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☐ Civil Construction	☐ Failure Mode/Tests	☐ Schedule
☐ Commissioning	☐ Front End	☐ SRF
☐ Controls	☐ Injector	☐ Test Results
☐ Cost	☐ Installation	☐ Vacuum
☐ Cryogenics	☐ Integration	☐ Other

ABSTRACT

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Low Energy Neutron Shielding for the Hall A Detector Huts

K.A. Aniol, CSULA and CEBAF

Abstract

Neutron shielding calculations for $E_n \leq 20$ MeV are described for the Hall A detector huts. Estimates are made for the dominant part of the neutron spectrum. Monte Carlo neutron and neutron induced photon transport calculations are detailed and expected rates for detector hut scintillators are computed.

Contents

(A) Total neutron rate

In order to decide on the thickness of the shield house walls an estimate of the total rate of neutron production must be made. There are three sources of neutron background in the hall;

(i) thin target and gas bag yield
(ii) outscattered beam
(iii) backward flux from the beam dump

The following discussion of the source terms comes from ref. (1).

(i) Thin target yield

The yield of neutrons from thin targets is estimated by determining a thick target equivalent power. Hadron yields scale as a ratio of photon track lengths. If we assume the following

- 4 GeV e^-
- 200 μA
- 15 cm He target at 2.55g/cm^2

then the equivalent thick target power is 8 Watts. For the 26 meter long He gas bag(1 atm) the equivalent thick power yield is 3.5 W. The total thin target yield is then equivalent to a thick target yield of 8W + 3.5W $\approx$ 12W.

(ii) Multiple scattering

Due to its passage through the target plus gas bag a certain portion of the beam power is diverted to the inside of the hall, rather than being deposited in the beam dump. This scattered power produces a thick target yield when it enters the walls of the hall near the beam dump entrance. The estimate[1] of the scattered beam power is 11W.

(iii) Beam dump back shine

The Hall A beam dump design is not yet finally established, but assuming a typical size of 2.1m$\times$2.1m aperture and 21.3m long we can estimate about 11W equivalent thick target yield.

The total thick target equivalent yield from these sources is then 12W + 11W +11W = 34W. A typical power loss in the halls has been estimated by Stapleton[1] to be 40W. We will use the latter figure. From the empirical results at SLAC[1] on an Al target say, we get 1.3×10^{12} n/s/kW. For 40W we therefore expect into the entire hall

$$Y_n = 4.4 \times 10^{10} n/s.$$

(B) Neutron spectrum shape

A model of the neutron spectrum shape used here has two basic components; a spectral shape determined by PICA calculations[2] at 750 MeV and an evaporative shape. This model will be used for the "direct" spectrum, i.e., the spectrum produced by the electron beam before the neutrons scatter. The direct spectrum is to be expected from the electrons scattered into the hall walls and viewed directly by the hut.

(i) PICA calculations

The PICA calculations extend from $E_n = 15$ MeV upwards. Although they were done at substantially different beam energies, $E_e = 300$ and 750 MeV, they reveal a similar exponential shape to the neutron energy spectrum between $E_n = 15$ and 100 MeV. We will assume that the same slope applies to the 4000 MeV electron beam for this neutron energy range. The exponential (integrated over 4π) spectrum is

$$Y_{exp}(E_n) = C_1 exp(-\alpha E_n),$$

with $\alpha = 0.0382$ MeV^{-1}.

(ii) Evaporation spectrum

Photonuclear excitation by the stopping electron beam will produce excited nuclei which will contribute a significant evaporation spectrum. We use for the nuclear temperature parameter a = 1.289 MeV(as suggested by the MCNP Monte Carlo code). The evaporation component is then

$$Y_{evap}(E_n) = C_0 E_n exp(-E_n/a).$$

(iii) Empirical SLAC yields

A measurement of stopping electrons at $E_e = 6300$ MeV for various materials has been reported[3]. For an Al target the following results were obtained.

TABLE 1 - Neutron yields for 6300 MeV electrons stopping in Al[3]

	E_n	number of neutrons(relative)
(a)	$1\text{keV} \leq E_n \leq 10\text{MeV}$	4.4
(b)	$2.5\text{MeV} \leq E_n \leq 25\text{MeV}$	2.3
(c)	$E_n \leq 25\text{MeV}$	5.6
(d)	$E_n \geq 25\text{MeV}$	0.88

We can use this table to fit the parameters C_1 and C_0 in the two component model of the neutron spectrum,

$$Y(E_n) = C_0 E_n exp(-E_n/a) + C_1 exp(-\alpha E_n).$$

From case (a) and (c) in Table 1 we surmise

$$Y(E_n) = C(12.2 E_n exp(-E_n/a) + exp(-\alpha E_n)).$$

This model spectrum produces a ratio

$$R_{mod} = \frac{\int_0^{25} Y(E_n) dE_n}{\int_0^{\infty} Y(E_n) dE_n} = 0.78,$$

compared to the empirical result

$$R_{meas} = \frac{5.6}{5.6 + 0.88} = 0.86.$$

From this measurement it is clear that the low energy neutrons, $E_n \leq 25$ MeV are predominant in the direct spectrum. For parts of the hut, the top and back, for example, that do not view directly the electron beam , neutron scattering will produce an even softer spectrum.

The overall normalization "C" can be determined by requiring that the integral of the spectrum over energy and angle be consistent with the total power lost(40W). Since the measurements show that the low energy neutrons are isotropically distributed we require for 40W

$$4.4 \times 10^{10} n/s = 4\pi C \int_0^{\infty} dE_n (12.2 E_n exp(-E_n/a) + exp(-\alpha E_n).$$

