CALT-63-302
DOE Research and
Development Report

NEUTRINO DETECTOR*

A PROGRESS REPORT

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*WORK SUPPORTED BY DOE EY-76-C-03-0063

DISCLAIMER

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The help of V. Akylas, E. Garcia, S. Kellogg, G. Pauls and E. Redden, is gratefully acknowledged.

CONTENT

A. GENERAL REMARKS

1. Summary

Several prototype target counters and a veto tank have been built. The entire veto house has been designed. The electronic system has been planned and partially implemented. Our PDP 11/40 is being adapted and programmed for CAMAC.

All fundamental technical problems associated with the above mentioned tasks are resolved. For example, a neutron rejection in the target counter by a factor >100 has been achieved.

2. Remaining Problems

a) The most serious problem encountered in estimating background, accidentals and fake events, are the neutrons from cosmic rays. Accidental rates due to the large rate of thermalized cosmic neutrons in the He^3 counter are unacceptable. It is necessary to improve the shielding drastically (water tanks, more concrete, Cd inside veto, etc). Additional experiments should be carried out in Grenoble, using the NE 235 C or NE 213 to measure the fast neutron flux behind 0.3 m of Pb in B42. The slow neutron rate in He^3 should also be measured for a realistic configuration, i.e., He^3 counter surrounded with water equivalent of the target counters. It appears difficult to reconcile the reported slow neutron rates of 0.016 sec^{-1} for a 1500 cm^2 He^3 counter with the values taken from the work of Hess *et al.*, (also quoted in Hayakawa, p. 431) which gives 10^3 n per sec between 0.01 and 1 eV per cm^2 and MeV interval at sea level. The expected rate thus is $1500 \times 10^3/10^6 = 1.5\ sec^{-1}$.

b) Other problems include the mechanical aspects of mounting and demounting the veto house as well as the shielding assembly and mobility of the entire detector system.

B. TARGET DETECTORS

Three prototype detectors were tested and their performances are described in this chapter.

1. Description of the Prototype Detectors

All three detectors use NE-235C, a liquid scintillator that gives a pulse height of 60% of anthracene, has a transmission length longer than 3 m, and a H:C ratio of 1.67. It is well suited for $n-\gamma$ discrimination.

a) MkI (Fig. 1. top). The tank of MkI is made from 0.6 cm thick UVT lucite. The external dimensions are 8x12x70 cm. The useful volume is 5 ℓ. Optimum light collection is achieved by total internal reflection. The tank is wrapped with Aℓ foil, to reflect back the primary light that escapes. The two smaller faces (Fig. 1) are covered by 5" XP-2041 photomultipliers.

b) MkII. (Fig. 1. middle). This version employes the same tank as MkI. It has two 3" XP-2312 photomultipliers. The surface of the end faces which is not covered by the PMT is coupled over air to a TiO_2 reflector[1]).

c) MkIII. (Fig. 1. bottom). The tank made from lucite, measures 8x30x90 cm. The useful volume is 17 ℓ. The tank is surrounded by wavelength shifter bars[1,2]), which are not optically coupled to the tank. These bars are 1.6 cm thick and 4 cm wide. Two bars are arranged side by side. Each bar surrounds two adjacent sides of the tank, and its ends are optically coupled to a 2" XP-2230 PMT. Each PMT views two bars coming from opposite sides. There are altogether four PMT. In a

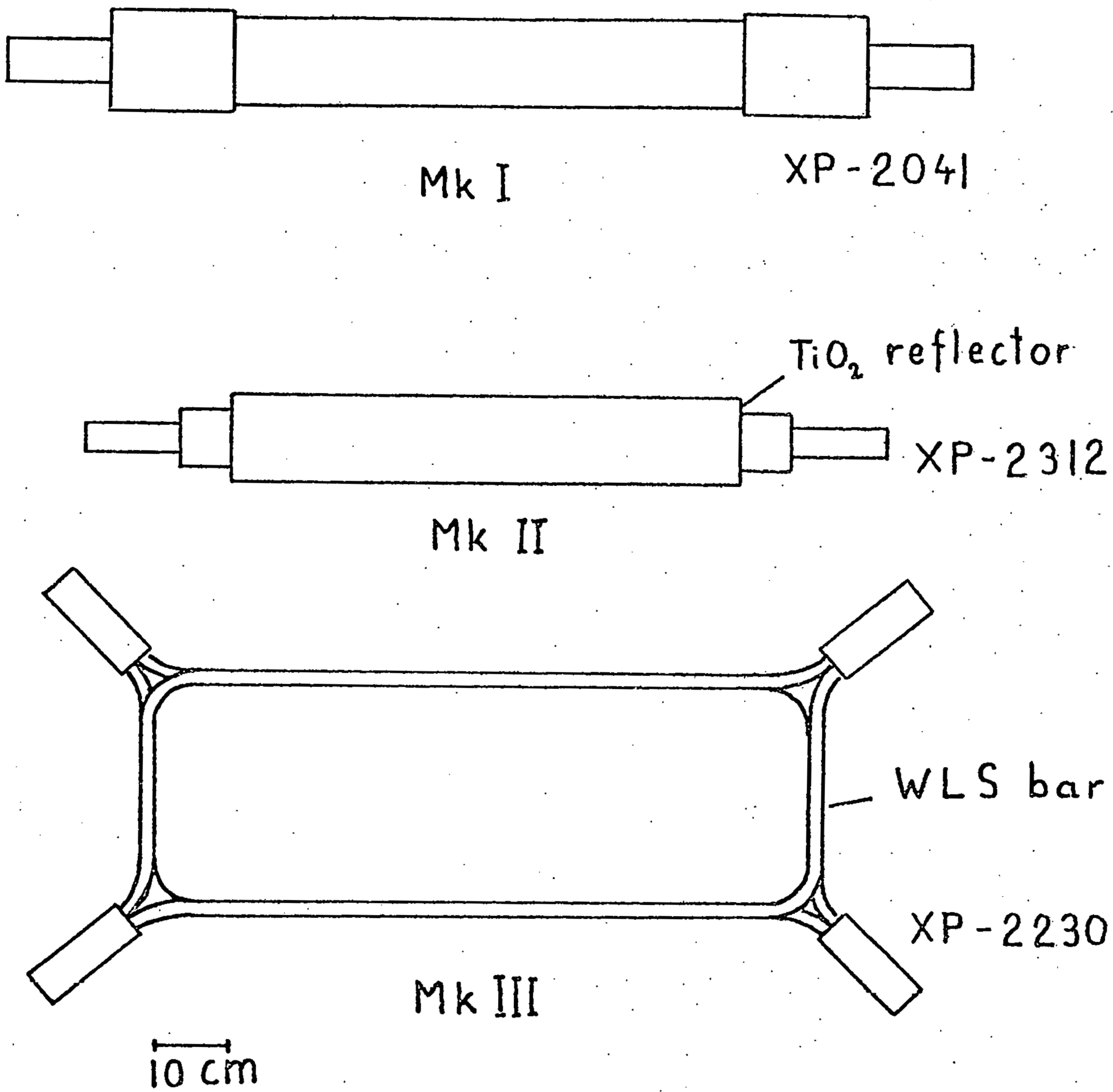


Figure 1. The three tested detectors. MkI has an 8 x 12 x 70 cm tank made out of 0.6 cm thick lucite. MkII uses the same tank. MkIII has an 8 x 30 x 90 cm tank, and is surrounded by wavelength shifter bars.

