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DESIGN REPORT ON A "SWIMMING POOL" HADRON CALORIMETER FOR FERMILAB EXPERIMENT 288

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ABSTRACT

Design principles, materials properties, and a preliminary design are presented for a low cost, large aperture hadron calorimeter/muon identifier. The design reported is for a large water tank with light collectors to measure the Cerenkov light produced by the hadronic (and electromagnetic) shower induced by incident hadrons.

I. INTRODUCTION

For several years a group of physicists from Columbia University and Fermilab have been designing and carrying out experiments at Fermilab to study the production of electrons, muons, and hadrons produced with large transverse momentum in hadronic collisions.[1-5]

In order to separate final state muons from hadrons in the large aperture of E70 or E288 it is more effective to detect the hadronic shower than to identify muons by range (penetration) only. A design study for such a detector was carried out and reported previously.[6] Based on that study a steel-scintillator muon identifier was designed and built for Fermilab Experiment #70. Preliminary results based on this as a muon identifier[4,5] have been reported. This device was designed for an aperture of 27 in. × 27 in. The aperture for Experiment #288 is ~30 in. × 66 in. so it was necessary to re-examine the design since two of these larger aperture devices were needed which would be costly with the earlier design.

II. DESIGN CRITERIA

The following items were of concern in designing a muon identifier/ hadron calorimeter:

1. Muon identification should produce hadron events identified as muons less than a few per cent of incident hadrons.

2. Any muon identifier based on hadronic showers will have some energy resolution so we will plan to use it as a hadron calorimeter and do the best we can consistent with other requirements.

3. For either muon or hadron identification the device must handle high rates and for hadrons must supply an energy threshold as a trigger with small biases across the aperture.

4. Keep the cost moderate (low?).

5. The experiment is complicated enough so make this device operationally simple as regards calibration, monitoring, and measurement of rejection.

6. Conserve manpower in design and fabrication by keeping design as simple as possible.

Since there is a very large number of particles in a typical high energy shower and the total energy is deposited in a few interaction lengths of material, the crucial problem for high energy calorimeters is to achieve adequate containment of the shower energy within the calorimeter and still obtain sufficient sampling and adequate collection uniformity in the sampling detectors. By collecting light from a sufficiently transparent medium one can look only at the boundary of the detector medium and measure all the energy, thus avoiding the mechanical and physics limitation of sampling. If in addition one uses the directionality of Cerenkov light one can take advantage of the inherent phase space (small forward cone) of the shower to guarantee that, with the help of mirrors, essentially all the light from a shower will hit one face of the detector. Thus one has reduced the problem of light collection from sampling through a large volume to one of collecting light from one face of that volume. Inherent problems of such a scheme are:

1. One samples only the Cerenkov light so no low energy hadrons or nuclear fragments contribute.

2. One obtains no longitudinal shower development information so it is imperative to contain the shower.

Assuming this to be a viable solution one had a new set of problems:

1. Find a suitable medium.

2. Find suitable reflectors for the sides, top and bottom.

3. Find a suitable light gathering scheme. At the end of the report we shall evaluate the solution we have found and discuss the physics uses of such a device.

III. MATERIALS FOR A CERENKOV DETECTING HADRON CALORIMETER

Cerenkov light is produced with a continuous spectrum which rises to the ultraviolet as $1/\lambda$. A suitable detector material must transmit this through a significant fraction of the shower development length. This length is dependent on both the hadronic absorption length and the electromagnetic radiation length of the materials. Transparent materials were sought with these things in mind.

A. Glass

Ordinary plate glass was considered. It was a good moderate atomic number material for good density and shower development. Sufficient material for the two detectors required for E288 was priced at ~ $15 K (not bad). Light transmission is not great and would require considerable effort at light collection.

B. NaCl

Ordinary salt is cheap and highly transparent in the ultraviolet. Large crystals are prohibitively expensive; water solutions are not dense enough to help much. It might be possible to submerge small crystals in an oil of the same refractive index. It is doubtful that the available crystals are clear enough for the resulting mixture to be highly transparent.

C. Solutions of Chemicals in Water

Few solutions are much denser than water. The only one found which looked promising at all outside of the rather dangerous and unpleasant lead solutions (consult Nuclear Enterprises Catalogue) is ordinary borax.

D. Water

Since the density of water is low it was originally believed that it would be unsuitable for a detector medium. The realization that it had a very low absorption for ultraviolet light caused a re-evaluation of the situation. An additional immediate advantage of water is the advanced state of technology for making water very pure. Important design properties for water are:

Absorption Length[7]	78.8 cm = 31.02 in.
Radiation Length[7]	36.4 cm = 14.3 in.
$\lvert dE/dx \rvert$ min.[7]	2.03 MeV/cm
Index of Refraction	1.33
Attenuation Length of Light[8]	3000 Å 1.56 m; 4000 Å 12.5 m

Since the path length of the photons is n times the path length of the producing particle ($\cos \theta \approx 1/n$) we see that a 6 interaction length calorimeter will be ~15 ft (4.62 m) long and the light produced at the front wall will travel ~6 m which is only 1 or 2 light absorption lengths in pure water.

IV. MIRRORS FOR A WATER CERENKOV COUNTER

As was previously stated, for a transparent rectangular medium of index n sitting in air (refractive index = 1) the Cerenkov light produced by a particle with velocity $\beta \approx 1$ which enters the box perpendicular to one face will all strike the opposite face. Proof: Consider the ray in the plane of the drawing.

$$\cos \theta_c = 1/n$$

$$\cos \theta_c = \sin \theta_{in}.$$

But since n = 1 outside we know that

$$\sin \theta_{in} = 1/n$$

which is exactly the relation for <u>total</u> internal reflection.

However, for angles of light production on other parts of the cone the angle of incidence can only be bigger than the angle of total internal reflection.

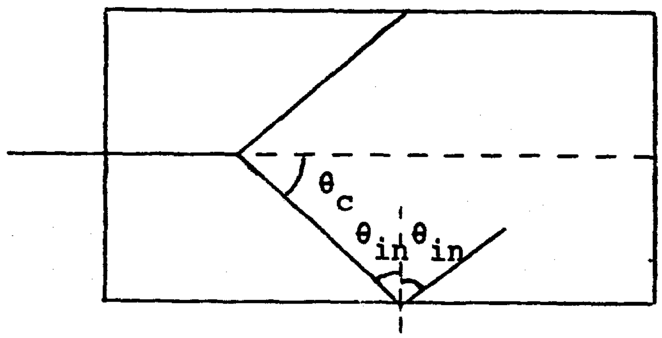


Fig. 1

For particles nearly parallel to the given one on one side (only) a portion of the cone will be incident on the side at angles less than that for total reflection. But they will be a small part of the produced light, will be partially reflected, and the escaping light can be reflected by an external mirror anyway.

Surrounding one transparent medium with another will not change these considerations at the surface at all provided the "outer" surface has air or vacuum outside. This is because by Snell's Law $n_1 \sin\theta_1 = n_2 \sin\theta_2$, and we will have still

$$n_1 \sin\theta_1 \geq 1.$$

So consider the following "mirrors" for defining the desired rectangular volume for a water Cerenkov counter. Basic mirror: two sheets of 1/8 in. acrylic sheet with an air gap sealed between [see Fig. 2(a)]. An improved version might have aluminum foil for a specular reflector and/or an aluminum screen or glue beads to guarantee an air interface at the surface of the lucite sheet. "Mirrors" of this design could be fabricated with large areas and with modest cost. They would allow the Cerenkov light produced in the water to strike the end of the tank. It can generally be assumed that total

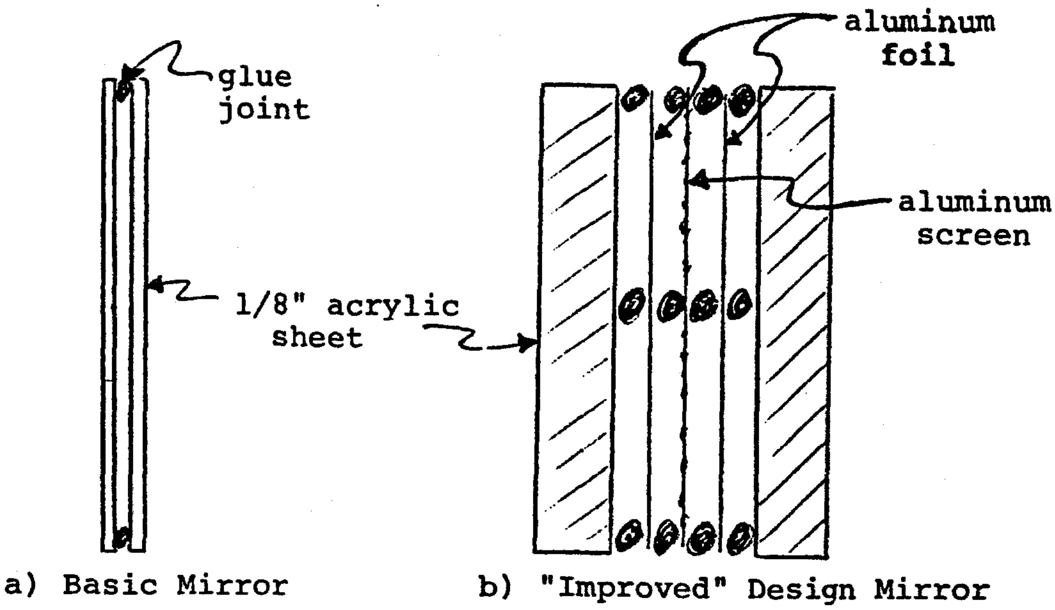


Fig. 2

internal reflection provides the best possible reflecting surface.