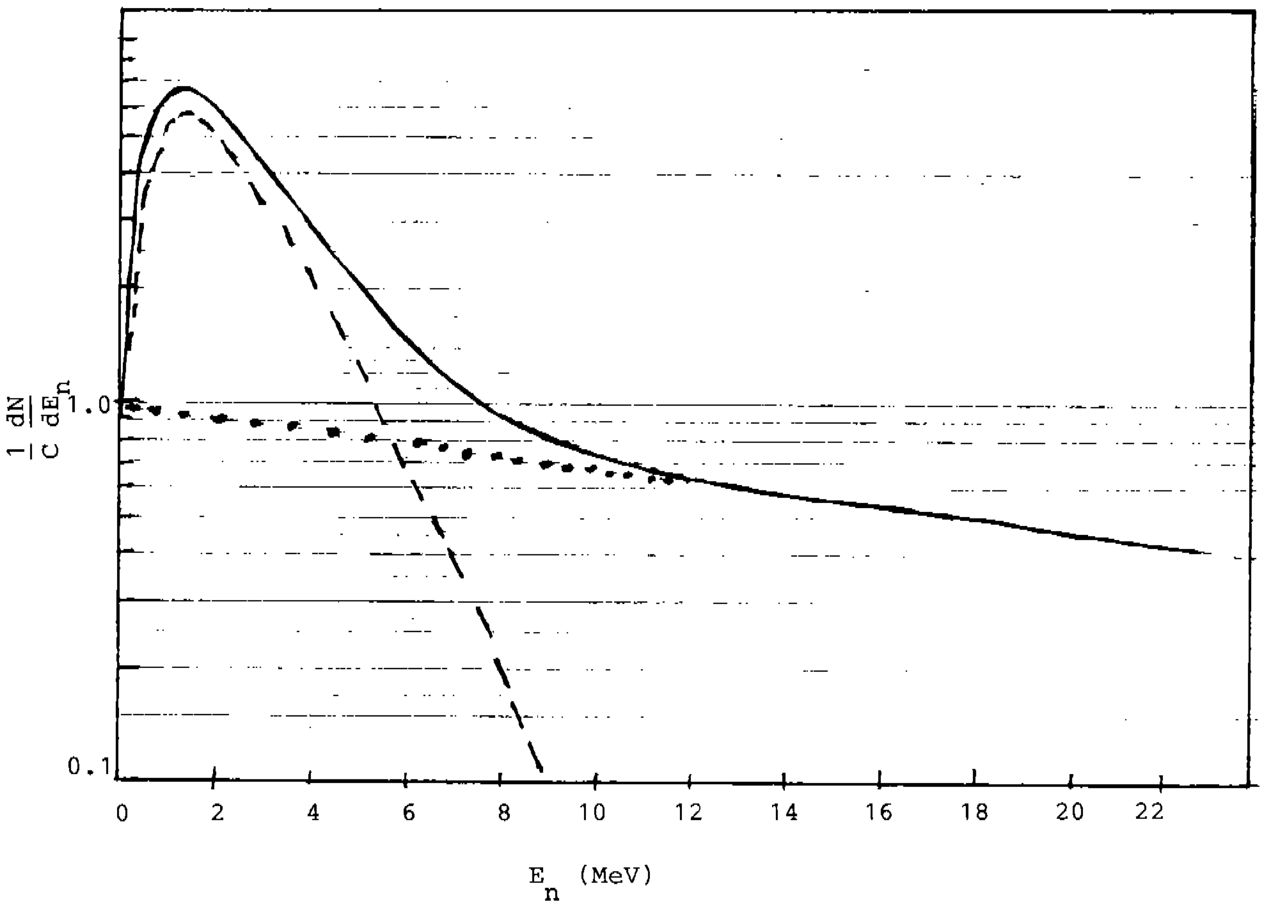
hence

$$\frac{dN}{dE_n d\Omega dt} = \frac{1.2 \times 10^9}{4\pi} (12.2 E_n exp(-E_n/a) + exp(-\alpha E_n)) \frac{n}{s \cdot MeV \cdot sr}.$$

with $a = 1.289 MeV$ and $\alpha = 0.0382 MeV^{-1}$. A plot of this spectrum is shown in figure 1.

Figure 1

Model of "direct" neutron spectrum with evaporative and exponential components



(C) Monte Carlo neutron transport studies for selected energies and materials

The neutron-photon transport code MCNP(3B)[4] was set up and run on CEBAF9 for these studies. Unfortunately, the cross section tables supplied with this code only go up to $E_n =$ 20 MeV. However, as we have seen from the previous discussion, most of the neutrons of concern fall within the energy range covered by these tables. It was noted[5] using FLUKA calculations for high energy($E_n \geq 50$ MeV) neutron transport and production that high energy neutrons were quite negligible sources of charged particle background in the hut compared to muons. Moreover, from a practical point of view there is very little we can do to shield against high energy neutrons. Even between $E_n = 1$ MeV and $E_n = 20$ MeV(see table 2) there is a factor of over 300 in the transmission through a 75 cm thick, boron doped concrete wall. Fortunately the neutron spectrum works in our favor so that the neutrons that are the hardest to stop are the least abundant.

In the models that follow discrete energy neutron beams were transported into the center of a wall 400cm$\times$800cm$\times$T. The thickness T was divided into two parts, T_1 with no boron, and T_2 with 1% boron by weight as B_4C(1% compared to ordinary LASL concrete,$\rho =$ 2.25 g/cm^3 = 150 lb/ft^3). The thicknesses were adjusted so that $T_1+T_2 = T$. In the case of high density concrete(ρ=3.03 g/cm^3 = 200 lb/ ft^3) the atomic fraction of boron was kept the same so the fraction by weight was set at 0.74%. Table 2 compares ordinary concrete and high density concrete where $T_2 = \frac{1}{3}T$, and a 5 cm thick Pb wall follows T_2. $N_0 = 10^5$ initial neutrons were used per case. A broader comparison is made in Table 3. Columns (E) and (D) in Table 3 show the benefit of adding boron to the concrete. Also it is useful to note that the boron need not be uniformly present in the concrete. A substantial savings in boron is possible by doping only a layer near the back wall. The results for pure iron are also shown in column (F). It is evident that iron compares poorly to concrete as a medium for stopping low energy neutrons. For example, for $E_n = 1$ MeV, a 75cm concrete-boron wall reduces the neutron flux by a factor of 600 better than a 75 cm thick iron wall. The table also reveals that we are better off with a 40 cm concrete-boron wall than a 20 cm iron wall for the top and back of the hut. As far as low energy neutron shielding is concerned there seems to be no useful place for solid iron walls in the hut.

Based on linear thickness, high density concrete is better than ordinary concrete. However, when the transmission is plotted vs ρT, ordinary concrete is more effective(see figure 2). A case in favor of high density concrete can be made in geometrically confined areas such as the top and back of the hut.

Table 2

Transmission through ordinary(2.25g/cm^3) and high density (3.03g/cm^3) concrete for 10^5 incident neutrons.

E_n (MeV)	T_1 (cm)	T_2 (cm)	Pb (cm)	trans. (2.25g/cm^3)	trans. (3.03g/cm^3)
1	25	13	5	1.1×10^{-2}	2.8×10^{-3}
1	50	25	5	8×10^{-5}	0
1	67	33	5	0	0
2.5	27	13	5	0.101	5×10^{-2}
2.5	50	25	5	6.89×10^{-3}	1.32×10^{-3}
2.5	67	33	5	7.6×10^{-4}	1.0×10^{-4}
5	27	13	5	0.15	7.4×10^{-2}
5	50	25	5	1.64×10^{-2}	3.3×10^{-3}
5	67	33	5	2.76×10^{-3}	3.8×10^{-4}
10	27	13	5	0.128	8.2×10^{-2}
10	50	25	5	1.35×10^{-2}	4.4×10^{-3}
10	67	33	5	2.28×10^{-3}	4.5×10^{-4}
20	27	13	5	0.227	0.15
20	50	25	5	2.73×10^{-2}	1.1×10^{-2}
20	67	33	5	5.58×10^{-3}	1.65×10^{-3}

