	22 in.
Photomultiplier tubes	
No.	4
Type	Dumont KM 2548
Cost	
Tank	$300
Scintillator	$100
Photomultiplier Tubes	$500
Light Tight Housing	$50

References

1. T. L. Jenkins and F. Reines, IEEE Trans. NS-11, No. 3, 1 (1964).

2. H. Faissner, F. Ferrero, A. Ghani and M. Reinharz, Nuc. Inst. Meth. 20, 289 (1963). See also J. Barton, et al., J. Sci. Inst. 39, 360 (1962); 41, 736 (1964).

3. Dr. M. Reinharz, private communication.

4. F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, G. R. Smith, B. Meyer and J. P. F. Sellschop, Phys. Rev. Letters 15, 429 (1965).

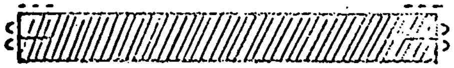
CONFIGURATION	E_{thresh} (Mev COT)	A (MIN^{-1})	B (MIN^{-1})	AB (MIN^{-1})	RELATIVE RATES	
					$\frac{1}{2}$(A+B)	AB
	9.6	2367	2348	11	1.1	28
	9.6	2055	2289	0.4	1	1

TABLE I EFFECT OF TANK MODIFICATIONS

	3	18051	24479	250	1	1
	8	1827	3106	0.7	1	1
	3	9747	8883	1623	0.44	6.5
	8	17.2	21.0	0.07	0.008	0.1