V. COLLECTION OF THE CERENKOV LIGHT

The basic fact in considering a photon gathering scheme is to realize that there are hundreds of photons produced for each centimeter of particle path in the shower (or for a muon straight through) so we will have a large number of photons from the shower. This allows us to make considerable compromises on the number of photons collected in order to have uniformity of light collection over the surface and simplicity of design.

A possible design is to consider covering a fraction of the end surface with phototubes. Since there is lots of light and since it is fairly uniformly distributed on the detector end one probably needs to consider only a small fraction of the area. Suppose the area of the end is 7 ft × 7 ft = 49 ft^2 or 7055 $in.^2$ For example 30 2-in. tubes uniformly spaced over the end will cover about 1% of the area while 20 5-in. tubes will cover about 5.5%.

Either of these would probably be a sufficient solution.

I will principally consider the following solution, however, since it is less expensive and more elegant. Since Cerenkov light is predominantly a short wavelength phenomena, it is possible to obtain wavelength shifter materials which will absorb this light and re-emit (isotropically) longer wavelength light. For example, a commercially available material (Pilot 425 - Nuclear Enterprises Inc.[9]) has (predominantly) Bis-MSB dissolved in acrylic to produce 1/4 in. thick sheets of material with index of refraction of about 1.48 and the ability to absorb 90% or so of the incident light in the absorption band. If this material is immersed in water there will be a considerable light pipe effect due to the fact that the refractive index for water is 1.33. This means that light parallel to the face within 26° will be transmitted in the acrylic. Thus a standard light guide placed at the end of the acrylic sheet will collect a substantial fraction of all the re-emitted photons. The proposed scheme is then to place a sheet of Pilot 425 at the end of the water box perpendicular to the incident particles and allow it to collect the Cerenkov light produced in the water. A fraction of the re-emitted photons will be light piped through the acrylic and collected by a good twisted light pipe. This will be viewed by a suitable phototube.

Having established a working hypothesis for the design materials I will proceed to establish the design details to the extent that they are determined by physics.

VI. CALCULATION OF THE SIGNAL FROM INCIDENT PARTICLES

In order to calculate the signal observed in the Swimming Pool Hadron Calorimeter we perform a three step calculation in the following fashion. First, we calculate the production, transmission, and absorption of the Cerenkov light produced by the hadronic shower and absorbed in the Pilot 425 detector material. Then the relative efficiency of the re-emission, collection, and detection of the absorbed photons is considered. Finally, a model for hadronic shower development is considered and calculations of light production made for various detector lengths.

To carry out the first step we will calculate a curve giving the number of absorbed photons per particle-centimeter as a function of the distance from the detector material. We begin with the formula for production of Cerenkov light in a medium of refractive index n (assumed independent of wavelength).

$$N(\lambda_1, \lambda_2) = 2\pi\alpha \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\left(1 - \frac{1}{n^2\beta^2}\right),$$

where $N(\lambda_1, \lambda_2)$ is the number of photons emitted between wavelengths λ_1 and λ_2 by a particle of velocity β in a medium of refractive index n. For now I leave $[1 - (1/n^2\beta^2)]$ as a separate constant and calculate

$$N = 2\pi\alpha \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

for 100 Å intervals from 2800 Å to 4000 Å. Column 3 of Table I shows this calculation. I next weight this spectrum by the absorption properties of the detector. I obtain a <u>relative</u> absorption curve for Bis-MSB from the book by

Berleman.[10] The data are (crudely) averaged over 100 Å bands and the peak absorption normalized to 1. This relative absorption ζ is shown in Column 4 of Table I. In column 5, I multiply Column 3 by Column 4 to obtain ζN as a function of wavelength.

Table I. Production of Cerenkov Radiation and Its Absorption By Bis-MSB.

λ (Å)	$\frac{1}{\lambda}$ (cm^{-1})	N (photons)	ζ	ζN (photons)
4000	2.5×10^4			
		29.4	.07	2.1
3900	2.564			
		31.2	.24	7.5
3800	2.632			
		32.6	.47	15.3
3700	2.703			
		34.4	.75	25.8
3600	2.778			
		36.2	.94	34.2
3500	2.857			
		38.5	1.00	38.5
3400	2.941			
		40.8	.88	35.9
3300	3.030			
		43.6	.67	29.2
3200	3.125			
		46.3	.50	23.2
3100	3.226			
		49.1	.35	17.2
3000	3.333			
		52.7	.22	11.6
2900	3.448			
		56.4	.12	6.8
2800	3.571			
TOTAL		491.2		247.3

$$N = 2\pi\alpha \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

ζ is relative absorption efficiency of Bis-MSB

The next problem is to obtain an estimate of the absorption of light in water. This is complicated by the uncertainty in the data and by the unknown quality of the water which we will obtain ultimately in our detector. The commonly measured quantity is the attenuation which is a sum of the absorption and scattering losses. The scattering in pure water is essentially isotropic (and calculable and small). However, scattering from impurities (which will probably dominate the scattering in our water sample) is peaked forward and may not correspond to light lost to our detector. However, for this calculation we will use measurements of attenuation on "pure" water as recommended by an oceanography expert[11] as representative of the best measurements.[8] In Table II we see these attenuation values and their inverse--the attenuation length as well as the attenuation coefficients for 1 through 5 meters of light path through water.

By now applying these attenuation coefficients to the absorption spectrum of Column 5 of Table I we obtain the spectrum of absorbed photons at various depths in the counter as shown in Table III. By summing the spectra we obtain the number of absorbed photons at various path lengths from the production point to the detector. These spectra are shown in Fig. 3. Note also in Table III the calculation of the effective absorption length of the detected photons. We see that as the short wavelengths are absorbed out, the attenuation length grows from 3.2 m to 4.2 m. At this point we also multiply by the hitherto neglected factor $\sin^2\theta_c = [1 - (n\beta)^{-2}]$ where we take $n = 1.33$, $\beta = 1$ giving $\sin^2\theta_c = 0.435$. This should give us actual numbers of absorbed photons per particle-cm.

TABLE II

ABSORPTION OF LIGHT IN H_2O

Data of: L. H. Dawson and E. O. Hulburt
"The Absorption of Ultraviolet
and Visible Light by Water"
J. Op. Soc. Am. 24, 175 (1934).

Table values interpolated from values at:

4000, 3600, 3200, 2800, 2400 Å

$i = i_o e^{-\gamma X}$ or $i = i_o e^{-X/L_o}$ and Att. Coef. $= e^{-x/L_o}$

			Attenuation Coefficient				
λ	γ (cm^{-1})	L_o (m)	1m	2m	3m	4m	5m
3950	$.85 \times 10^{-3}$	11.76	.918	.844	.775	.712	.654
3850	1.1	9.09	.896	.803	.719	.644	.577
3750	1.3	7.69	.878	.771	.677	.594	.522
3650	1.65	6.06	.848	.719	.610	.517	.438
3550	2.1	4.76	.811	.657	.533	.432	.350
3450	2.7	3.70	.763	.583	.445	.340	.259
3350	3.35	2.99	.715	.512	.366	.262	.187
3250	4.0	2.50	.670	.449	.301	.202	.135
3150	4.7	2.13	.625	.391	.244	.153	.095
3050	5.4	1.85	.583	.340	.198	.115	.067
2950	6.3	1.59	.533	.284	.151	.080	.043
2850	7.2	1.39	.487	.237	.115	.056	.027

TABLE III

SPECTRUM OF PHOTONS FROM A CERENKOV SOURCE

DETECTED AFTER VARIOUS DEPTHS OF H_2O

λ_1 (Å)	λ_2 (Å)	NUMBER OF PHOTONS 0m (Source)	1m	2m	3m	4m	5m
3900	4000	2.1	1.9	1.8	1.6	1.5	1.4
3800	3900	7.5	6.7	6.0	5.4	4.8	4.3
3700	3800	15.3	13.4	11.8	10.4	9.1	8.0
3600	3700	25.8	21.9	18.6	15.7	13.3	11.3
3500	3600	34.2	27.7	22.5	18.2	14.8	12.0
3400	3500	38.5	29.4	22.4	17.1	13.1	10.0
3300	3400	35.9	25.7	18.4	13.1	9.1	6.7
3200	3300	29.2	19.6	13.1	8.8	5.9	3.9
3100	3200	23.2	14.5	9.1	5.7	3.5	2.2
3000	3100	17.2	10.0	5.8	3.4	2.0	1.2
2900	3000	11.6	6.2	3.3	1.8	0.9	0.5
2800	2900	6.8	3.3	1.6	0.8	0.4	0.2
TOTAL		247.3	180.3	134.4	102.0	78.4	61.7
ratio to previous value			.729	.745	.759	.769	.787
effective att. length			3.17m	3.40	3.63	3.80	4.18
absorbed photons (multiply total by $\sin^2\theta_c$)		107.6	78.4	58.5	44.4	34.1	26.8