Table 3

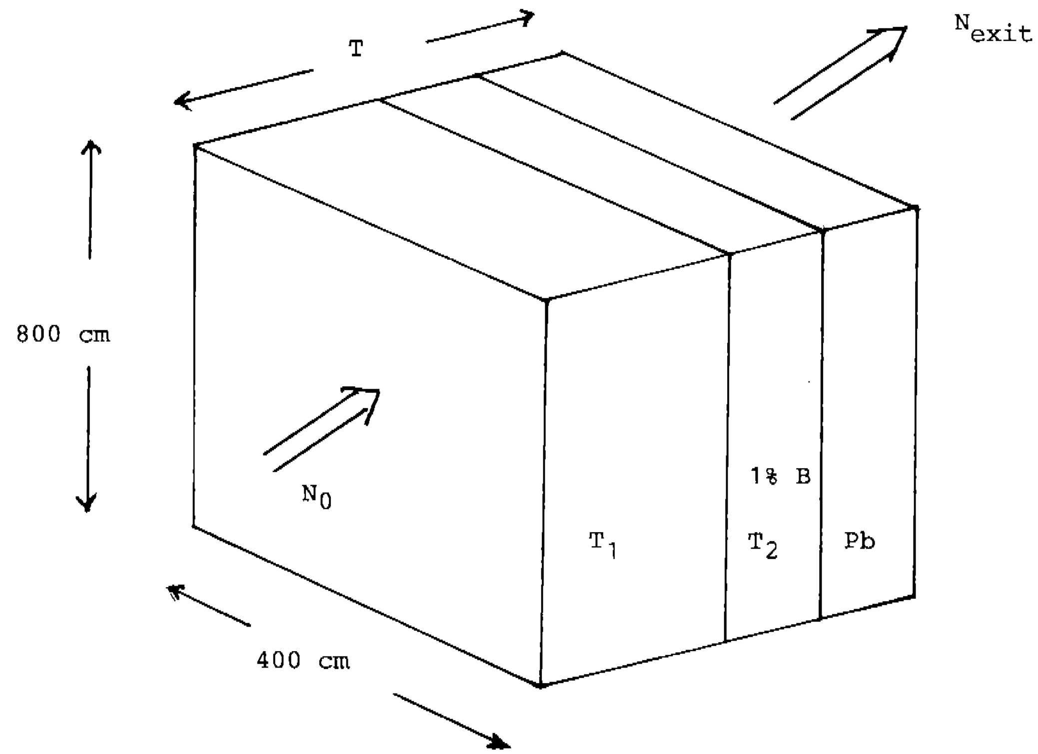
Neutron transmission for varied energies and wall compositions†

E_n (MeV)	T (cm)	A	B	C	D	E	F
1	10						0.42
1	15						0.33
1	20		0.15				0.28
1	40	0.011	0.019				
1	50		0.0052	0.0048	0.0046	0.031	0.121
1	75	0.00008	0.00012	0.00008	0.00011	0.0045	0.063
1	100	0.0	0.0	0.0	0.0	0.00042	0.032
2.5	10						0.49
2.5	15						0.39
2.5	20		0.45				0.32
2.5	40	0.101	0.14				
2.5	50	0.068	0.067	0.067	0.136	0.15	
2.5	75	0.0069	0.0099	0.0092	0.0093	0.031	0.086
2.5	100	0.00076	0.0011	0.0011	0.00099	0.0054	0.046
5	10						0.52
5	15						0.41
5	20		0.49				0.34
5	40	0.15	0.19				
5	50		0.11	0.11	0.11	0.17	0.15
5	75	0.0164	0.022	0.022	0.021	0.0476	0.086
5	100	0.00276	0.00375	0.0035	0.0037	0.0115	0.045
10	10						0.55
10	15						0.43
10	20		0.41				0.35
10	40	0.128	0.15				
10	50		0.084	0.084	0.083	0.124	0.16
10	75	0.0135	0.0173	0.017	0.017	0.035	0.089
10	100	0.00228	0.0032	0.0032	0.0029	0.0078	0.048
20	10						0.73
20	15						0.63
20	20		0.55				0.55
20	40	0.227	0.23				
20	50		0.14	0.14	0.13	0.20	0.27
20	75	0.0273	0.03	0.03	0.031	0.06	0.15
20	100	0.0056	0.0066	0.0059	0.0061	0.015	0.08

† for 10^5 incident neutrons

A	5cm Pb,ordinary concrete,$T_2 = \frac{1}{3}T$,1% B
B	same as A except **no lead**
C	no lead,ordinary concrete $T_2 = \frac{1}{2}T$,1% B
D	no lead,$T_2 = T$, 1%B
E	ordinary concrete, no boron ,no lead
F	iron, no lead