TABLE II EFFECT OF TANK MODIFICATIONS

	3	18051	24479	250	1	1
	3	16072	12965	644	0.68	2.6

TABLE III EFFECT OF TANK MODIFICATIONS

List of Figure Captions

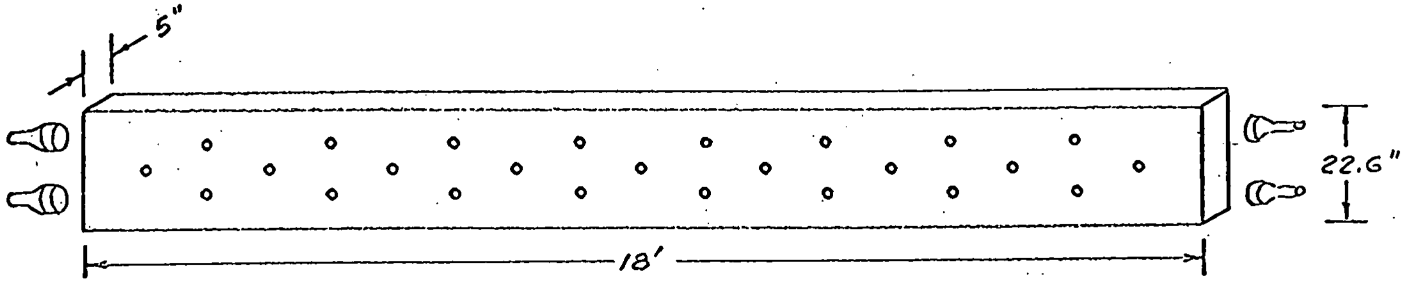