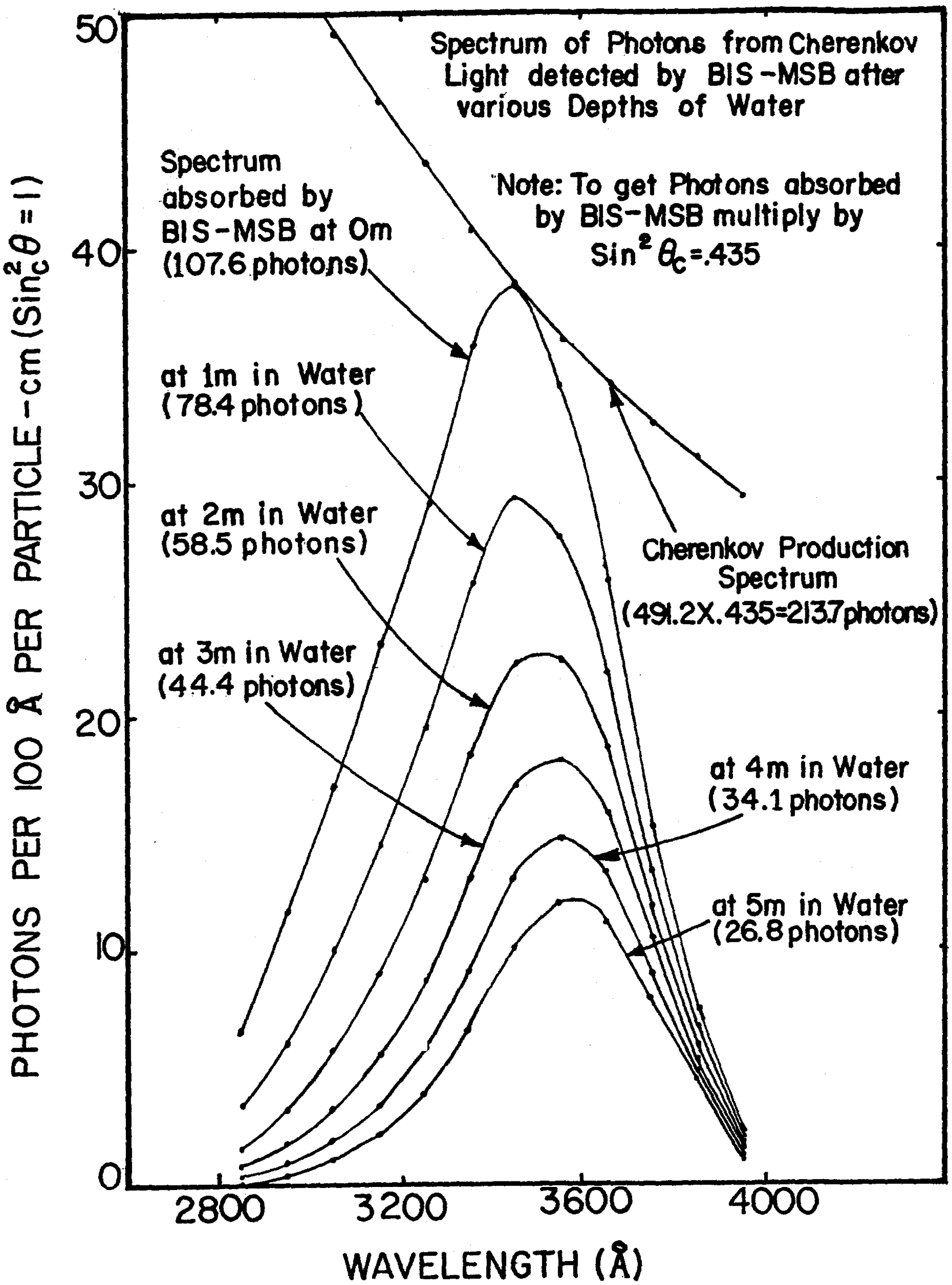

Spectrum of Photons from Cherenkov Light detected by BIS-MSB after various Depths of Water
Note: To get Photons absorbed by BIS-MSB multiply by Sin² θc=.435
Spectrum absorbed by BIS-MSB at 0m (107.6 photons)
at 1m in Water (78.4 photons)
at 2m in Water (58.5 photons)
at 3m in Water (44.4 photons)
at 4m in Water (34.1 photons)
at 5m in Water (26.8 photons)
Cherenkov Production Spectrum (491.2X.435=213.7photons)
PHOTONS PER 100 Å PER PARTICLE-cm (Sin²c θ = 1)
WAVELENGTH (Å)
0
10
20
30
40
50
2800
3200
3600
4000

Fig. 3

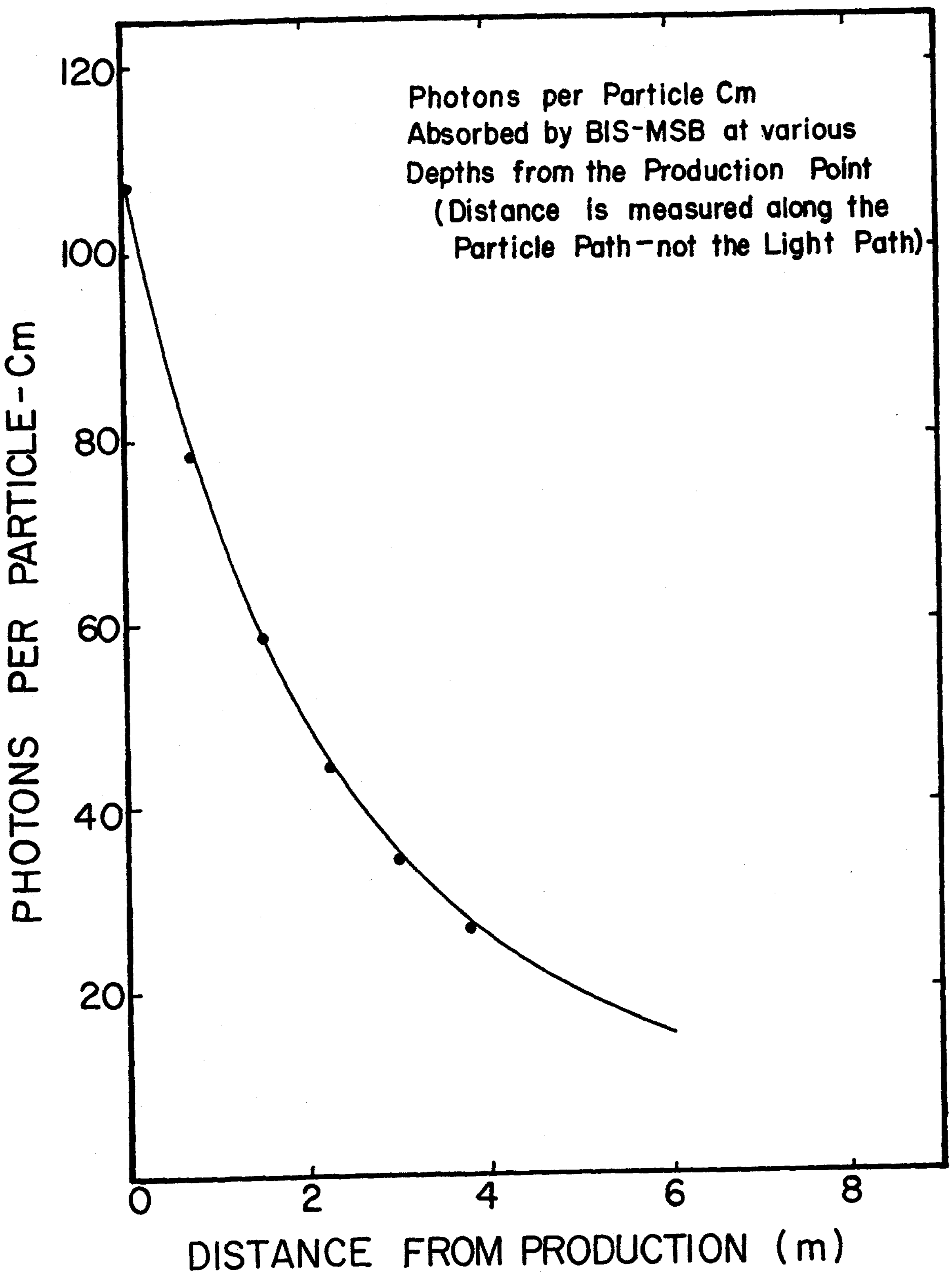

Photons per Particle Cm
Absorbed by BIS-MSB at various
Depths from the Production Point
(Distance is measured along the
Particle Path-not the Light Path)
PHOTONS PER PARTICLE - Cm
120
100
80
60
40
20
0
2
4
6
8
DISTANCE FROM PRODUCTION (m)

Fig. 4

The line labeled "Absorbed Photons" contains the result of this step in the calculation--the number of photons/particle-cm of path absorbed by the wavelength shifter material after transmission through n meters of light path. This result is plotted in Fig. 4 but after a change in abscissa--we plot not versus the light path but versus the distance along the incident particle direction by dividing by $n = (\cos\theta)^{-1}$. From this curve we will obtain the needed conversion from particle density in the shower to light absorbed in the detector.