final version, the bars could be bent back, 45^{0} to the short side of the tank, so that several tanks can be stacked with a maximum of tank volume.

2. Results

The energy resolution and the pulse decay time spectrum, which is relevant for the $n-\gamma$ discrimination were measured for various energies.

For the energy resolution measurements, single-line γ-ray sources were used. Only those events were selected, in which the Compton scattered γ-ray escaped in the backward direction. The energy of the Compton scattered electrons is then kinematically well defined and monochromatic. The backscattered γ's were detected in a Na(I) detector placed behing the source.

For the decay time spectra, an Am(Be) neutron source was used, and windows were set on the energy spectrum.

Some of the spectra obtained with the three tanks are presented in Fig. 2. For the decay time spectra, the spectrum measured with a pure γ source is superimposed to the one obtained with the mixed $n-\gamma$ Am(Be) source.

To characterize the quality of the $n-\gamma$ discrimination, we define the neutron background reduction factor (NBR). We set a threshold on the decay time spectrum so that 96% of the γ events are below it. The NBR is the ratio of the total number of neutron events to the number of neutron events below this threshold.

The results of the tests are given in Fig.2 and table 1. The energy resolution (FWHM) at 0.9 MeV is given. It scales with the square

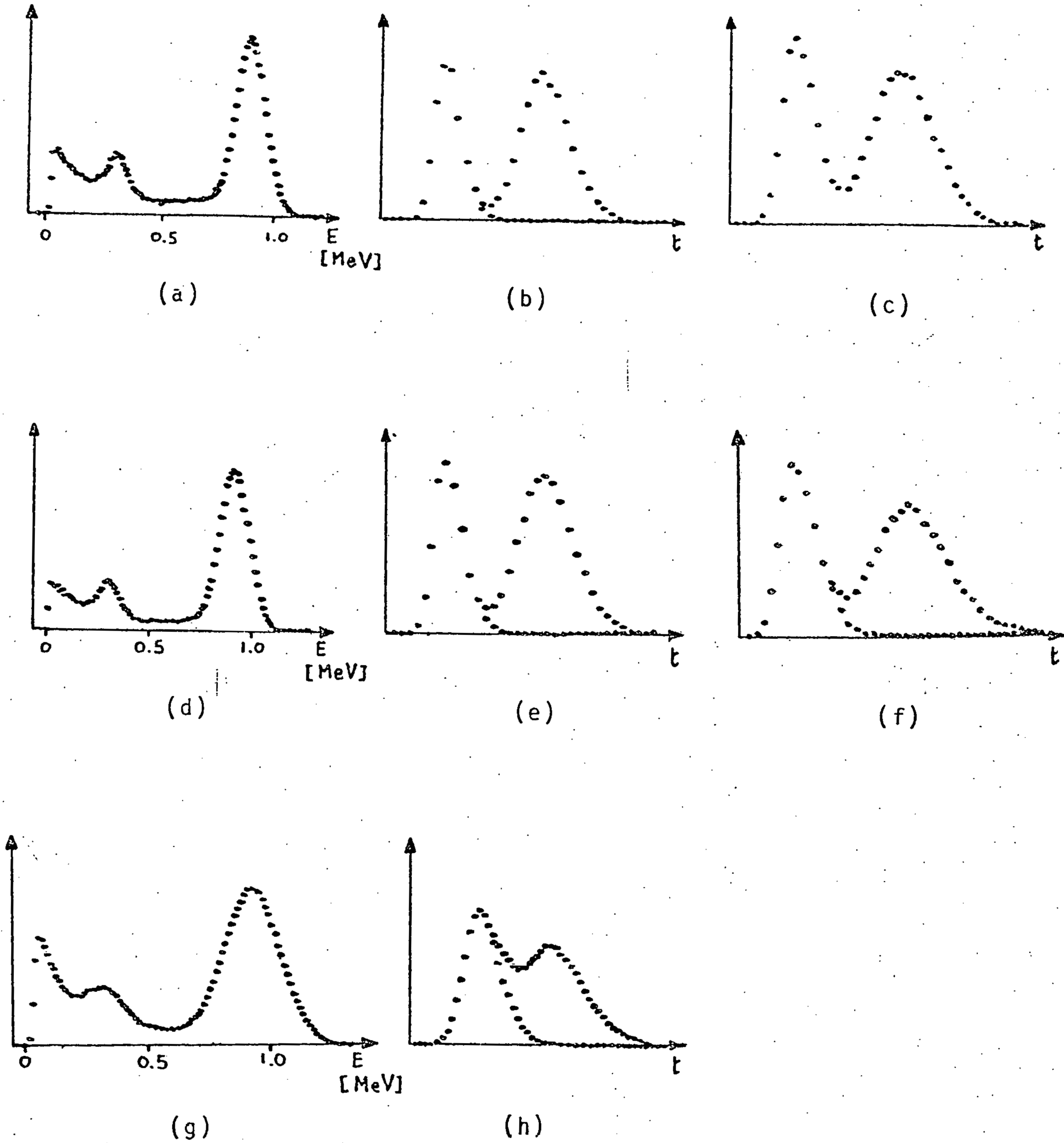


Figure 2. (a), (d) and (g): Energy spectra obtained with MkI, MkII and MkIII respectively, using a Zn^{65} source; (b), (e) and (h): Decay time spectra for the same detectors for an equivalent electron energy of 1MeV; (c) and (d): the same for 0.6 MeV.