Figure 1: The Detector Tank

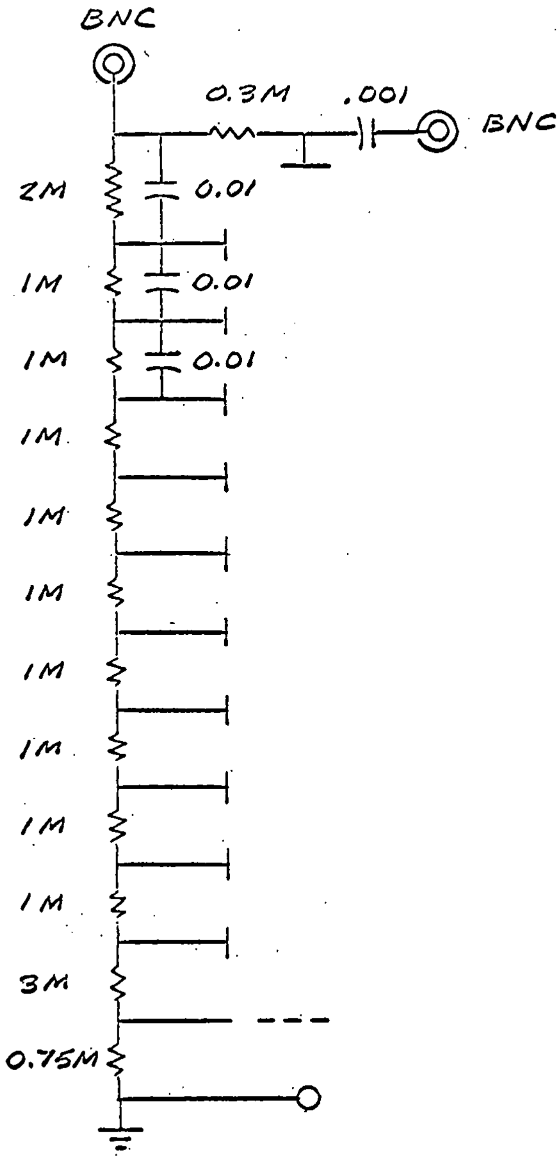


Figure 2: Photomultiplier Tube Circuit

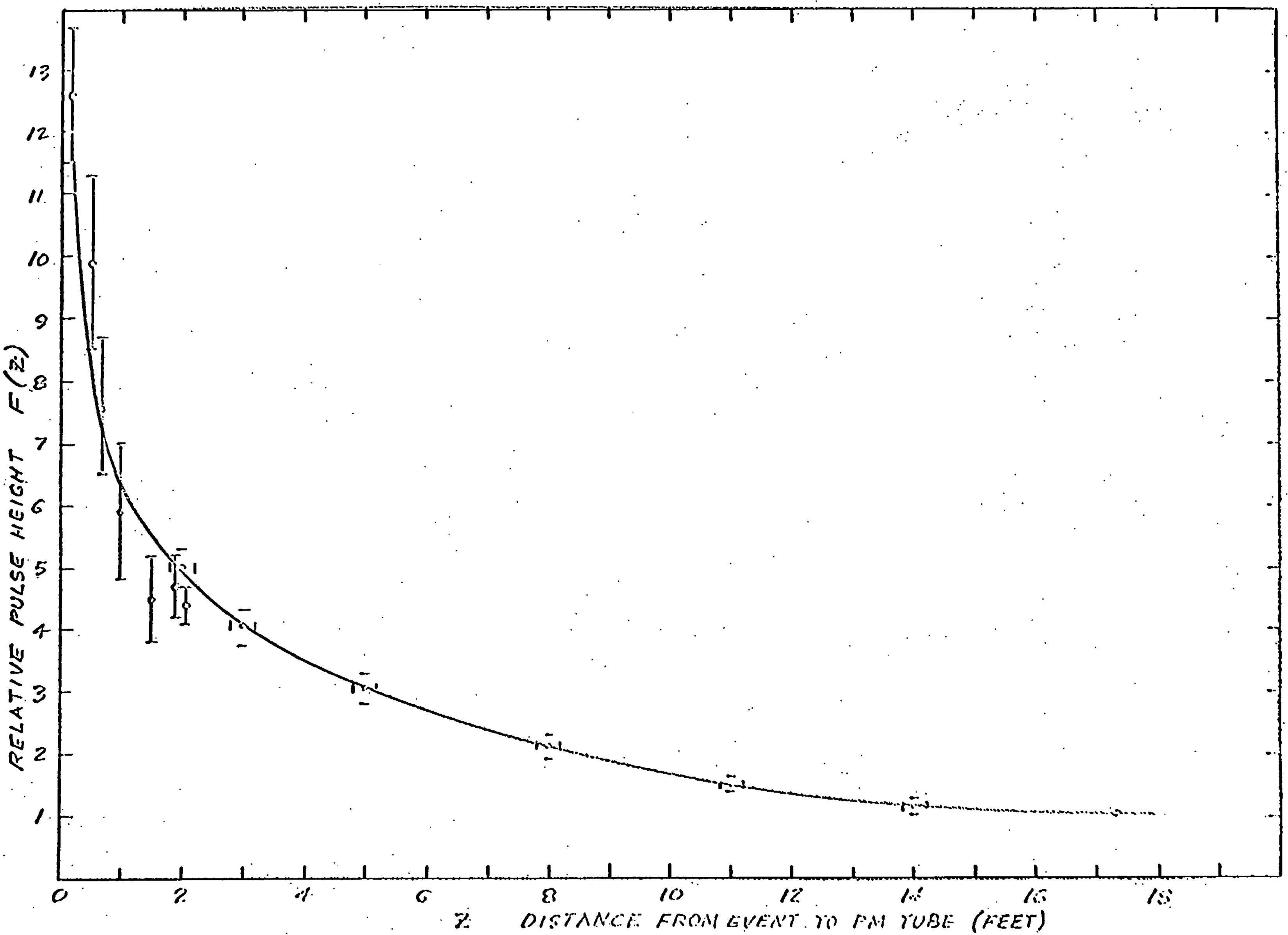


Figure 3: Detector Response Function F(z)