We must now consider how the light is collected from the wavelength shifter. For this purpose we will use the properties expected for the E288 detector. Here the wavelength shifter will be in the form of sheets of Pilot 425 12-in. wide, 90-in. long, and 1/4-in. thick. It will be viewed from one end by a photomultiplier through an adiabatic light pipe. The detector material is far enough from the peak of the shower that we can consider it to be uniformly illuminated.

In Table IV we find the various efficiency factors listed. The previous calculation used a normalized absorption curve. The actual absorption is determined by the thickness of the lucite sheet and the concentration of wavelength shifter material. The manufacturer quotes a >90% absorption of incident light at the peak so we use that figure.[12] (Note that this method of calculation is not very accurate. A more careful technique would involve calculating exponential absorption using the relative absorption lengths in the detector.) On pure faith we use a 100% re-emission efficiency. The attenuation length for the emitted light is ~1 m so for a 7-ft long detector

Table IV. Conversion Efficiency for Detecting Light Absorbed In the Wavelength Shifter.

Absorption Efficiency of Wavelength Shifter		0.9
Re-emission Efficiency		1.0
Transmission of Emitted Light		0.35
Capture of Emitted Light by Internal Reflection		0.05
Light Pipe Efficiency		0.75
Photocathode Efficiency		0.2
	Product	2.36×10^{-3}

uniformly illuminated the average light sees one attenuation length loss of 0.35. The only light actually observed is that which is totally internally reflected. The angle of total internal reflection is

$$\sin\theta = n_1/n_2 = 1.33/1.48 = 0.899$$

$$\theta = 63.98^\circ \quad 90^\circ - \theta = 26.02^\circ.$$

The light captured by the detector is that which falls in a 26° cone and is the fraction of light captured in that solid angle.

$$\frac{\Omega}{4\pi} = \frac{1}{2}(1 - \cos 26^\circ) = 0.05.$$

Since the detector is 1/4-in. thick and the light pipe only 3/16 in. thick the maximum efficiency of the light piping is 0.75. We will assume that we approach this. We will plan to use phototubes with quantum efficiencies of ~20% or better. We see that this gives us an overall conversion factor of 2.4×10^{-3} photoelectrons per absorbed photon.

One other step in the detection process needs to be considered. The mirrors are essential for the detector. If the water volume is left undivided (by angle) then we will still need one or two reflections from the mirrors. We assume that the entire loss is from absorption in the acrylic.

We take transmittance data from manufacturers' data sheets as shown in Table V.[13] We remove the reflection effects, since they only help us, then

TABLE V

TRANSMITTANCE OF UVT ACRYLIC SHEET

Wavelength	Transmittance T	T/.92 T'	$T'^2 \times 1.5$ T"
2750	.25	.272	.020
2850	.42	.457	.095
2950	.64	.696	.337
3050	.77	.837	.586
3150	.86	.934	.817
3250	.90	.978	.936
3350	.92	1	1
3450	.92	1	1
3550	.92	1	1
3650	.92	1	1

PHOTONS PER PARTICLE CM. ABSORBED

	0 Reflection	1 Reflection	2 Reflections
1m	78.4	71.8 (.916)	68.6 (.875)
2m	58.5	54.8 (.937)	52.9 (.904)
3m	44.4	42.3 (.952)	41.1 (.925)
4m	34.1	32.9 (.964)	32.2 (.944)
5m	26.8	26.1 (.974)	25.7 (.958)

assume two passes through the 1/8-in. thickness with an angle near θ_c in lucite so the path will be 1.5 longer and the transmission will be ~$T!^3$. Applying these loss factors to the data of Table III we obtain losses at each wavelength. By resumming the totals we see that the net loss is always < 10% for one reflection. Since most of the light we detect passes through at least 3 m of water the reflection losses are of order 5% and can be neglected to the accuracy we can hope to carry out the present calculation.

At this point we need some model of a hadron shower from which to calculate the particle density of $\beta = 1$ particles at each depth. For this I will take data by Benvenuti et al. from the HPWF neutrino detector of Fermilab Experiment #1A.[14] Since the shower development depends on both the hadronic absorption length and the radiation length it is easiest and most accurate to use data from a material which has a similar ratio of absorption length per radiation length. Let us compare liquid scintillator and water

	Absorption Length L_{ab}		Radiation Length l_R		Ratio
material	cm	ft	cm	ft	l_{ab}/l_R
liquid scintillator	84	2.76	53	1.74	1.58
water	78.8	2.59	36.4	1.19	2.16

Since other data come from iron detectors where the ratio is near 10, these data are by far the most suitable.

The calculation will be done for convenience by taking one foot thicknesses of absorber. We use the data of Benvenuti et al., Fig. 11. We use the smooth curve for 35 GeV incident hadrons and scale the data by the relative absorption lengths of scintillator and water. We slightly extrapolate the calculated light production curve and obtain light production values for each one foot interval from the absorber plane. Using the density of particles produced in the shower and assuming they are dominated by $\beta = 1$ particles we obtain the number of particle-cm of light production path at each depth. The numbers used are shown in Table VI. Then we can simply sum the absorbed photon contributions for any chosen depth of counter and apply the previously obtained detector ratio of 2.36×10^{-3} to give photoelectrons detected at the photocathode.

By applying this procedure to various depths of counter from 7 to 18 feet in length we obtain light production curves shown in Fig. 5 and recorded in Table VII. We calculate the relative containment by following the shower to 21 ft at which point we have only 2.4 particles mean density (versus 6 particles at 18 ft), calculating the total number of particle-cm of light production and comparing that to the fraction contained in the counter length. These results are also given in Table VII. By multiplying the total particle-cm (16599.7) by the photons absorbed when there is no attenuation (107.5 photons/particle-cm) and multiplying by the conversion to photoelectrons we find that a totally contained shower would produce 4211 photons. We can now also calculate average attenuation in the water by multiplying 4211 by the containment factor and dividing by the detected photoelectrons.

The next observation we should make concerning these calculations is the non-uniformity of response due to the shower development. If, the shower begins in the first foot of the counter we will get the response shown.

TABLE VI

SHOWER DEVELOPMENT AND LIGHT PRODUCTION

35 GeV HADRON IN WATER

Distance from detector (Col. 2) or from point of incidence (Col. 3, 4) in feet	Photons per particle-cm.	Particles	Particle-cm per foot
0	107.5	1	30.5
1	94.5	7	213.4
2	83.0	20	609.6
3	74.0	38	1158.2
4	65.5	47	1432.6
5	58.5	50	1524.0
6	52.0	53	1615.4
7	46.0	52	1585.0
8	41.5	47	1432.6
9	37.5	43	1310.6
10	34.0	38	1158.2
11	30.5	33	1005.8
12	27.5	28	853.4
13	25.5	21	640.1
14	23.5	17	518.2
15	22.0	14	426.7
16	21.0	11	335.3
17	20.0	8.5	259.1
18	19.0	6	182.9

Table VII. Shower Containment and Light Production.

Counter Length	Absorbed Photons	Detected Photo-electrons	Energy Contain-ment	Attenua-tion	Uniformity Ratio
7 ft	679.6k	1610	.492	.777	
8	755.0k	1789	.578	.735	
9	809.3k	1910	.657	.690	1.19
10	841.6k	1995	.727	.652	1.12
11	854.9k	2026	.788	.611	1.06
12	851.5k	2010	.839	.569	1.01
13	826.6k	1959	.878	.530	.97
14	792.5k	1878	.909	.491	.93
15	753.8k	1779	.935	.452	.91
16	710.9k	1685	.955	.419	.90
17	678.6k	1608	.970	.390	.90
18	619.9k	1469	.981	.356	.87

If it begins later we can get the response by considering an appropriately shorter counter (the light from the incident particle is negligible). We will then show this non-uniformity by comparing light from a given shower with that from a shower which begins 2 ft (0.77 int. lengths) later. This ratio [light (L)/light (L-2)] is given in Column 6 of Table VII. The resolution loss due to this non-uniformity is to be balanced against that due to leakage fluctuations.