Geometry for Monte Carlo calculations



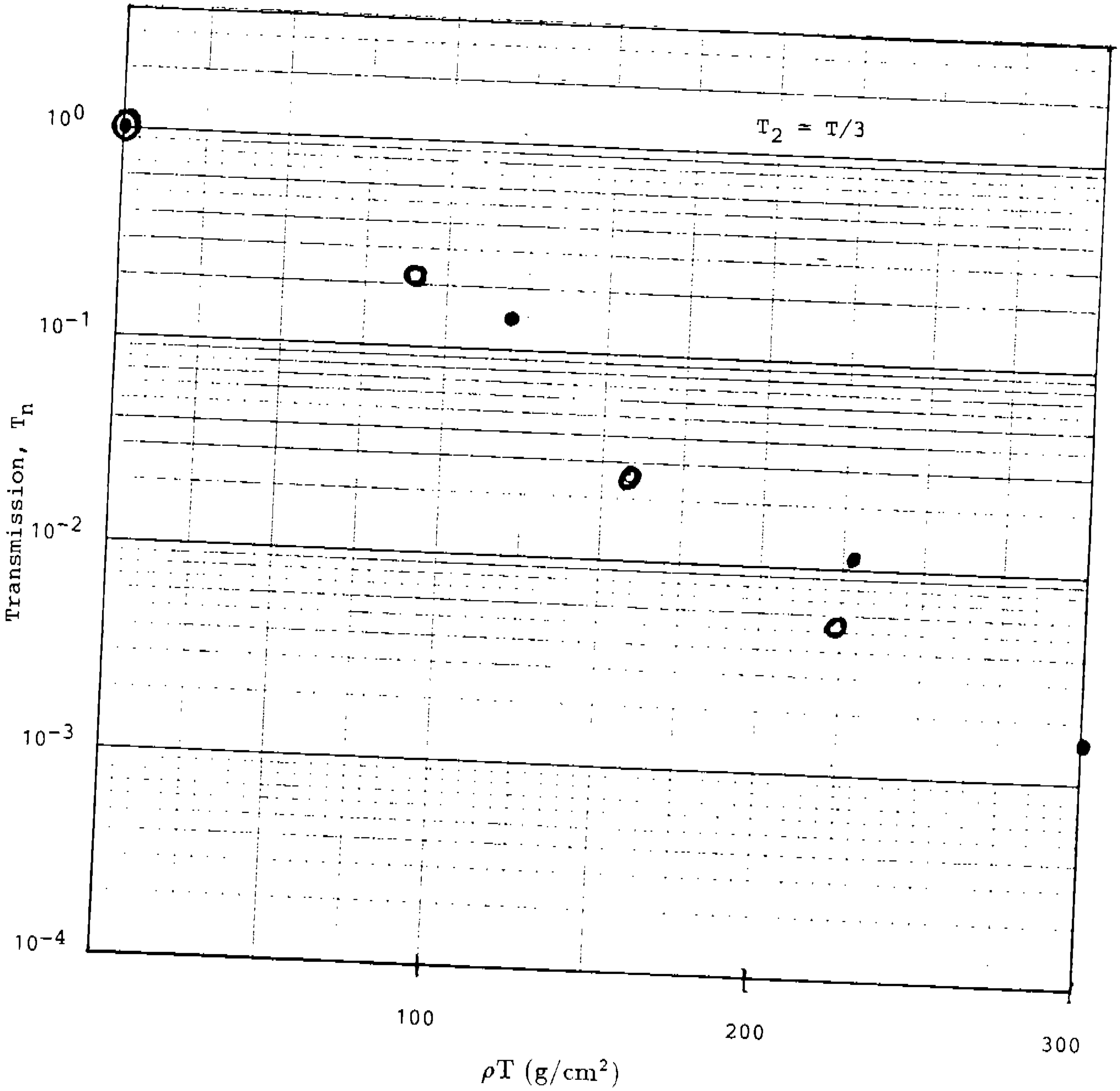
transmission = N_{exit}/N_0

Figure 2

Transmission of 20 MeV Neutrons through a 400 × 800 × T cm^3 wall.

● = high density concrete, ρ=3.03 g/cm^3, 0.74% B in T_2

○ = ordinary concrete, ρ=2.25 g/cm^3, 1% B in T_2



(D) Transmission studies using a model neutron spectrum

(i) High density concrete

If the spectrum from figure 1 is incident on a wall of $T_2=\frac{1}{3}T$, boron concentration = 0.74% in T_2, high density(ρ=3.03 g/cm^3) concrete plus 5 cm of lead (as depicted in the figure in Table 3), a neutron spectrum emerges from the Pb wall as shown in figure 3. Notice the log-log scale. The total transmission probability of neutrons (summed over energy and across the whole lead wall) is shown in figure 4 plotted against ρT.

(ii) Ordinary concrete

Figures 5A,B,C are the counterparts of figure 3 for the same geometrical thickness. The total transmission probability vs ρT is also plotted on figure 4. The number of incident neutrons in these cases was 500000 and their initial velocities were perpendicular to the surface. Cases were also run (for $N_{incident}$ = 200000) where the initial directions were isotropically chosen. In these cases the photons generated by neutron interactions were also tracked. A particular case for ordinary concrete and T = 80 cm with varying T_2 is shown in table 4. The transmission probabilities T_n and T_γ give the total number of neutrons or gammas appearing after the lead wall per incident neutron. From table 4 one notes that not very much boron is needed to reduce the neutron flux. In fact, with 5 cm of boron doped concrete the minimum neutron transmission is already attained. The number of neutron induced photons is more sensitive to the thickness of boron used, however, the total transmitted gamma flux is at least about four times smaller than the transmitted neutron flux. Figure 6 shows the transmitted neutron induced gamma spectrum for T = 80 cm and T_2 = 20 cm.

Table 4

T_n and T_γ for T=80 cm, and 1% B doping in $T_2^\dagger$

T_2(cm)	T_n	T_γ
0	6×10^{-3}	8.2×10^{-4}
5	2.6×10^{-3}	7.2×10^{-4}
10	2.55×10^{-3}	6.4×10^{-4}
20	2.52×10^{-3}	4.8×10^{-4}
35	2.65×10^{-3}	2.8×10^{-4}
50	2.38×10^{-3}	2.0×10^{-4}
65	2.59×10^{-3}	1.83×10^{-4}
80	2.43×10^{-3}	1.19×10^{-4}

† for 200000 isotropic incident neutrons

Figure 3

Neutron energy spectrum leaving lead wall for model incident spectrum, $N_{incident} = 500000$, $T_2 = \frac{1}{3}$ T , and high density concrete, $\rho = 3.03$ g/cm^3.

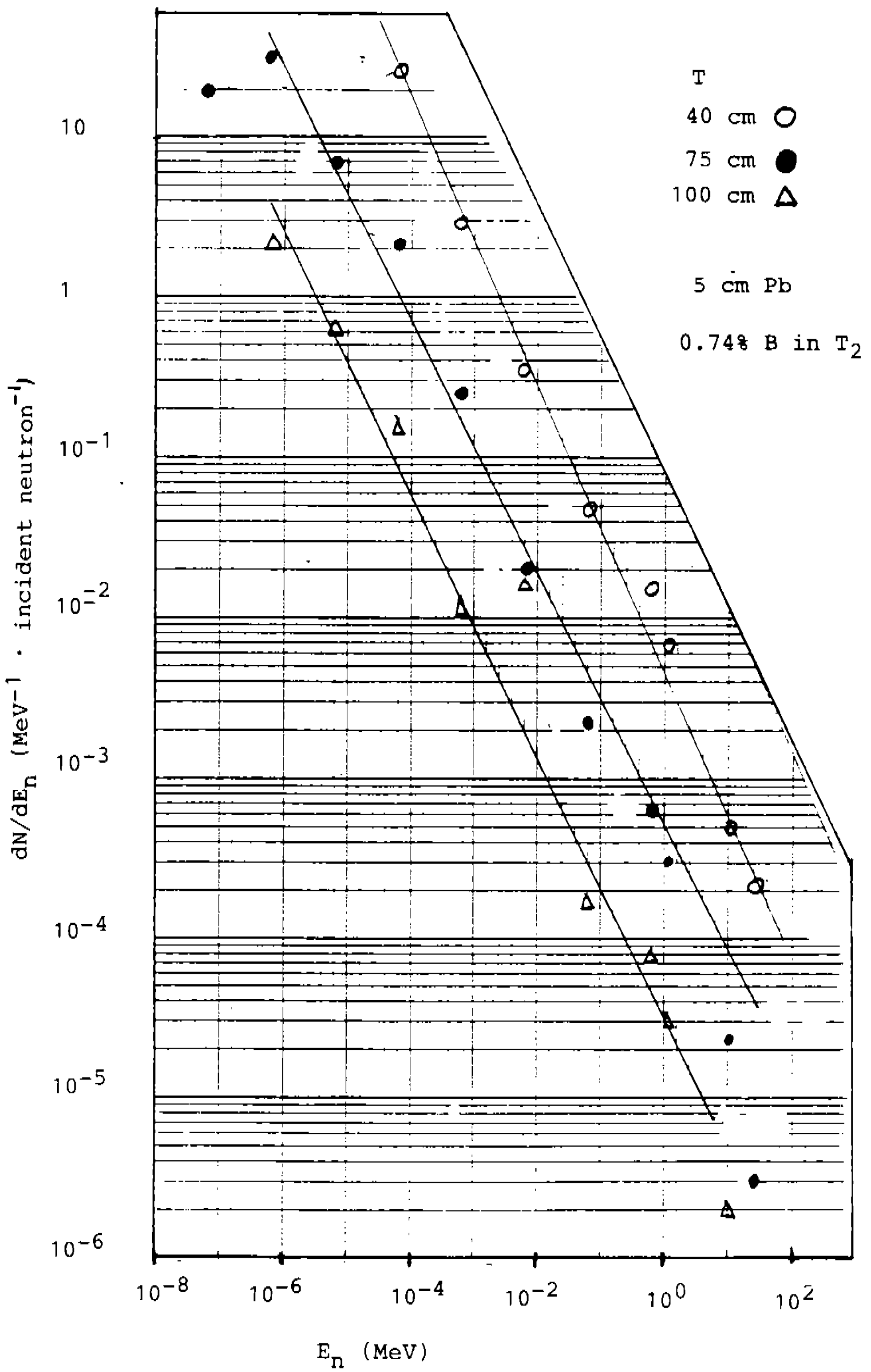


Figure 4

Total neutron transmission probability for the model neutron spectrum for a $400\times 800\times$ T cm^3 wall for $T_2 = \frac{1}{3}$ T.