TABLE 1. Performance of Prototype Detectors

Detector	ΔE (FWHM) at 0.9 MeV)	Number of photoelectrons at 0.9 MeV	Non-uniformity	NBR at 0.6 MeV[1)]	NBR at 1 MeV[1)]	NBR at 2 MeV[1)]
MkI	16%	215	3%	> 50	> 100	> 100
MkII	18%	170	7%	> 30	> 100	> 100
MkIII	28%	70	2%	-	10	15

[1)]Equivalent electron energy.

root of the energy. Assuming a Poisson distribution, we also derived the number of photoelectrons collected. The non-uniformity of the response is given, which is the maximum pulse height variation for a given energy when the source is at the center and near the ends of the tank. The NBR is given for three equivalent electron energies, 0.6, 1.0 and 2.0 MeV.

As one sees, the best results were obtained with MkI. The NBR is almost perfect (> 100). MkII is practically as good, although the uniformity is at the limit of the tolerable. It shows that the ratio of the photocathode area to the area of the tank end should not be reduced more. The uniformity with MkIII is again excellent. However the number of photoelectrons per 1 MeV quantum is only about one third of that of MkI. As a consequence, the energy resolution is worse than with MkI, but still good enough for our purpose. The NBR at 1 MeV however, is only 10, which does not compare well with either MkI or MkII. Although MkIII is the most economical solution, it should only be considered in case the neutron background is not severe.

3. Proposed Configurations

From the results of section 2 it is clear that a configuration close to that of MkI or II should be an acceptable solution. However the final choice will depend on

n γ separation needed
energy resolution needed
useful volume
optimum thickness (n and e^+ efficiency)
cost of PM and labor.

a) Final MkI. Using 5" PM for each cell (made of 0.6 cm lucite) several dimensions can be contemplated. The maximum length given by the dimension of the veto tank (130 cm) and PM tubes is 66 cm. (Outside dimensions are given).

# Cells	Cell Cross Section	Volume	Performance
5 x 9	8 cm x 12 cm	211 ℓ	Same as MkI
	11.3 cm x 13.3 cm	351 ℓ	Similar to MkII
	13.3 cm x 13.3 cm	421 ℓ	Somewhat worse than MkII

Requires: 45 cells, 90 5" PM ($54,000).

Note that the 5" PM is 13.3 cm wide incl. shield.

b) Final MkII. Using two 3" PM per cell and TiO_2 reflector on short sides. Maximum length of cell is 90 cm (the length of the 3" PM with socket is 20 cm).

# Cells	Cell Cross Section	Volume	Performance
5 x 12	8 x 10 cm	317 ℓ	Same as MkII
→ 5 x 6	9 x 21 cm	412 ℓ	Same as MkII

Both versions require 120 PM ($42,000). In the version quoted on the second line there are 4 PM per cell. This version is more economical, saving manufacturing of cells and increasing the total volume. All four PM are connected together to give one output signal.

c) Final MkIII. This version is worth considering if a neutron suppression of less than 10:1 is required.

# Cells	Dimension of Cell	Volume	Performance
5 x 4	29 x 8 x 90 cm	340 ℓ	As MkIII
Requires wave length shifter bars and 80 2" PM ($17,000).			
5 x 4	29 x 12 x 90 cm	536 ℓ	Worse than MkIII

Requires 3" PM ($28,000).

d) Conclusion. It appears that the configuration marked → quoted in b) is probably best. In this configuration the inside thickness is 7.8 cm.

References

[1]G. Keil, NIM 87 (1970) 111.

[2]B. Barish *et al.*, CALTECH report 68-623 (1977).

C. VETO COUNTER

The veto counter consists of 6 mechanically and optically independent liquid scintillator planes, arranged in such a fashion that the "radiation leaks" between plane boundaries are only 9 mm wide. The inner dimension of the veto house is 130 x 129 x 90 cm, however the 90 cm dimension can still be altered. The tanks have an inner thickness of 12 cm and are filled with NE 235 H. The outer dimension of the house without tubes, is 169 x 169 x 129 cm. For details see drawings Fig. 1-3. Each tank has two sides provided with lucite windows allowing the scintillation light to escape into a wave length shifter bar (ref. 2, Chapter B). On each side, three 1.6 x 4 cm bars arranged next to each other are used. A single 5" PM views the light from two adjacent sides. Altogether only 6 5" PM are needed for the entire veto system.

The tanks, made of aluminum, are provided with reflectors. The reflectors on the large sides are lucite panels sealed on the edges to an aluminum sheet, thus taking advantage of the total reflection of the lucite air interface. The reflectors on the short sides opposite to the lucite windows are aluminum sheets painted with TiO_2, and covered and sealed with a lucite sheet. (This latter version is the optimum reflector that can be conceived).

The volume of the front and rear tanks is 250 ℓ, that of the other tanks is 180 ℓ.

One full size tank (the front panel tank) has been completed and is being tested.

<u>Cost Estimate</u>. Fabrication of the present tank cost about $4,400. Each additional tank can probably be built for $2,000. Cost of NE 235 H (1220 ℓ) is about $5,000. Cost of PM and shifter bars $5,000. There is a support platform needed to accommodate the target cells. Total estimated cost is about $25,000.