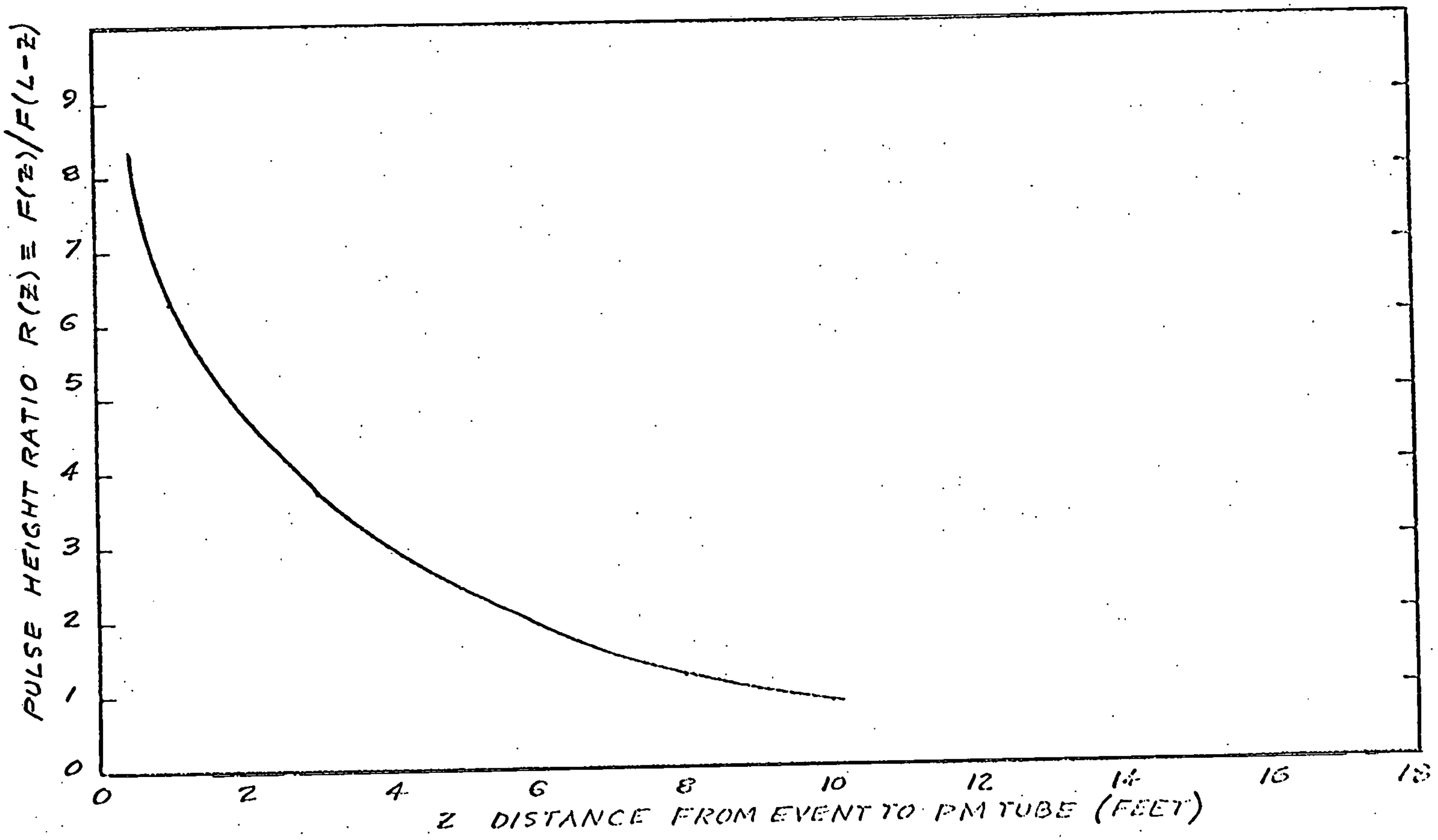