● = high density concrete, ρ=3.03 g/cm^3, 0.74% B in T_2
O = ordinary concrete, ρ = 2.25 g/cm^3, 1% B in T_2

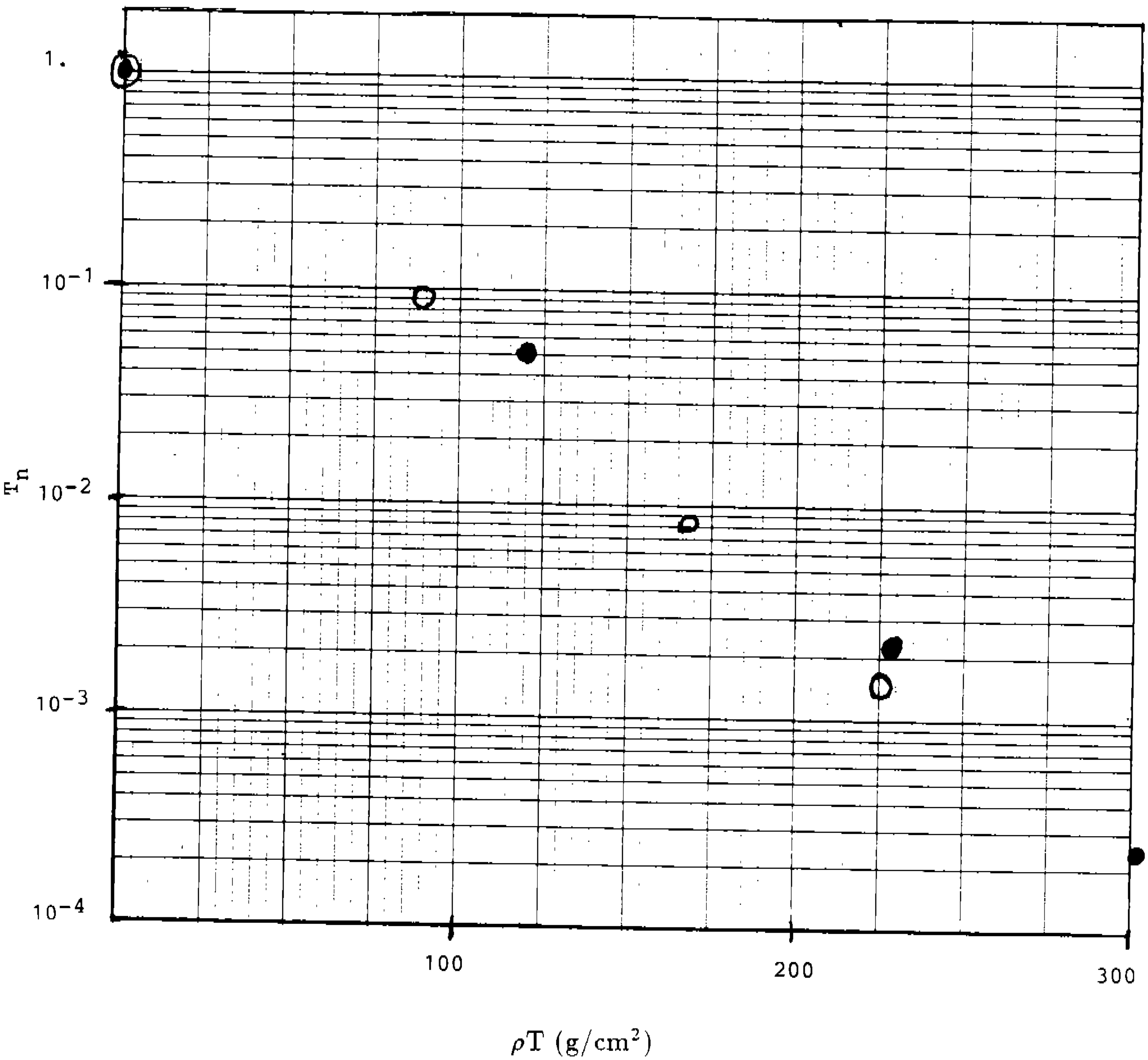


Figure 5A

Neutron energy spectrum after passing through wall for incident model spectrum, T = 40 cm, ordinary concrete, $T_2 = \frac{1}{3}$ T , 1% boron doping in T_2.