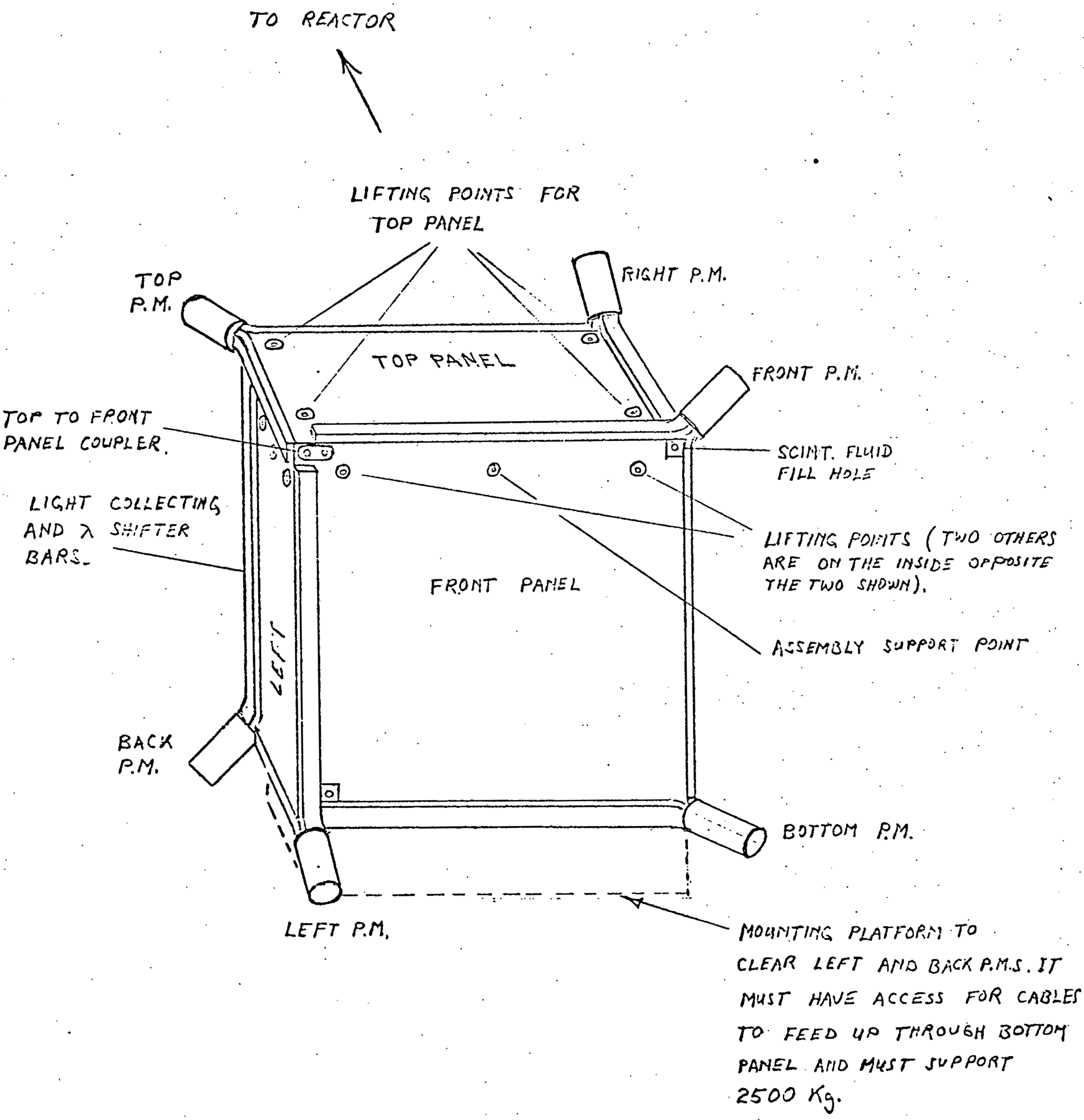
<u>Notes</u>. If it turns out that the 9 mm cracks represent a serious "leakage", it will be possible to cover them with strips of Cerenkov plastic.

Also, to further improve the efficiency of the veto (reduction of neutron background by vetoing muons stopped in the lead shielding) a large wire chamber umbrella could be installed.

Attention should be paid to the logistic problem of assembling and disassembling of the veto panels. This operation will have to be performed frequently in the early phase of the experiment. An overhead crane or precision fork lift will be needed.

VETO TANK

Jan. 1978



CROSS SECTION OF VETO TANK

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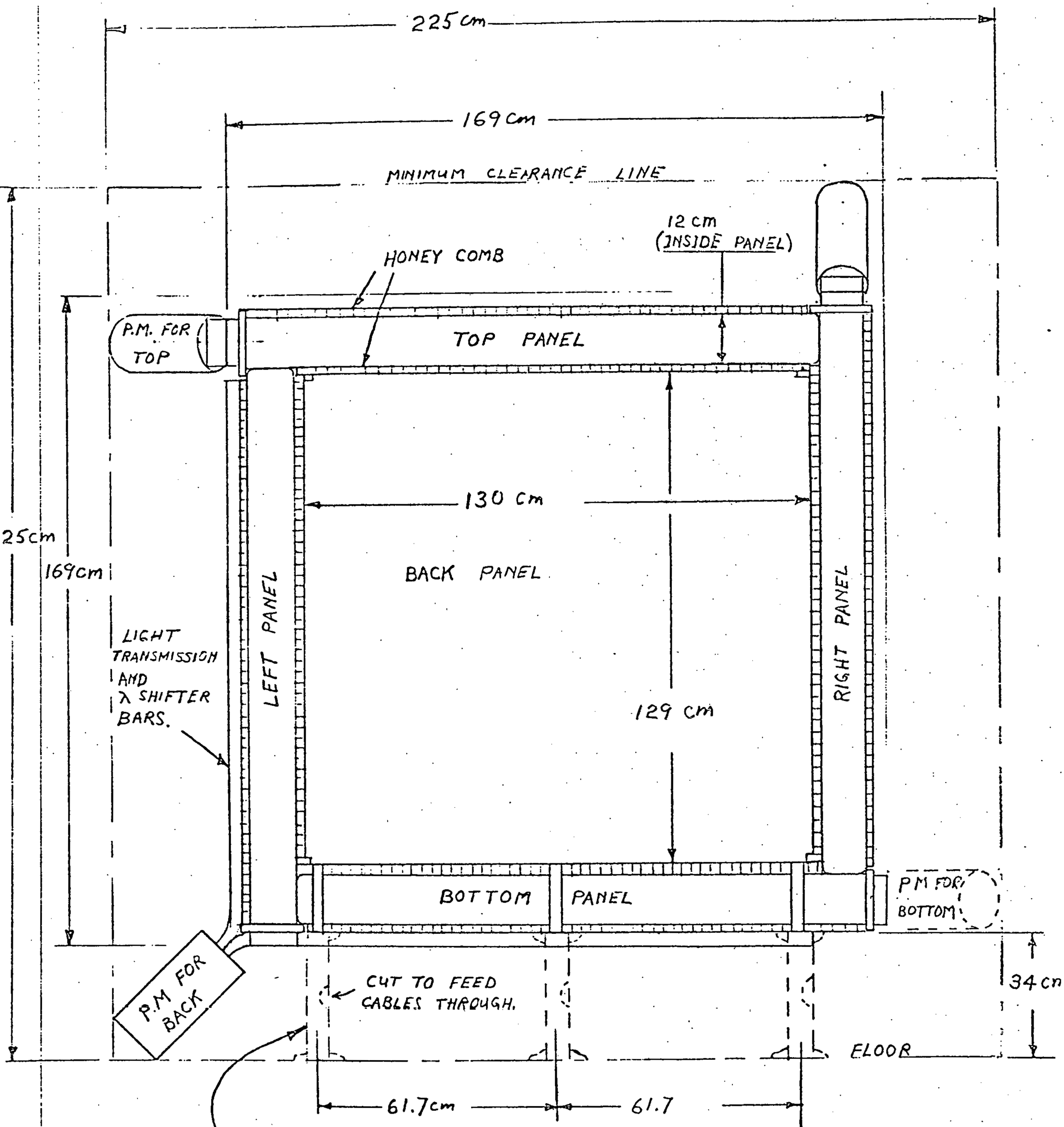