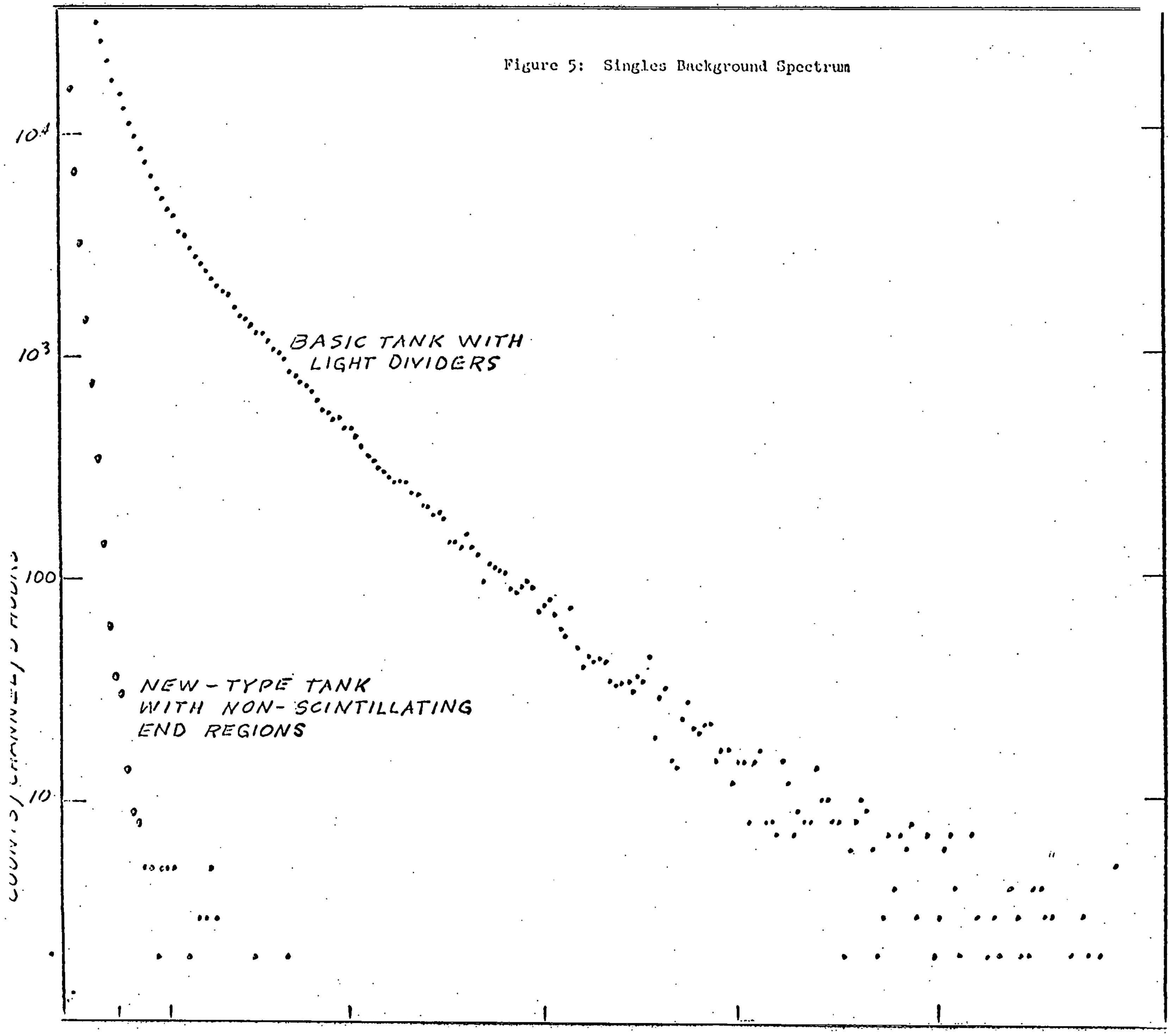