We shall also want to get a definite muon signal from these counters for use both in positive muon identification for muon experiments and as a

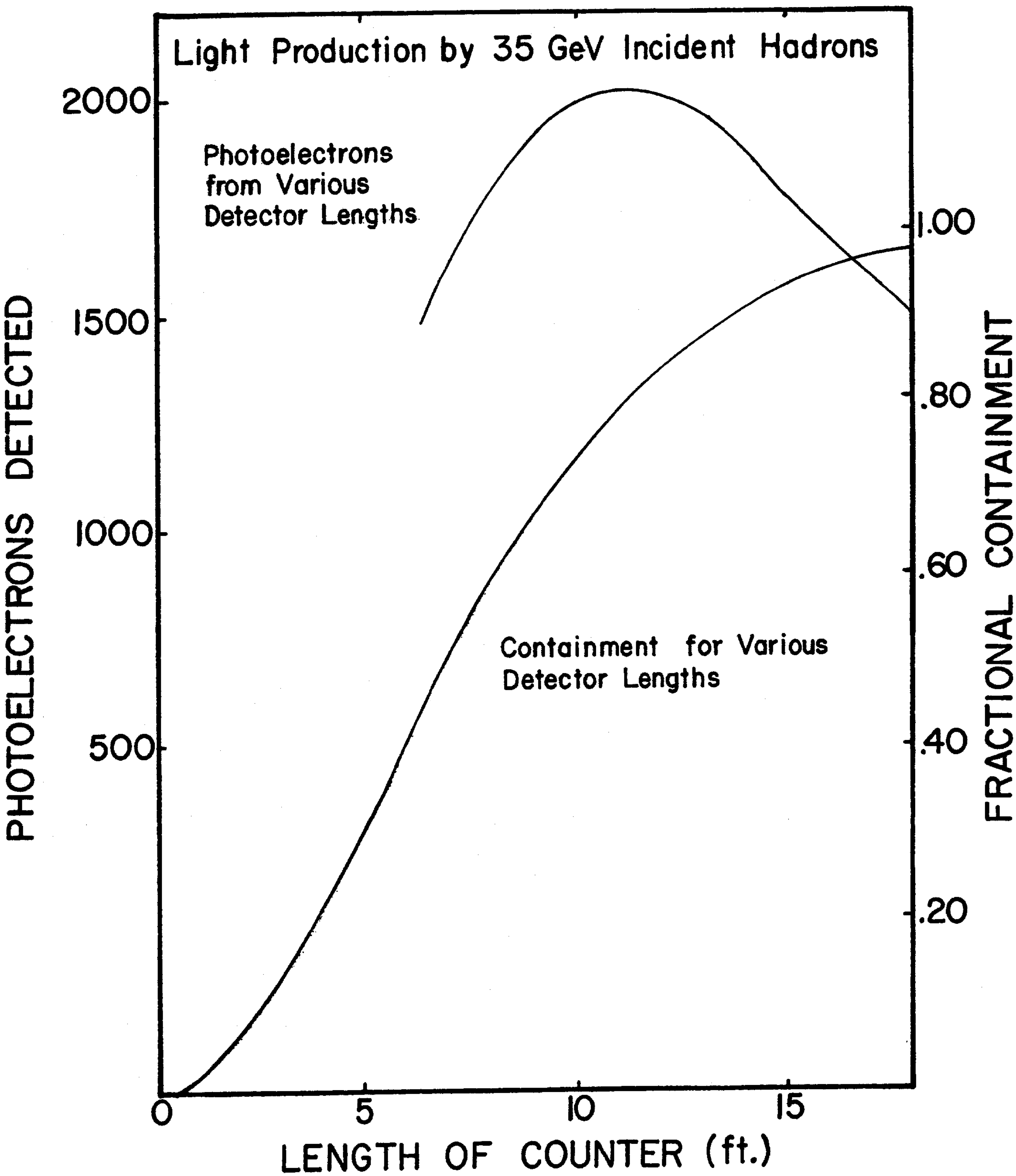

Light Production by 35 GeV Incident Hadrons
Photoelectrons from Various Detector Lengths
Containment for Various Detector Lengths
PHOTOELECTRONS DETECTED
2000
1500
1000
500
FRACTIONAL CONTAINMENT
1.00
.80
.60
.40
.20
0
5
10
15
LENGTH OF COUNTER (ft.)

Fig. 5

calibration and gain monitor for the hadron experiments. With the data in Column 2 of Table VI it is trivial to calculate the response of the system to a through-going muon. We find that a 10-ft counter gives 50 photoelectrons while an 18 ft counter gives 63.6 photoelectrons. By comparing to the results for a 35 GeV hadron and assuming that the counter responds linearly to hadron energy we find that the muon equivalent energy will be 0.877 GeV for the 10-ft counter and 1.5 GeV for the 18-ft counter (actual muon energy loss at minimum dE/dX is 0.63 GeV and 1.09 GeV respectively).

VII. CONTAINMENT CRITERIA AND APERTURE CONSIDERATIONS

In order to design a calorimeter for a given application one must consider the physical dimensions allowed by other constraints and the aperture and resolution demands of the experiment. In order to understand this one must then know what energy loss and what corresponding resolution loss are implied for various containment radii and depths. For longitudinal containment there are several sources of data including that already used.[14] A current discussion of these matters is available in the review article by Sciulli.[15]

Let us first examine the discussion on longitudinal containment. We see that the containment curves for steel and liquid scintillator scale with respect to each other but the scaling factor is not the ratio of absorption lengths (about 5) but is nearer to the ratio of densities (about 9). We also note the calculated effect of longitudinal losses on containment. We see that for a 90% containment at 35 GeV we can expect about 30% worse resolution than for full containment. A containment of 95% will result in only about 10% worse resolution. We can then determine the depth of water needed to avoid degradation of the resolution. Fortunately we have the data on shower development in liquid scintillator to suggest the longitudinal containment we will obtain.

A more pressing problem with the present data is to anticipate the effects of the finite transverse size of the detector on the energy loss and the resolution loss in the present calorimeter design. Some data and some calculations exist for transverse development in the steel-scintillator type calorimeters.[15-18] Sciulli discusses his calculations of the containment and resolution effects. His results are in rough agreement with the newer, high energy data of Hilscher et al. and Selove et al., but the data of Hughes et al. shows a somewhat larger development radius. [Care must be exercised to distinguish radial cuts on the data from transverse (x direction) cuts.] Again the question of how to scale the results from steel to water presents a problem. Let us be optimistic and assume scaling by the absorption length. To use the steel-scintillator results of Selove we will use an effective absorption radius in the spirit of the discussion of Sciulli (p. 83) and will assign an effective absorption length of 10 in. to the configuration of Selove et al. We see in his Fig. 14 that a particle entering 4.5 in. from an edge will be 90% contained and one entering 6 inches away will be 95% contained. Scaling these results to water using the absorption length would give 90% and 95% containment at 13 inches and 18 inches respectively. An interesting prediction of the calculation of Sciulli is the smaller effect of radial losses on the resolution when compared with the resolution effects of longitudinal losses.

VIII. CURRENT STATUS AND PHYSICS OPPORTUNITIES

The essential physics for the design of a Swimming Pool calorimeter has been presented in the previous sections. We will leave to appendices current thoughts on phototube requirements, mechanical requirements on the tank and a summary of tests conducted until now. Work on the calorimeter is proceeding with mechanical design near completion and many materials in hand (November 1975). The phototube and mechanical specifications shown in Appendix 1, 2 are those given to the engineers--not the results of the engineering. The tests reported in Appendix 3 were very encouraging and our current plans call for building calorimeters with water volumes (8 ft $\times$ 8 ft) $\times$ 10.5 ft and (8 ft $\times$ 9 ft) $\times$ 18 ft. These calorimeters will be used with spectrometers which accept particles from 50-95 mrad (lab angle) and 25-175 GeV in one setting of the magnet. We plan to use an aperture of about 36 in. $\times$ 66 in.

The physics available with these is exciting. I will describe a few opportunities:

1. μ-pair production. The counter allows good hadron rejection so the attenuation of the hadron beam need only be sufficient to reduce the decay muon contribution to well below the level for target-produced muons.

2. μ-hadron or μ-e production. We can clearly select muons and can select hadron energy at the trigger level.

3. Hadron-hadron production. We can look at massive pairs of hadrons. By allowing an energy trigger to select useful events we should be able to study the cross section over many decades of production cross

section. By having a good energy measurement we can reject many backgrounds which our simple magnetic analysis might let through.

APPENDIX A. PHOTOMULTIPLIER TUBE REQUIREMENTS FOR THE SWIMMING POOL HADRON CALORIMETER

In order to obtain the resolution and rate capabilities inherent in the Swimming Pool calorimeter design one must carefully select a tube and a base design to avoid degradation of the linearity (due to pulse saturation effects) and the resolution due to rate effects on the gain stability. This appendix is intended to provide a guideline for such a tube selection and base design. Figure A-1 shows a schematic circuit diagram.

We will distinguish two cases for consideration depending on the physical construction of the tank. If the tank is undivided then the total energy will fall almost equally on all the tubes (assume 9). On the other hand if we put mirrors into the tank (increasing reflection losses) we can separate the regions of the tank and then obtain the energy in each region (production angle range) separately. This will concentrate all the light on a few (assume 1) tubes. Assume the digitizers are 1024 channels with 500 pC/full scale (0.5 pC/channel). This description is approximately that for the Columbia University (Nevis Lab) digitizers in E288. We will assume an active fan in and ≥ 30 mV discriminator thresholds. We need to calculate the required gain, peak current, and average current (by assuming a beam rate).