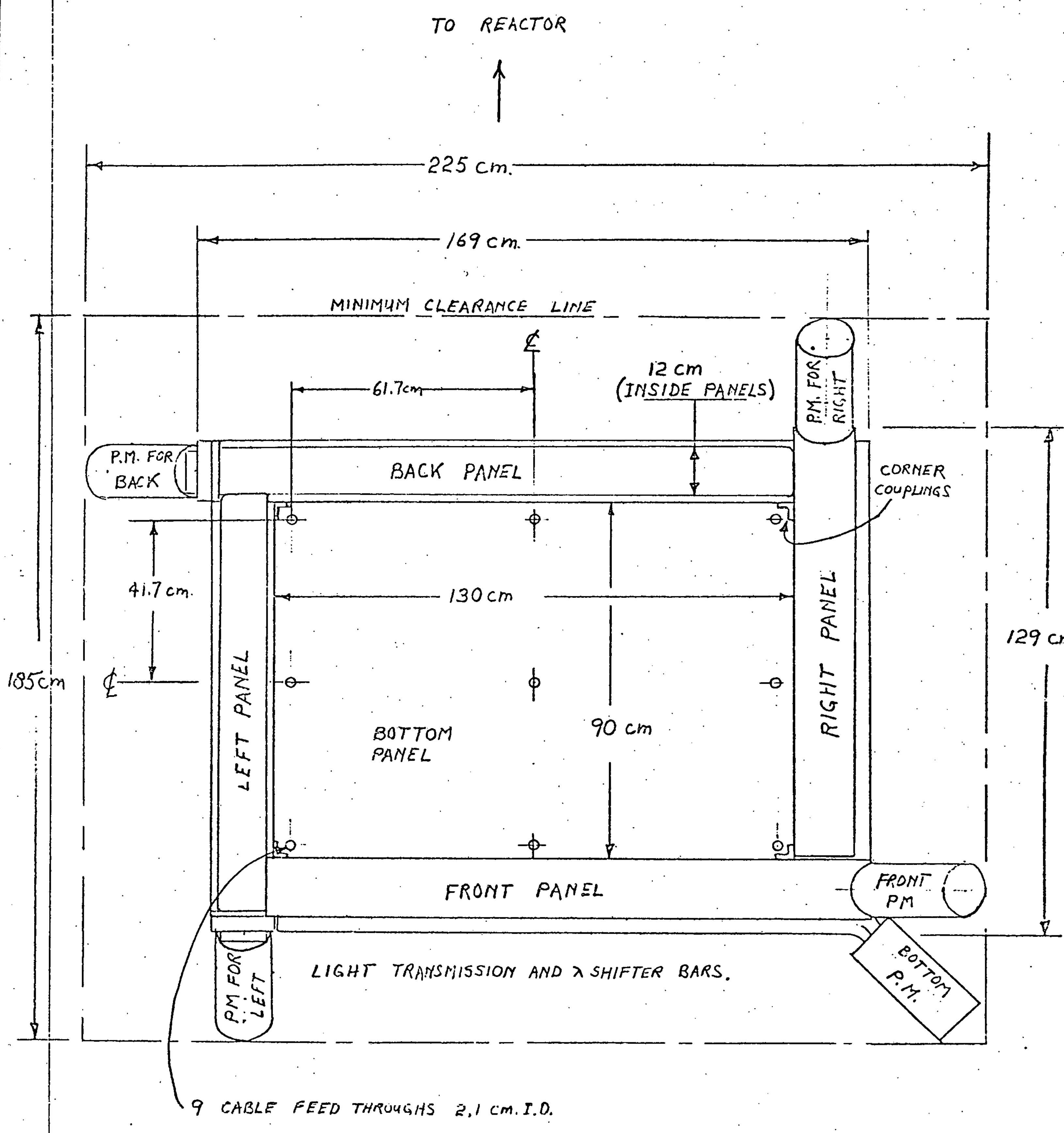
ENTIRE TANK MAY BE SUPPORTED BY NINE TUBES

6 cm. O.D. x 4 cm I.D. x 34 cm LONG SPACED AS SHOWN

OR A PLATFORM 34 cm HIGH x 125 cm x 85 cm

PLAN VIEW OF VETO TANK (TOP PANEL REMOVED)

Jan. 1978



D. ELECTRONICS

The suggested circuit diagram is presented in Fig. 1. It is essentially self-explanatory, and only a few remarks are given in the following.

The two buffered ADC's (12 channels per module, charge sensitive, 8 bits, dead time of 3 μs) analyze all the pulses originating in the target and veto tanks. Only the events coinciding with low energy veto signals (Veto Low) are rejected. The pulse areas and, for the target tanks, decay times, are digitized. Up to 6 modules share the same ADC channel. Tag words (Attenuator 1/2... 1/64 in logic signal) are used to identify the detectors which fire. In parallel to the pulses, the amplitude of two continuously cycling sawtooth signals is analyzed. It provides the time information. The first sawtooth signal has a period of 250 μs. Since the ADC has 8 bits, we have a time resolution of about 1 μs. The second signal is a sawtooth like stepfunction which switches when the first signal ends a cycle. There are 128 steps, and the cycle duration is 32 ms. Ambiguities may occur when the ADC's try to analyze the signal height when one or both sawtooth signals end a cycle. A tag word is used to indicate if this is the case. When the slow sawtooth ends a cycle, the ADC's are caused to digitize. This is done to notify the data acquisition system that a new cycle has begun.

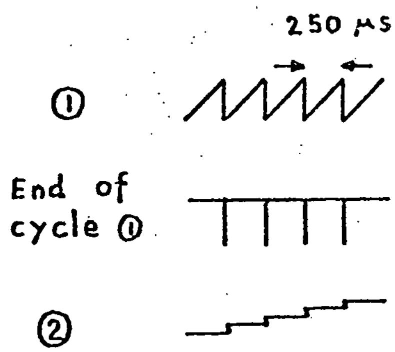


FIG. 1. Circuit diagram. It is assumed that the target consists of 5 planes of 6 scintillation detectors, each being fitted with 4 PMT. There are 4 He^3 chambers, and 6 independent veto detector panels.

PSD: Pulse shape discriminator.