Figure 4: Pulse Height Ratio vs. Event Position

Figure 5: Singles Background Spectrum



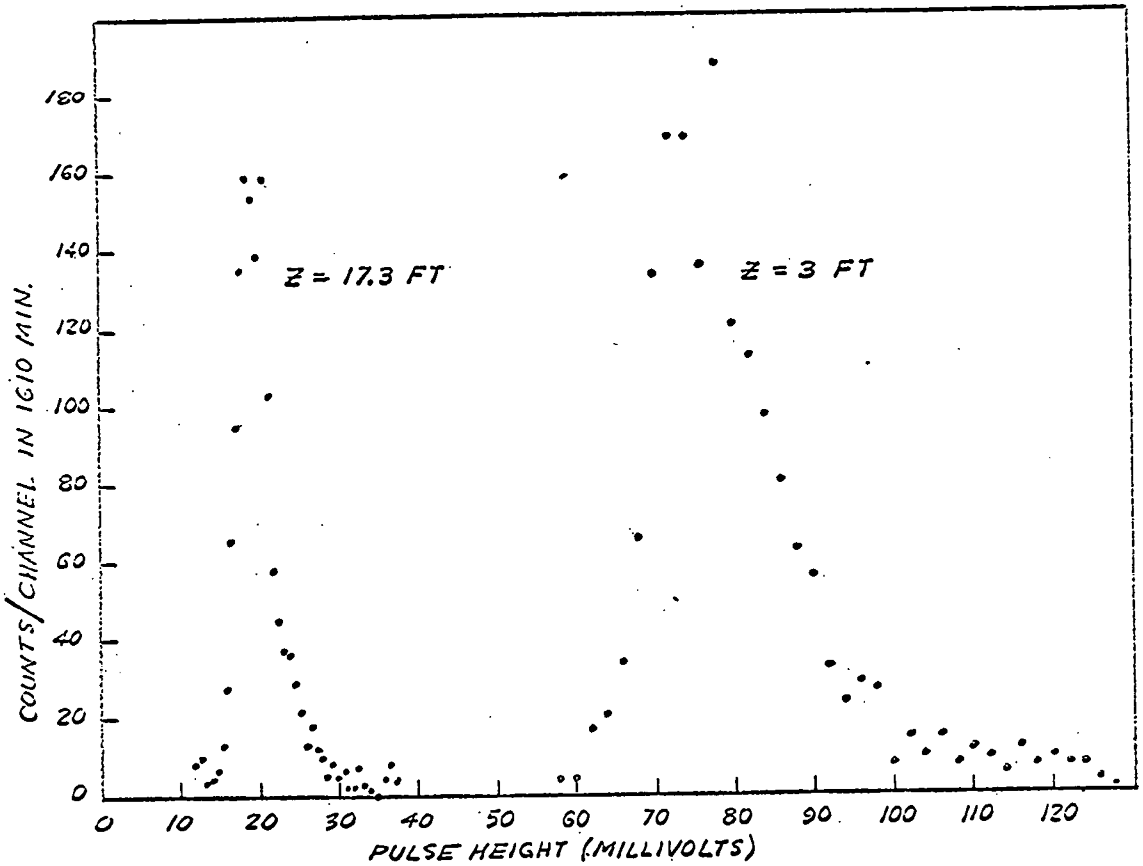


Figure 6: Pulse Height Spectra for Muon Events