Gain Requirements

Assume we want a muon to appear in channel 15 of the digitizer. Since it has a hadron equivalent energy of 1.5 GeV we have 10^{-1} GeV/channel or 100 GeV full scale. Using the photoelectron yield predicted from the shower development and light gathering we can then calculate the required gain. We also want to be able to trigger a discriminator on the muon output--this is a separate gain requirement which can be satisfied using an amplifier if necessary. A maximum peak current is also defined by the digitizer sensitivity and range.

$$\text{GAIN} = \frac{\text{Charge out}}{\text{Charge in}}.$$

Charge in is 63 photoelectrons for a muon. If the light is all on one tube then we want a Gain

$$G_1 = \frac{7.5\times10^{12}}{63\times1.6\times10^{-19}} = 7.4\times10^5.$$

If it is divided among 9 tubes then it requires

$$G_9 = \frac{7.5\times10^{-12}}{7\times1.6\times10^{-19}} = 6.7\times10^6.$$

If we use a fast tube (6655A or 8575, for example) then we can assume a pulse width of ~10 nsec FWHM. Thus for 500 pC out we need

$$A_{peak} = \frac{5\times10^{-10}}{10^{-8}} = 5\times10^{-2} = 50 \text{ mA}.$$

This translates to 2.5 V into 50Ω. The muon signal of 7.5 pC gives peak currents of 0.75 mA or 37.5 mV. This may be directly adequate for triggering a discriminator. If it is set up for each tube to have 7.5 pC for a muon then the muon signal will be 600 mV into the discriminator while 100 GeV will give 2.5 V (or 22.5 V! too much! But easily solved!)

The other design number required is the average anode current. For this we need to make an assumption about the operating rates for the experiment. We will assume that the experiment can take a rate of 10^6 hadrons of

20 GeV energy. These will produce a pulse in Channel 200 (100 pC). This means that the average current (1 sec beam on time) is

$$I = 100\times10^{-12} \times 10^{6} = 100\ \mu A.$$

This result will hold for either the design with the signal going to 1 or to 9 tubes if we adjust in both cases to get muons into channel 15.

We need to make quantative requirements of linearity and gain stability. These are based on the physics expectations for the calorimeter and the experiment. The calibration and monitoring with muons will find a 2% linearity at 1 mA to be useful. We would want to be within 5% of linear at full scale (50 mA → 2.5 V).

Two issues are at stake for the gain stability. Gain variation will affect the resolution which may in turn affect the background rejection in the experiment (we will undoubtedly compare "energy" and momentum). We may hope for 20% FWHM at high energies. A 5% gain shift (rate induced) will add linearly to this resulting in a significant degradation of the energy/momentum background rejection.

The other more serious issue is the trigger problem. If we seek to use data where the trigger is less than 100% effective we will have to demand a very small gain shift in order to be able to make sensible corrections. Otherwise it we accept data with efficiency of 0.5 and a 5% energy uncertainty in the trigger carries us to a point of 0.4 efficiency then we will have a 25% normalization uncertainty on these data. We cannot better estimate this effect without knowledge of the resolution. Since we know that the hadron spectrum falls steeply we can be sure that it would be helpful to be able to analyze these data taken with efficiencies of 0.5 or so since such data will certainly comprise a significant fraction of our triggers. Thus it would be useful to have small (1%) gain shifts at 100 μA average current.

A separate question to ask is the effect of high rates on the linear fan-in if it is capacitively coupled. With 37.5 mV for muons we will have 500 mV for a 20 GeV hadron. A rate of 10^6 pulses 10 nsec wide of this amplitude gives a dc shift of 5 mV. Thus if we raise the gain only a little we can trigger even on muons with very little effect on the trigger level--only a 1% effective shift at 20 GeV.

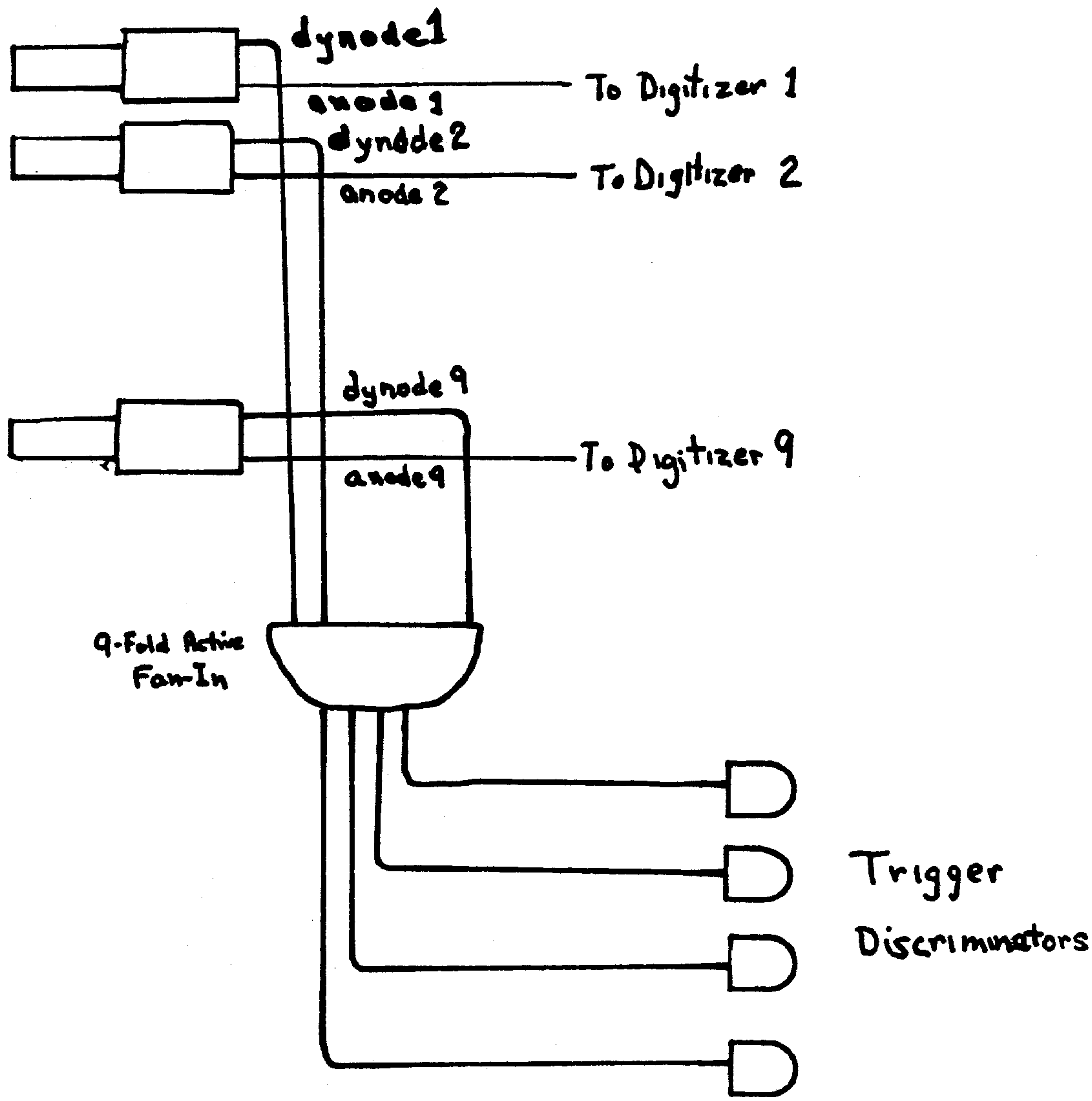


Fig. A-1

Proposed Electronic Diagram for the Swimming Pool Hadron Calorimeter

APPENDIX B. REQUIREMENTS FOR MECHANICAL DESIGN

(May 5, 1975)

What is needed for the desired detectors is a pair of large water tight boxes which will allow mounting of mirrors and detectors in the water volume.

The water will be highly purified. Highly deionized water is quite corrosive. This dictates that no metal parts can be used. Most plastics will be acceptable but each part should be considered for possible chemical contamination of the water. The usual deionizing systems all will remove dissolved CO_2 from the water. If air freely circulates above the water CO_2 will rapidly be taken up and the deionizer will be rapidly exhausted. Thus the boxes must be sealed tightly enough at the top to reduce air flow. Since the detectors are photomultpiliers, the water volume must be light tight.

The detectors must be mounted at the downstream end of the box. Supports for the detectors and the light pipe and phototube assembly must be provided. Supports for mirror assemblies on the sides and bottom (and possibly as dividers in the middle) are needed. Provivision should also be made for connections for the water purifier system. Fig. B-1 shows such a box.