CFTD: Constant fraction timing discriminator.

τ: Pulse decay time.

E_T: Energy deposited.

TW_T: Tag word. Indicates what combination of cells fired.

(τ, E_T, TW_T: Each plane of 6 cells has a channel.)

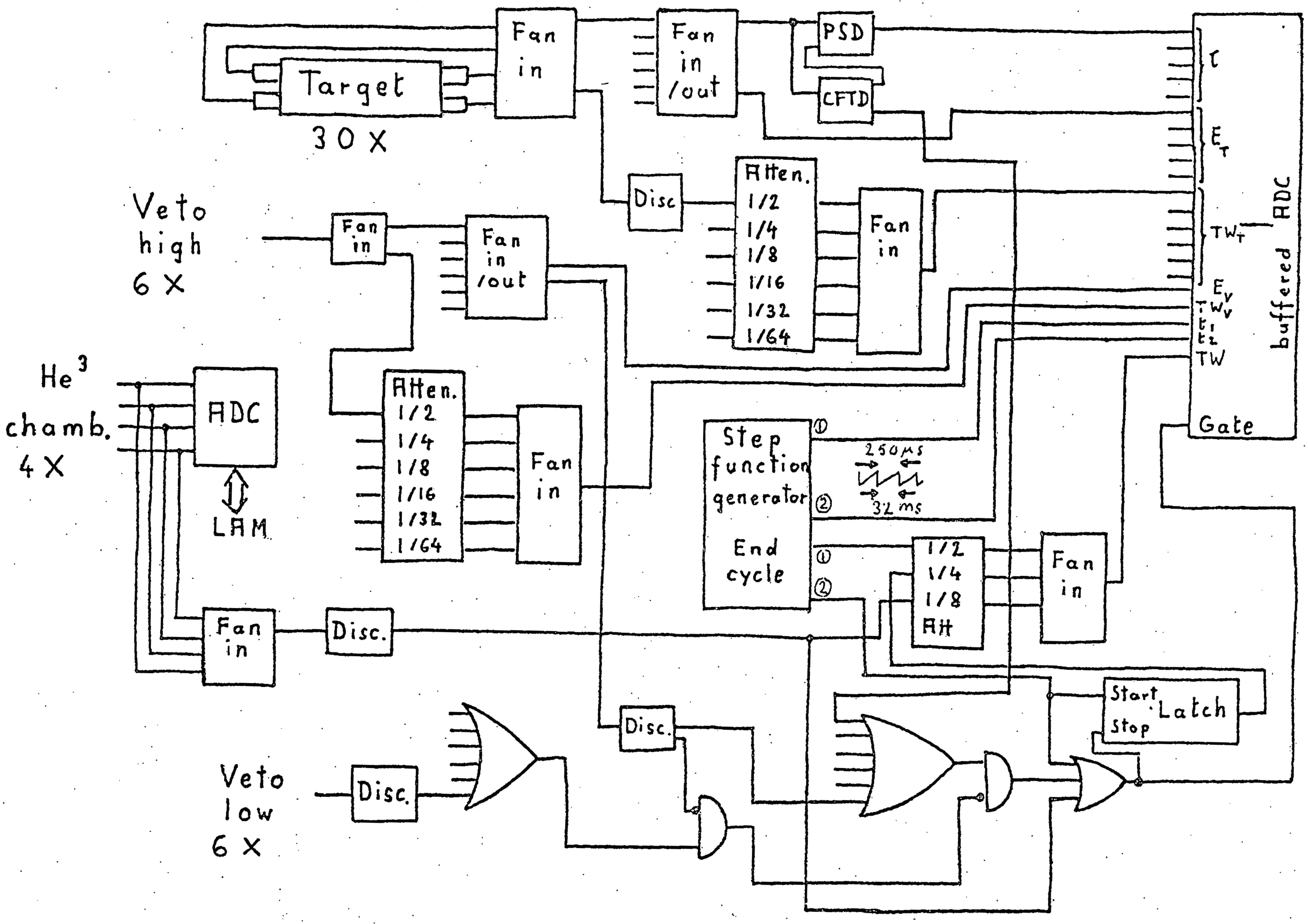
E_V: Energy deposited in the veto tanks.

TW_V: Tag word veto tank. Indicates what combination of panels fired.

t_1: Fine time given by the height of the fast stepfunction generator (250 μs for 1 cycle).

t_2: Coarse time given by the height of the slow stepfunction generator (32 ms for 1 cycle).

TW: Tag word. Indicates if the He^3 chambers or the end of cycle of the step function generator caused the ADC's to digitize.



Target
30 X
Fan in
Fan in /out
PSD
CFTD
τ
E_T
TW_T
buffered ADC
E_V
TW_V
t1
t2
TW
Gate
Veto high 6 X
Fan in
Fan in /out
Disc
Atten. 1/2 1/4 1/8 1/16 1/32 1/64
Fan in
He3 chamb. 4 X
ADC
LAM
Atten. 1/2 1/4 1/8 1/16 1/32 1/64
Fan in
Step function generator
250 µs
32 ms
End cycle
1/2 1/4 1/8 Att
Fan in
Fan in
Disc.
Disc.
Start Stop Latch
Veto low 6 X
Disc.

Each channel of the ADC has a 32 word memory where the results of the digitalization are stored. The memory is of the last-in/first-out type and always contains the last 32 events.

The pulses from the He^3 chambers are analyzed in an 8-channel peak sensing ADC. Whenever a neutron is detected, a LAM signal is generated. The content of all the ADC buffers and registers is then transferred to the computer.

We conclude this section by giving a list of modules necessary to build the circuit given in Fig. 1.

	Necessary Channels(# units)	Already bought (# units)	Type Price US$
Linear fan in/out	56(14)	(3)	LRS 428F (675)
Discriminator	37(5)	(2)	LRS 623 (1195)
PSD	5	(6)	Canberra 2160 (1250)
CFTD	5	(6)	Canberra 1428 (750)
Logic fan in/out	5(2)	(1)	LRS 429 (545)
Slow ADC	4(1)	(1)	Ortec AD811 (1450)
Buffered ADC	20(2)	(2)	LRS 2250L (2250)
Coincidence	2(1)	(2)	LRS 365AL (745)
Latch	1	(2)	LRS222 (875)
Step function generator	1	being built	Caltech
HV power supply	66[1](3)	(3)	2 LRS 4032P (4100) 1 Canberra 3002 (575)
NIM bin	3	(2)	LRS 108P-6 (820)
CAMAC crate	1	(1)	NE 9503,9513 (1675)
CAMAC interface	1	(1)	Standard DCC-11 (1425)

In addition, several delay lines, cables, terminators have to be bought.