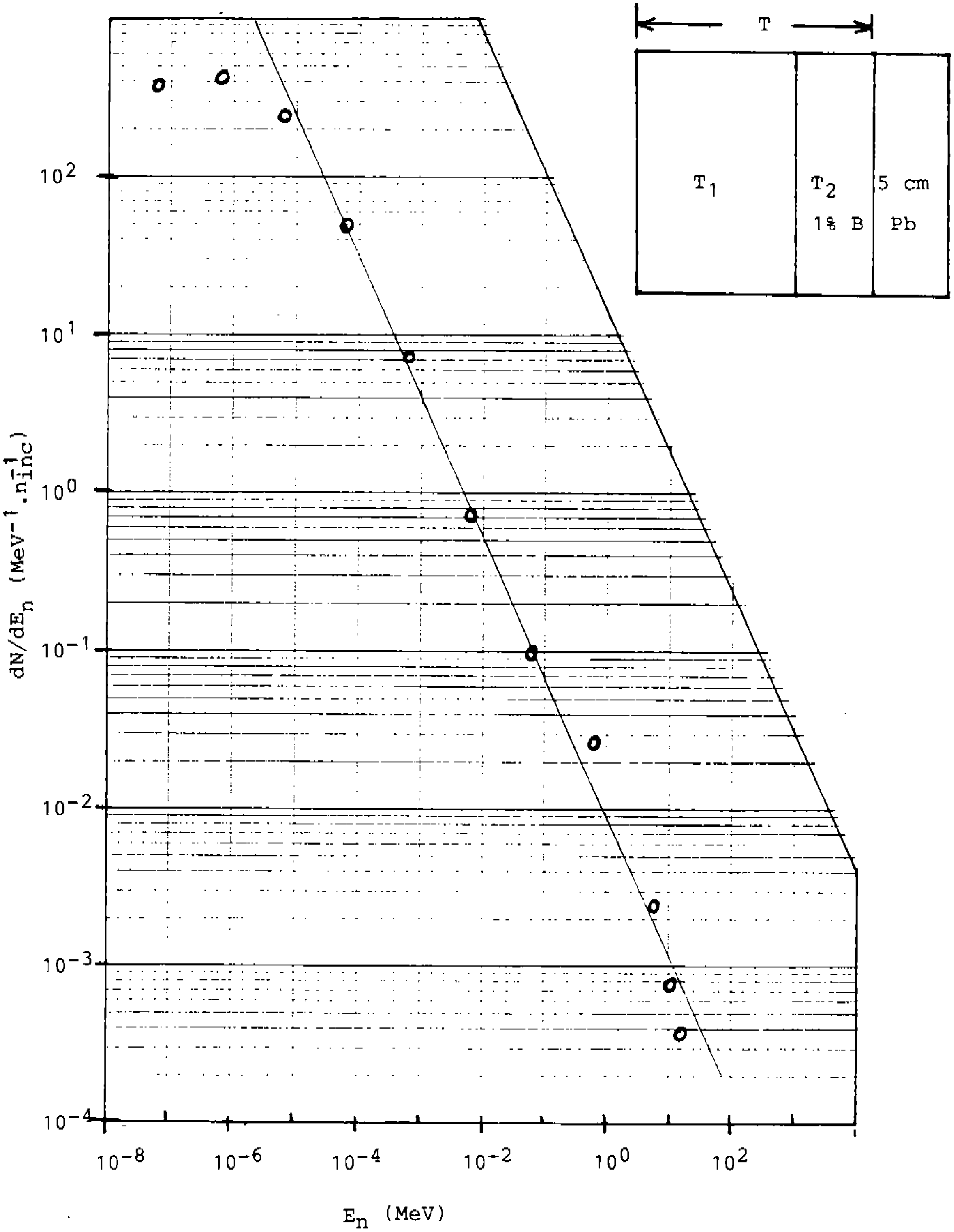


Figure 5B
Same as 5A except T = 75 cm

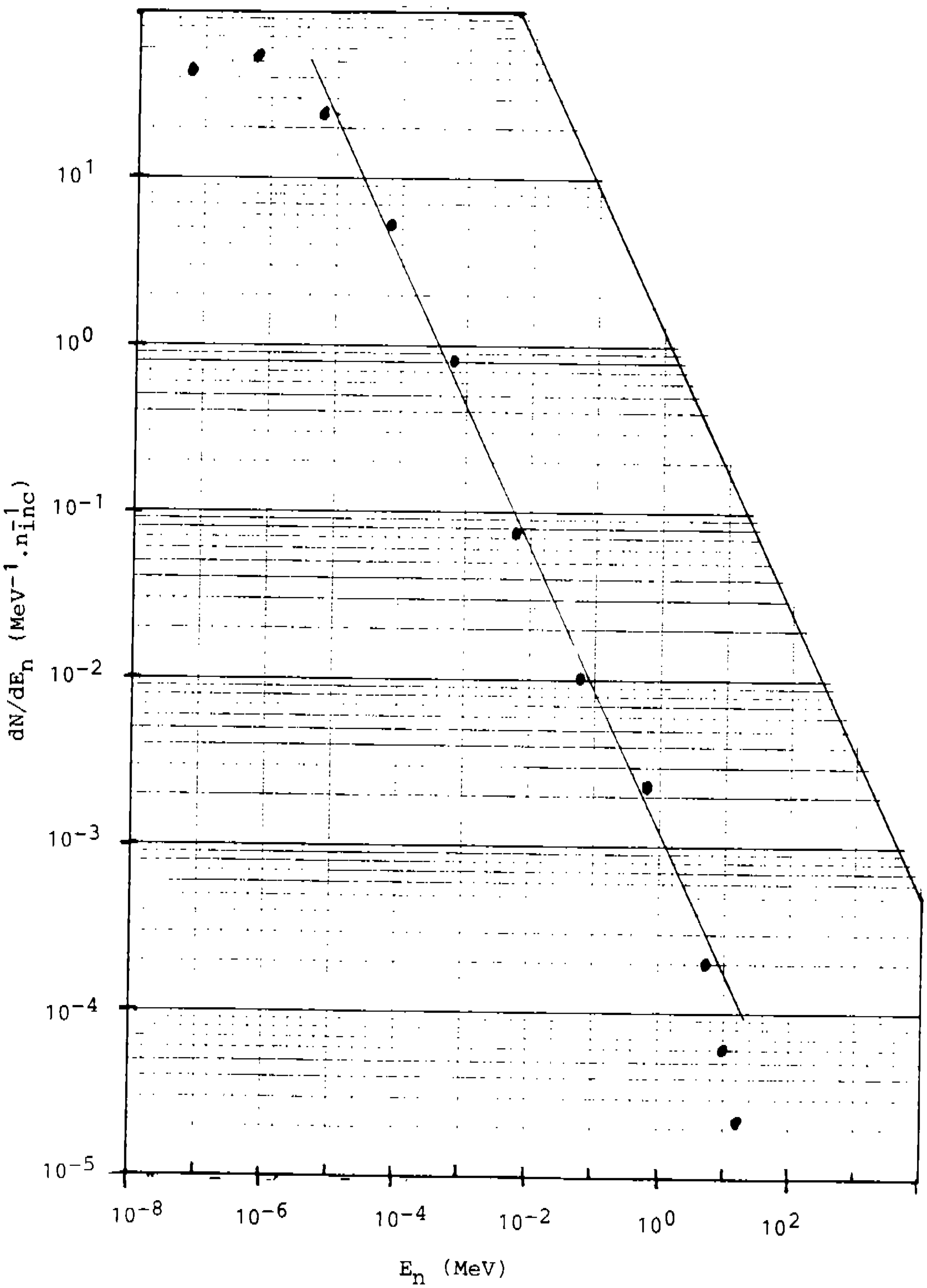


Figure 5C
Same as figure 5A except T = 100 cm