Design Criteria

Up Arm Calorimeter

Fiducial Area	36 in. × 72 in.
Minimum Shower Dev. Radius	12 in.
Minimum Transverse Size	60 in. × 96 in.
Length	16 ft. = 192 in.
Desired Transverse Size	84 in. × 108 in.

Detectors

Pilot 425 Cerenkov Detector Material

Total Area	90 in. × 108 in.
Made up of 9 strips	12 in. × 90 in.

Phototubes - 9 required

Type to be specified.

Suggested Fabrication Technique

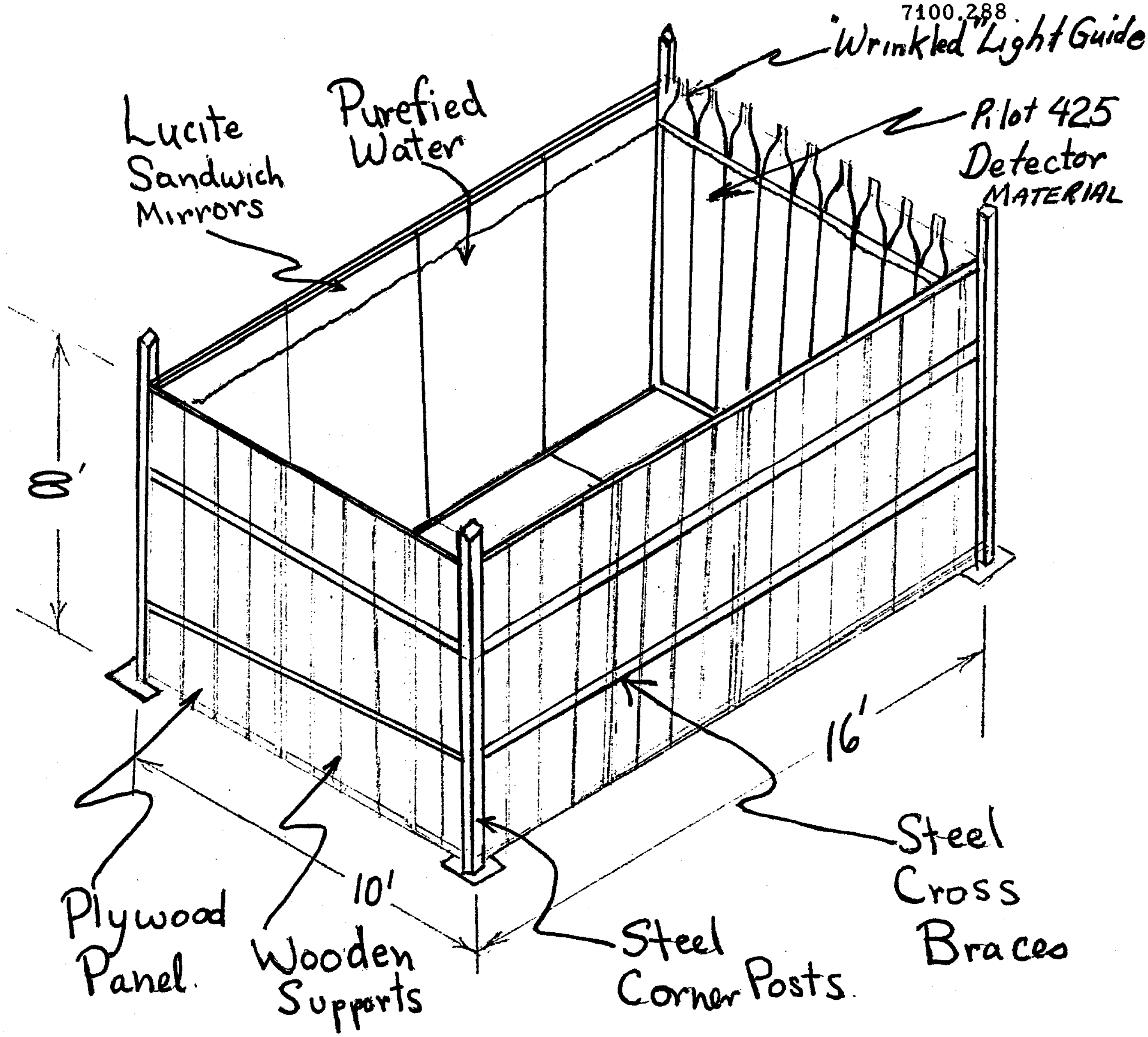
1. Wooden framework
2. Steel corners and support braces
3. Vinyl liner (Swimming Pool Liner). This needs to be light tight as well as water tight.
4. Support structure in water--make this of PVC pipe glued with appropriate cement.
5. Mirrors--UVT acrylic sandwiches (see report). Mounted on sides and bottom to cover most of the area.
6. Need to design a top for the counter which
   a) Provides light tight seal.
   b) Is reasonably air tight.
   c) Both air and light tight seal is to the vinyl liner of the water tank.
   d) The top must support all mirrors and the detector array.
   e) If possible the top should be provided with a way to lift assembly out of the water for easy servicing.

7. The detector material will be glued to Nevis "Wrinkled" Light pipes and these should be supported near the phototube.

8. Rigid support should be supplied for the phototube base which will hold the P. M. magnetic shield and the tube. Tube to be mounted with air gap to light pipe.

9. A (reasonably) light tight path for cabling should be provided from the bases to the outside world.

10. The center of the vertical aperture will be about 72 in. above the concrete floor. Provision for support must be worked out.



Preliminary Design
"Swimming Pool" Hadron Calorimeter
Exp. 288

Fig. B-1

5/5/75 B.C.Brown

APPENDIX C. A TEST COUNTER FOR THE SWIMMING POOL HADRON CALORIMETER

In order to test the principles of detecting light from a shower by use of a water volume and a wavelength shifter light gathering scheme, a test was carried out. Data were collected with muon and hadron beams incident on the detector. The test allowed checking of the light gathering scheme and an indication of the separation possible between hadrons and muons.

A wooden test box 79 in. × 14 in. × 18 in. was lined on sides and bottom with Alzac (shiny aluminum). A 14 in. × 14 in. × 1/4 in. piece of Pilot 425 wavelength shifter material was placed on the downstream end of the box with a high quality twisted light guide (end area 1/4 in. × 14 in.) carrying the light to an RCA 8850 phototube. The box was filled with distilled water.

The muon test was performed using the background muon flux in the Proton Center area at Fermilab. A counter in front and in back of the test box defined a muon. Pulse height measurements on the light production were carried out using a linear gated stretcher amplifier (gated by a coincident of the defining counters) and a pulse height analyzer. By installing a black plastic sheet in the water volume, path lengths of 0 in., 17 in., 37 in., 57 in., and 79 in. could be defined. Pulse height data for these lengths are shown in Fig. C-1. One sees immediately that there is significant light absorption in even this short test box. The data are consistent with about a 40 in. absorption length. The test is not conclusive on that point. It is probably reasonable to ascribe the losses to reflection losses, since with about a 14 in. width one will reflect off of the sides every 18 in. -20 in. One can fit the data adequately assuming a 70% reflectivity and no attenuation loss at all in the water.

A good measure of the light production by muons is possible with these data, however. This is because the phototube is a quantacon type. This means that the noise will be dominated by single photoelectron pulse heights. At 2000 V the noise band had a pulse height of 5-8 mV. The pulse height for the entire length was about 220 mV or 30-45 photoelectrons. Since this number is affected by attenuation effects we shall use the pulse height ratio for 17 in. and compared to 79 in. We thus measured $(40 \pm 10) \times (91/225) = 16 \pm 4$ photoelectrons. We obtain the expected photoelectron yield as follows:

Assume a mean of 100 photons/particle-cm and 17 in. = 43 cm	4300 absorbed photons
Absorption efficiency	0.9
Transmission of absorbed light	0.7
Capture efficiency for internal reflection	0.05
Photocathode efficiency	0.25
Conversion efficiency	8×10^{-3}
Detected photoelectrons	34

Thus this test checks within a factor of 2 of our calculations.

An additional test of the counter was carried out by incorporating it in the "down" arm of the apparatus of the experiment to search for ϕ meson production carried out by the Columbia-Fermilab Group.[19] To improve the shower probability, 4 in. of iron was stacked in front of the counter.

Spectra recorded during a typical run are shown in Figs. C-2(a) and (b). Fig. C-2(a) shows the raw spectrum while Fig. C-2(b) shows the hadrons plotted with Energy/Momentum and implies a resolution (FWHM/PEAK) of 93%. The muon peak shows up clearly in Fig. C-2(a).

The test is considered a success and although we still have only upper limits on light absorption in water and no data on the reflectivity of our mirror design we feel prepared to design a major system.