Total remaining cost of electronics: about $13,000

[1]Each channel of the LRS 32 channel unit supplying two PM.

E. BACKGROUND AND ACCIDENTALS

Based on data discussed in Grenoble last July and handbooks on cosmic rays, the accidental rates, cosmic related neutron rates (which would simulate a good event) and dead time of the system have been estimated. The lower part of Table 1 shows the values reported in Grenoble in July 1977. The upper part gives forecasts assuming the Grenoble γ-ray flux data and the literature value for $\mu^{\pm}$ fluxes at sea level (Hayakawa).

The obvious serious problem is the large number of accidentals, caused mainly by the estimated large number of cosmic originated neutron pulses in the He^3. This number is at variance with the measured Grenoble He^3 background rate.

The discrepancy can also be seen by comparing the literature neutron flux (Hayakawa) of 10^3 n per sec between 0.01 and 1 eV per cm^2 and MeV, giving rise to an expected rate of 1.5 sec^{-1} in the 1500 cm^2 He^3 detector, with the observed value of $<0.016\ sec^{-1}$.

TABLE 1. Background Events (Rates in $Sec.^{-1}$)

	Flux ($2m^2$)	Singles He^3 4x90x150 cm	Singles Target >1MeV, 360 ℓ 30 cm Pb	Accidentals (200 μs)	Fake Events	Veto ($2m^2$) (1600 ℓ)	Veto Dead Time
Cosmic	$125\mu^+$ $100\mu^-$	-	100	-	-	225	0.05 for 200 μs
Cosmic fast n from μ^-stop in Pb	80 [3]		0.8 [1]		0.4/NBR (1500/NBR hr^{-1})		
Cosmic slow n from above	40	40 [2]		0.8 (3000 hr^{-1})			
$\gamma > 1$ MeV			100			500	5×10^{-5} for 100 ns
Grenoble Input 1977		(1000 cm^2) 7 hr^{-1}	(25 ℓ) (10 cm Pb) 90				
Scaled up by volume or surface		01	100	6 hr^{-1}			

[1] With e^- threshold 1 MeV (corresponding to E_n 2.5 MeV) 10% of n detected, with efficiency 20%, veto reduction 0.5.

[2] Fast n thermalized in Liquid Scintillator.

[3] Assume 0.3 m Pb on top and bottom of veto stop 70 sec^{-1} μ^-. Take solid angle and n multiplicity 2.5 in capture. (Hayakawa, Cosmic Ray Physics).

F. APPENDIX

Notes on Reactor antineutrino spectrum

1. The rate in the neutrino detector at distance d is given by

$$R(d) = \frac{R_o}{4\pi d^2}\int_{E_o-\Gamma/2}^{E_o+\Gamma/2} \sigma(E)\,N(E)\,dE \cdot (1 - \sin^2(2\theta)\,F(\lambda = \Delta^2 d)), \qquad (1)$$

where R_o is the number of fissioning ^{235}U/sec, Γ resolution of the detector, θ neutrino mixing angle, Δ^2 neutrino mass difference,

$$F(\lambda) = \int \tfrac{1}{2}(1-\cos(2.54(\lambda/E))\,G(E)\,N(E)dE \Big/ \int \sigma(E)\,N(E)dE.$$

The oscillation function $F(\lambda)$ only weakly depends on the detailed shape of the $\bar{\nu}$ spectral function $N(E)$, provided the resolution is sufficiently good, $\Gamma \lesssim 2$ MeV.

2. For absolute determination of the cross section, one has to know the $\bar{\nu}$ spectrum $N(E)$. There are three sources of $N(E)$ in the literature.

2.1 Carter *et al.*, Phys. Rev. 113, 280 (1959) measured the β^- spectrum and converted it approximately into a $\bar{\nu}$ spectrum. They obtain

$$N(E) = 5.01 \exp(-0.505E - 0.0544E^2). \qquad (2)$$

2.2 Nezrick and Reines, Phys. Rev. 142, 852 (1966) measured the β^+ spectrum in the inverse neutron β decay. Assuming that they know the elementary cross section

$$\sigma(E) = 8.85 \times 10^{-44}\,(E-1.29)\sqrt{(E-1.29)^2 - .511^2}\ \text{cm}^2. \qquad (3)$$

they fit the shape of N(E) to

$$N(E) = (19.4 \pm 1.3)\ \exp(-1.28E + 0.040E^2). \qquad (4)$$

The constant 19.4 ± 1.3 is determined from the condition that the total number of neutrinos with energies > 1.8 MeV per fission is given by

$$\int_{1.8}^{\sim 10} N(E)dE = 2.1 \pm 0.1. \qquad (5)$$

The function (2) also fulfills condition (5).

2.3 Avignone and Greenwood, Phys. Rev. 16 D, Dec. 1, 1977 determine N(E) from recent experimental decay data. Their N(E) also obeys eq. (5).

3. The three distributions (2), (4) and 2.3 are compared in the lower part of Fig. 1. Note that (2) and (4) decrease considerably faster in the relevant region between 2-6 MeV. The distributions are up to 30% different.