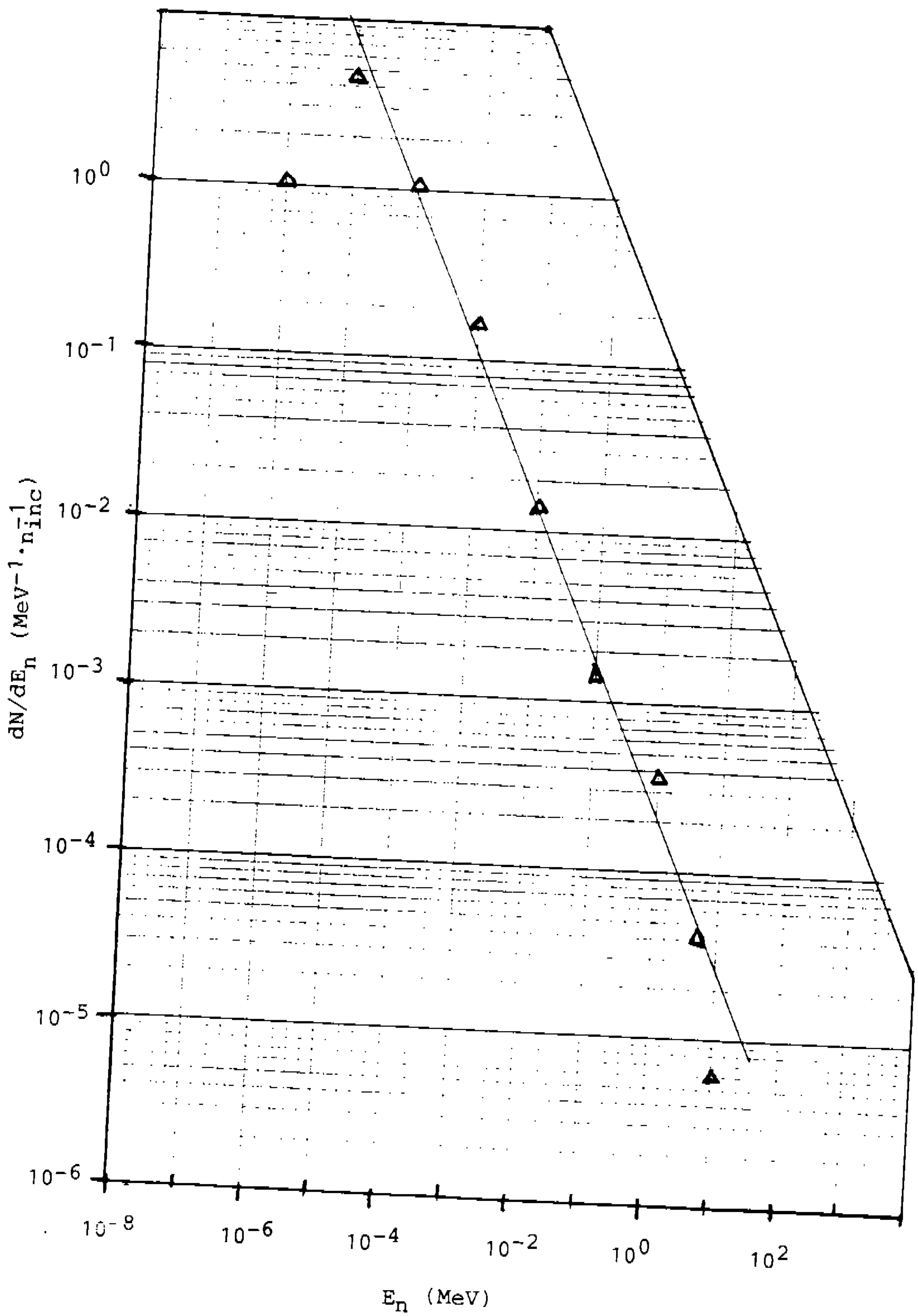
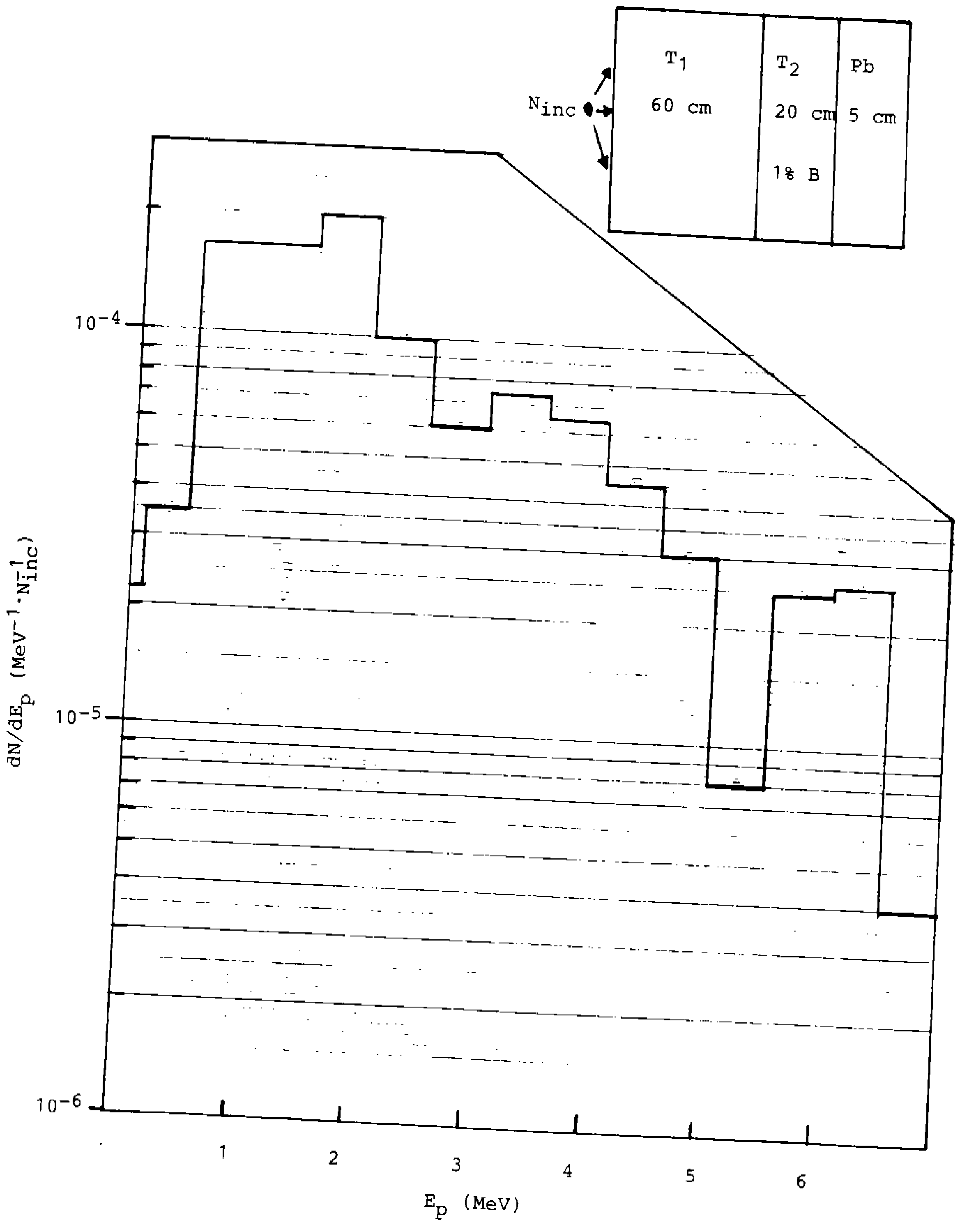


Figure 6
Gamma ray spectrum entering hut induced by incident (isotropic) model neutron spectrum