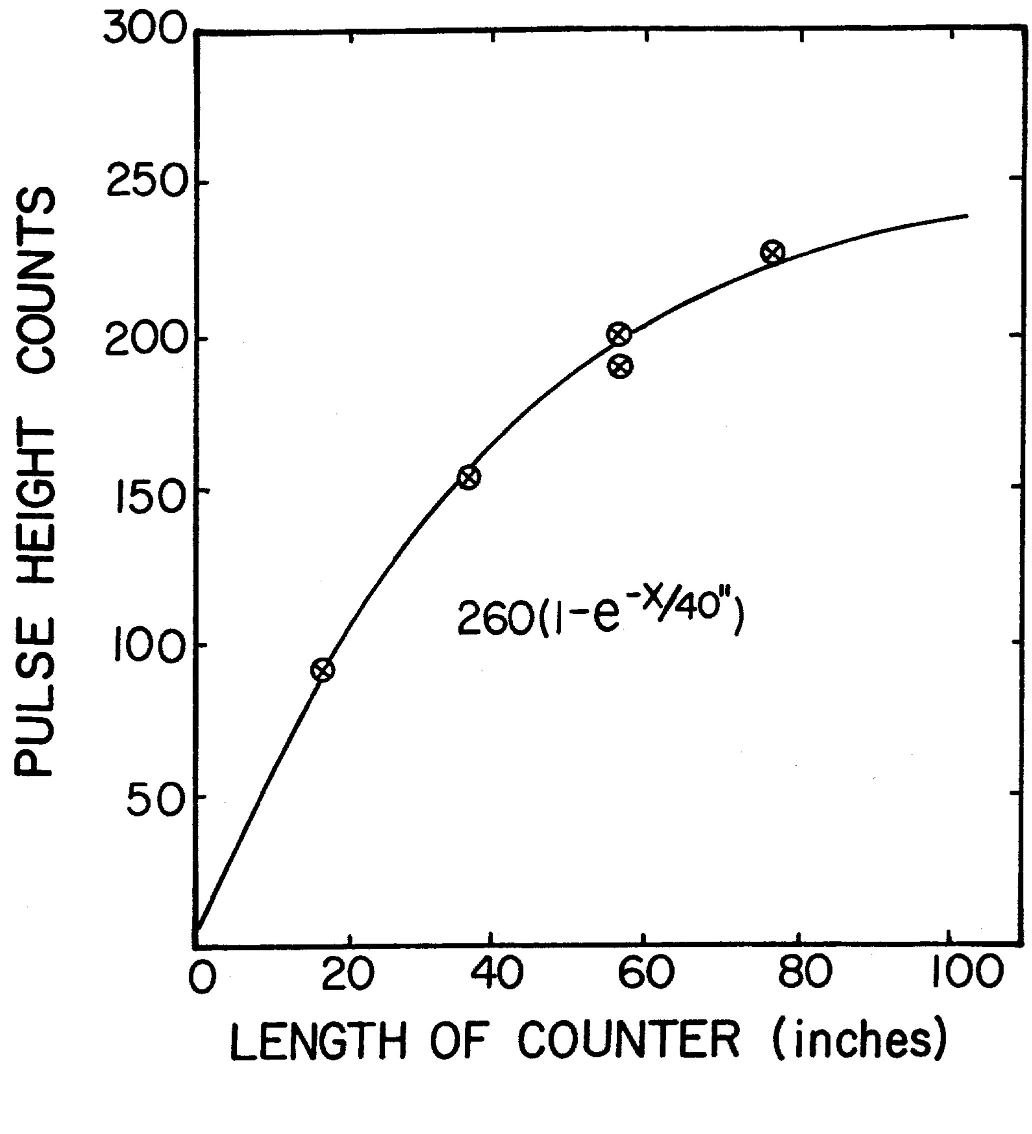


Fig. C-1
Light Detected from Muons Incident on Test Calorimeter for Various Lengths

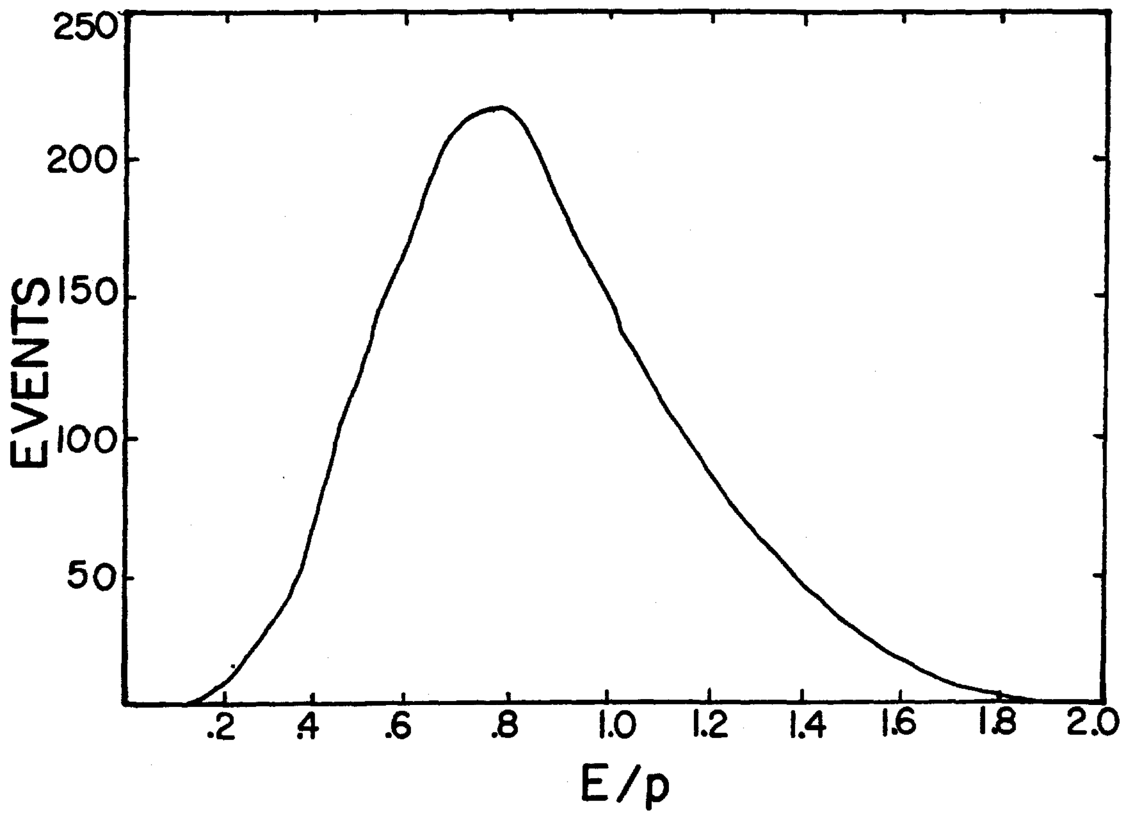


Fig. C-2(a). Pulse Height Momentum in Test Calorimeter Cut for Hadrons.

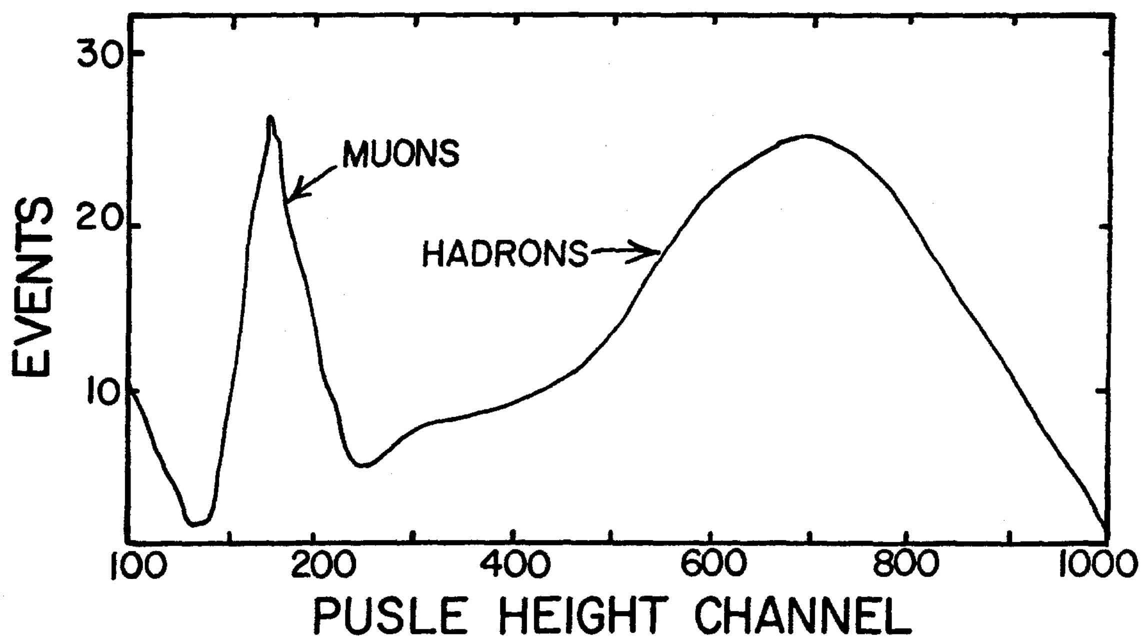


Fig. C-2(b). Raw Pulse Height Spectrum for Particles Incident on Test Calorimeter.

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