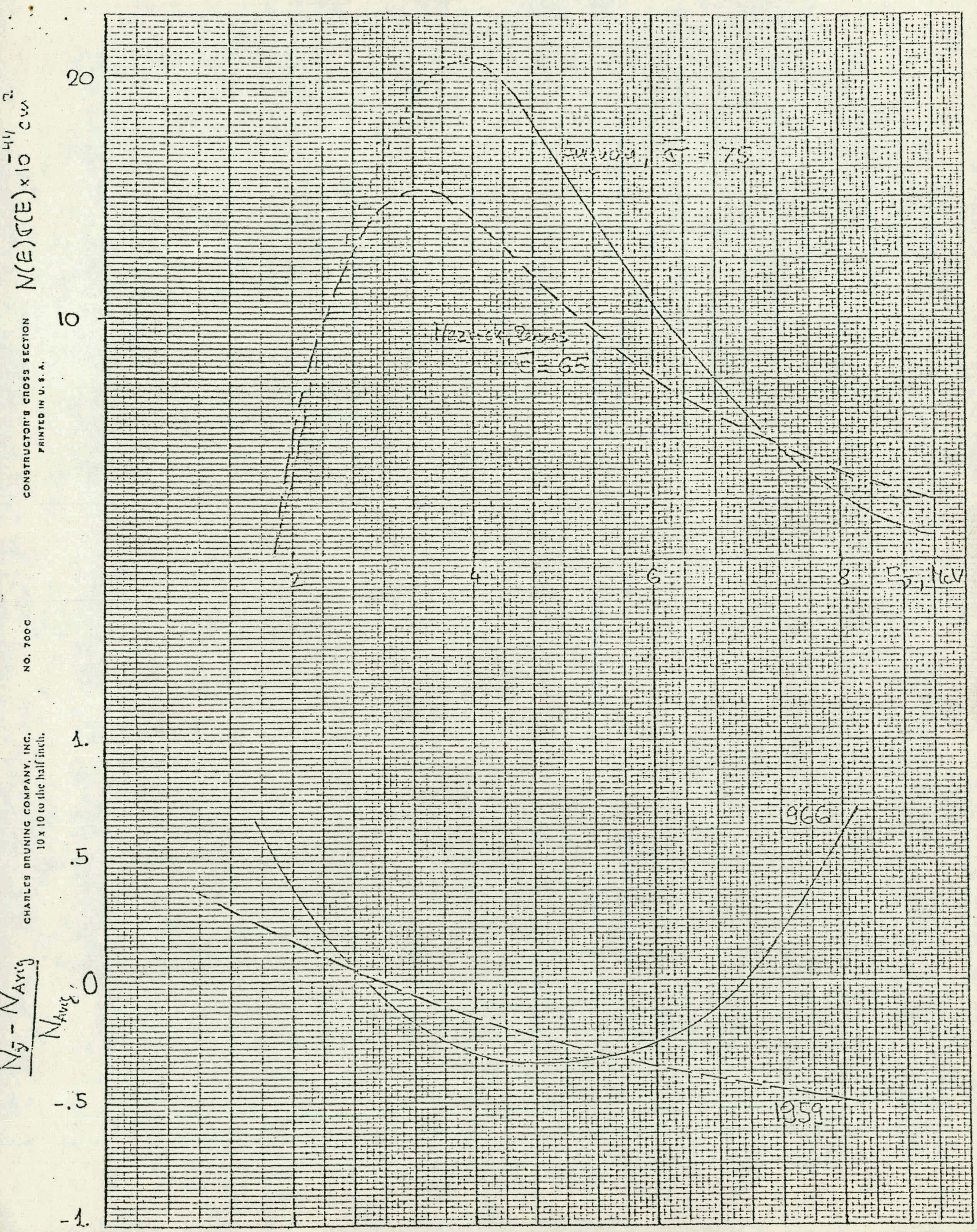
4. The function $\sigma(E)\ N(E)$ using $\sigma(E)$ eq. (3) and N(E) eq. (4) (dashed) and 2.3 (full curve) are shown in the upper part of Fig. 1. Note that the full curve is inconsistent with the measured β^+ spectrum by Nezrick and Reines. Besides, the integrals

$$\overline{\sigma} = \int_0^\infty N(E)\,\sigma(E)dE \qquad (6)$$

are 65×10^{-44} cm^2 for eq.(4) and 75×10^{-44} cm^2 for 2.3. If one compares the total rate of Nezrick and Reines with $\overline{\sigma}$ based on eq. (4) or 2.3 one finds

$$\bar{\sigma}_{exp} / \bar{\sigma}_{th} = \begin{cases} 0.88 \pm 0.13 & \text{(Nezrick and Reines)} \\ 0.75 \pm 0.13 & \text{(Avignone and Greenwood)} \end{cases} \qquad (7)$$

5. Conclusion: 1) The existing information on N(E) is inconsistent. It would be important to use the reactor data library, such as ENDF-IV (see R.E. Schenter *et al.*, HEDL-SA-1346, Hanford (1977)) to determine N(E) independently. 2) The result of Nezrick and Reines does not rule out neutrino oscillations.


N(E)σ(E) x 10^-44 cm^2
20
10
2
4
6
8
E, MeV
1.
.5
0
-.5
-1.
(N_y - N_Avg)/N_Avg
1966
1959

NEUTRINO SPECTRA N(E)/MeV FISSION

FROM DIFFERENT SOURCES

E	Avignone 77 1.	Carter and Reines 59 2.	Nezrick and Reines 66 3.	Tsoulfanidis 71 4.
1.5	1.53×10^{0}	2.08×10^{0}	3.11×10^{0}	2.70×10^{0}
2.0	1.27×10^{0}	1.47×10^{0}	1.76×10^{0}	1.89×10^{0}
2.5	9.19×10^{-1}	1.01×10^{0}	1.02×10^{0}	1.30×10^{0}
3.0	6.57×10^{-1}	6.75×10^{-1}	5.99×10^{-1}	8.64×10^{-1}
3.5	4.76×10^{-1}	4.39×10^{-1}	3.60×10^{-1}	5.65×10^{-1}
4.0	3.23×10^{-1}	2.78×10^{-1}	2.20×10^{-1}	3.63×10^{-1}
4.5	2.10×10^{-1}	1.71×10^{-1}	1.38×10^{-1}	2.28×10^{-1}
5.0	1.30×10^{-1}	1.03×10^{-1}	8.80×10^{-2}	1.40×10^{-1}
5.5.	8.48×10^{-2}	6.01×10^{-2}	5.73×10^{-2}	8.50×10^{-2}
6.0	5.30×10^{-2}	3.42×10^{-2}	3.81×10^{-2}	5.04×10^{-2}
6.5	3.27×10^{-2}	1.89×10^{-2}	2.58×10^{-2}	2.94×10^{-2}
7.0	1.79×10^{-2}	1.02×10^{-2}	1.79×10^{-2}	1.67×10^{-2}
7.5	1.07×10^{-2}	5.32×10^{-3}	1.26×10^{-2}	9.25×10^{-3}
8.0	5.54×10^{-3}	2.71×10^{-3}	9.08×10^{-3}	5.03×10^{-3}
8.5	3.08×10^{-3}	1.34×10^{-3}	6.67×10^{-3}	2.64×10^{-3}
9.0	1.97×10^{-3}	6.49×10^{-4}	5.00×10^{-3}	1.32×10^{-3}

Notes:
1. Calculated by Avignone and Greenwood, Phys. Rev. D, 1977.
2. Converted β^- spectrum, Phys. Rev. 113, 280 (1959).
3. Deduced from β^+ measured spectrum, Phys. Rev. 142, 852 (1966).
4. Converted β^- spectrum, as in 2. but using data by Tsoulfanidis *et al.*, Nucl. Sci. and Eng. 43, 42 (1971).