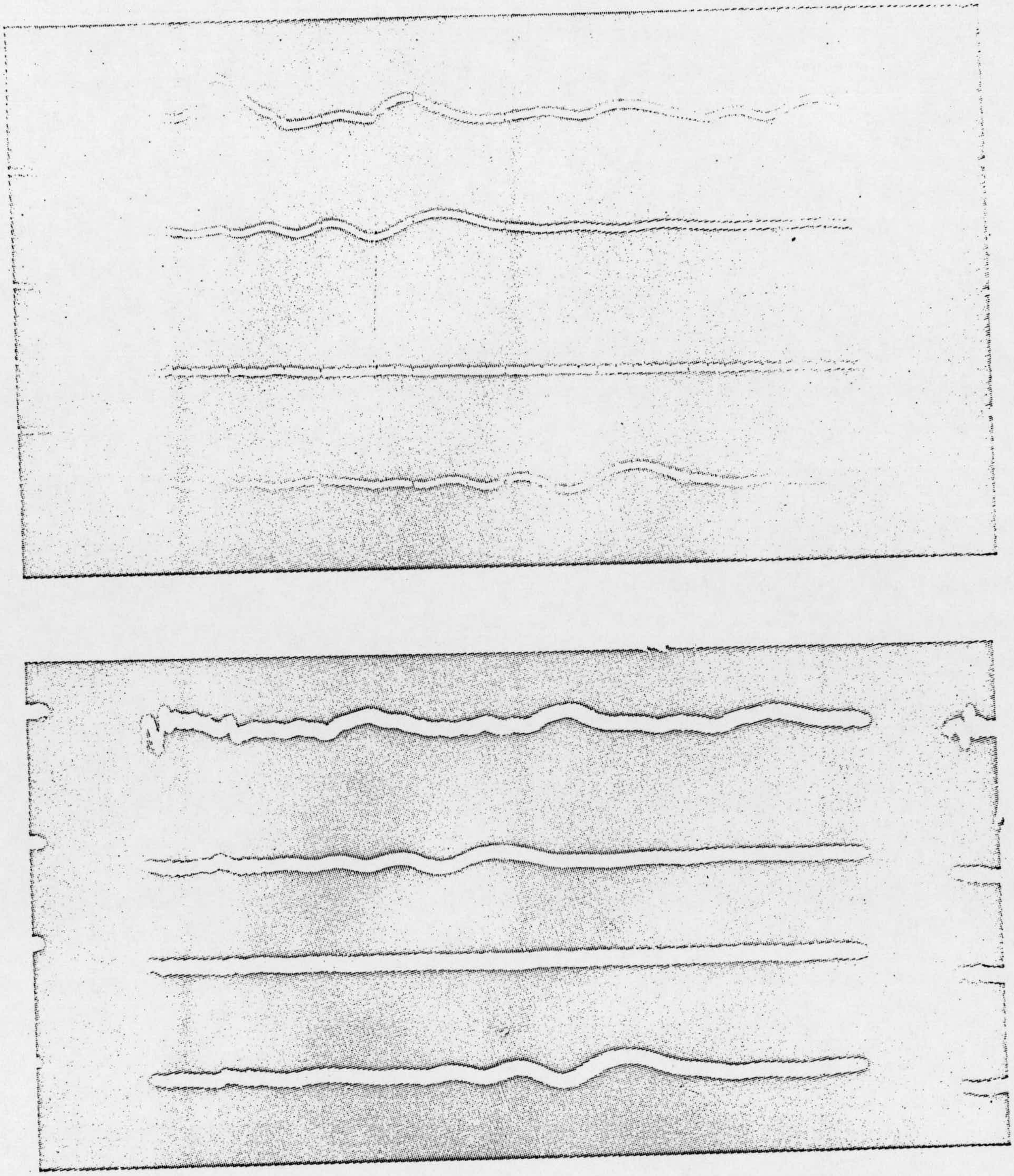


Figure 7: Detector Signal Due to a Relativistic Particle

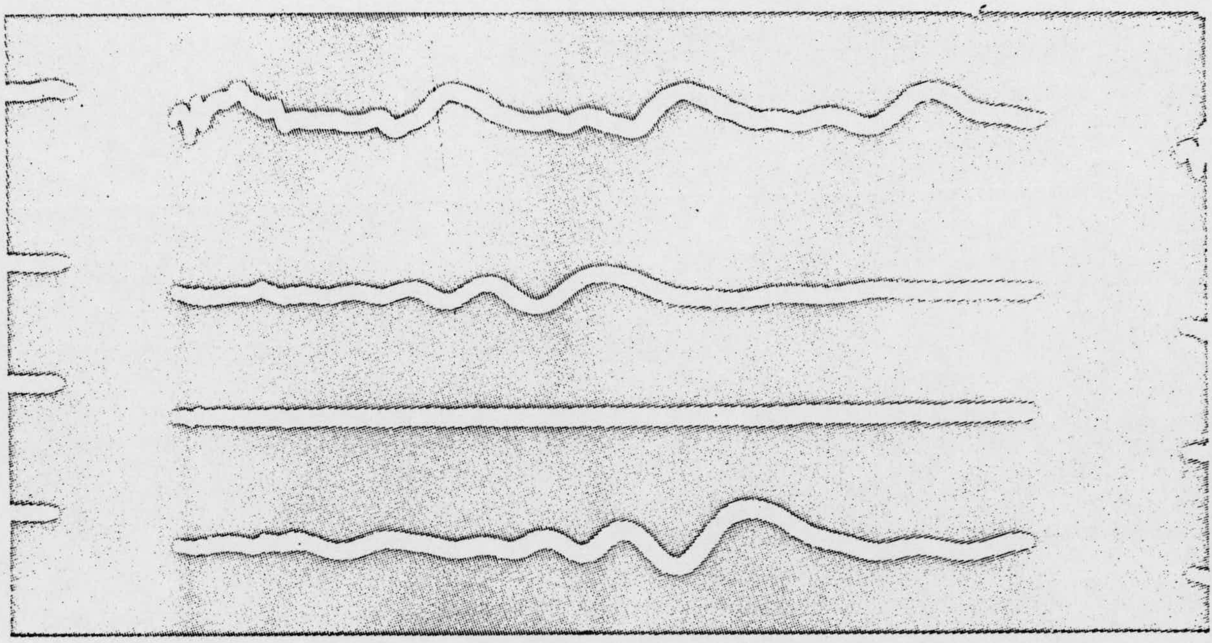


Figure 8: Detector Signal Due to Pulsed Light Source