(E) Estimate of rates in a 1 m^2 scintillator

Knowing the neutron spectrum entering the hut (i.e. Figs 3 and 5), we can now estimate the rate seen by a scintillator of area A_s. We assume a CH_2 slab ($\rho = 1$ g/cm^3). The area of the inside wall is $A_w = 32$ m^2. The thickness of the CH_2 slab was chosen to be 0.32 cm. Over the neutron energy range of 10^{-8} to 20 MeV we will include two processes in the neutron induced rate calculation, capture and collision. Since there will be a threshold on the scintillator counter, collisions will only be important for $E_n \geq 10^{-2}$ MeV. Capture processes can contribute to the rate at all energies. By running discrete energy neutrons through the CH_2 slab we obtain the capture and collision probabilities at these energies. In figure 7 we see a plot of these probabilities. The capture probability is at most a few percent and drops off rapidly with energy above 10^{-4} MeV. The collision probability is large for 0.01 to 0.1 MeV neutrons. Call $P_{react}(E_n)$ the probability that a neutron of energy E_n will interact in the CH_2 slab. The differential reaction rate for neutrons of energy E_n is

$$dR(E_n) = dE_n \frac{dN}{dE_n} P_{react}(E_n).$$

The total reaction rate, per incident neutron outside the hut is,

$$R = \int_{0MeV}^{20MeV} dR(E_n).$$

Both the transmitted neutron spectrum and the reaction probabilities were fitted to a form αE_n^β for different energy ranges. This enables an analytical integration to be performed. In all cases the rate due to capture is at least 100 times smaller than that due to collision. Once R (per incident neutron) is obtain the rate for the total incident beam of N_0 neutrons is

$$R_{tot} = \frac{A_s}{A_w} N_0 R.$$

N_0 can be estimated by assuming a spectrometer position of 12.5 deg. The hut sees the entrance to the beam dump where the out scattered beam strikes the hall wall. This produces the direct neutron spectrum. From part (A) we recall this represents about $\frac{1}{3}$ of the total power (thick target equivalent) in the hall. So N_0 can be obtained by

$$N_0 = \frac{1}{3} \Delta\Omega_{hut} \frac{1.29 \times 10^9}{4\pi} \frac{n}{s \cdot MeV \cdot sr} \int_0^\infty f(E_n) dE_n,$$

where $f(E_n)$ is the evaporative-exponential shape described in part (B). Estimating $\Delta\Omega_{hut}$ = 0.26 sr for $\theta_{spect} = 12.5$ deg. , we get

$$N_0 = 3 \times 10^8 n/s.$$

Table 5 compares the rates for ordinary vs high density concrete and also lists the reaction probability per incident neutron(external), R.

Figure 7

Reaction probabilies for neutrons of energy E_n in a CH_2 slab 0.32 cm thick, $\rho = 1\mathrm{g/cm^3}$

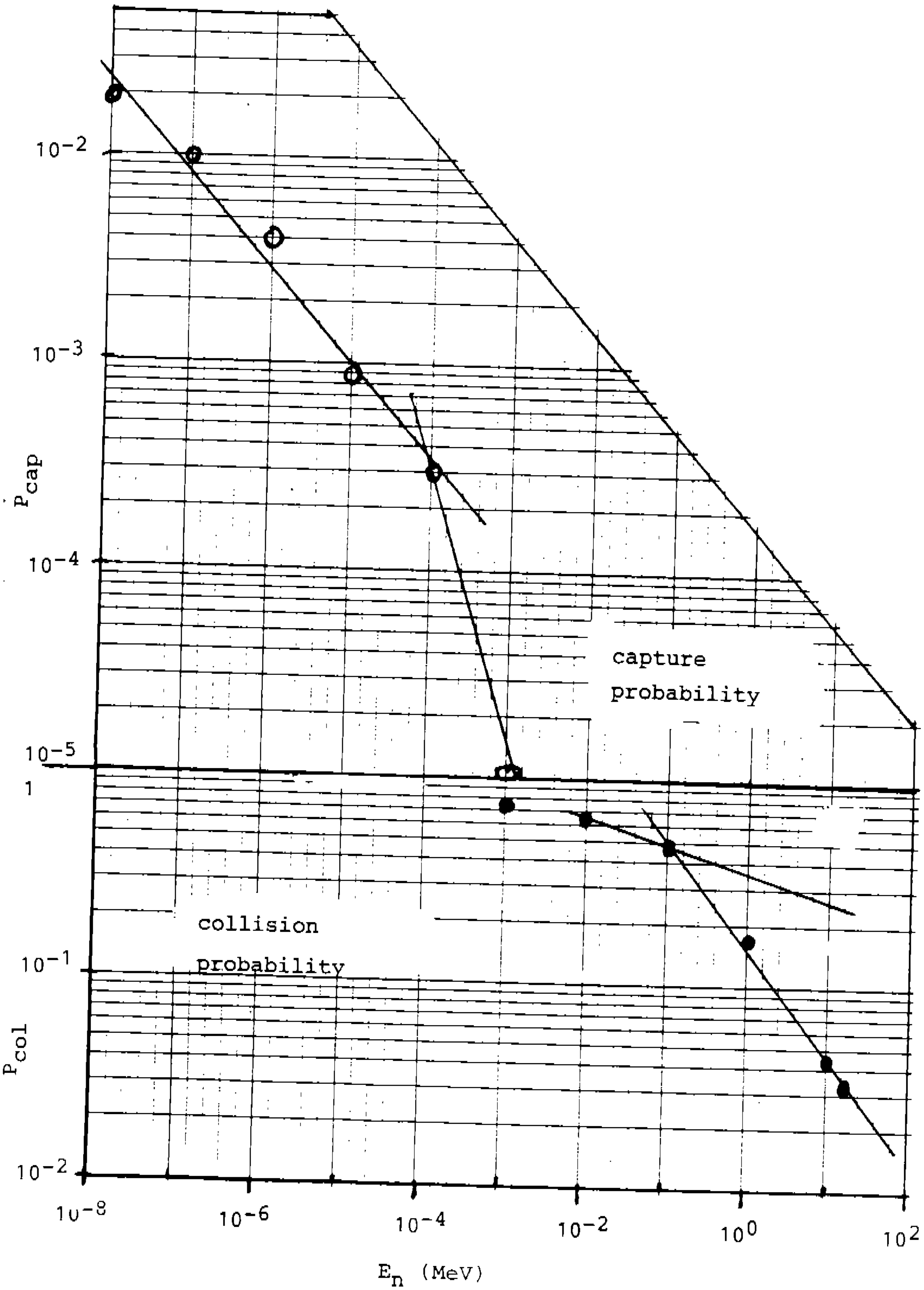


Table 5
Estimate of rates in a 0.32 cm thick scintillator
$N_0 = 3\times10^8$ n/s, $A_s/A_w = 1/32$, rates in m^{-2} s^{-1}

	ordinary concrete		high density concrete	
T(cm)	$R(n_{inc}^{-1})$	rate	$R(n_{inc}^{-1})$	rate
40	1.5×10^{-2}	142K	7.5×10^{-3}	70K
75	1.8×10^{-3}	17K	7×10^{-4}	6.6K
100	3.7×10^{-4}	3.5K	4.6×10^{-5}	0.43K

The rates in table 5 are plotted vs ρT in figure 8. It appears from figure 8 that we get better shielding for low energy neutrons by using ordinary concrete when compared to the total mass needed. High density concrete is only advantageous in tightly constricted geometries.

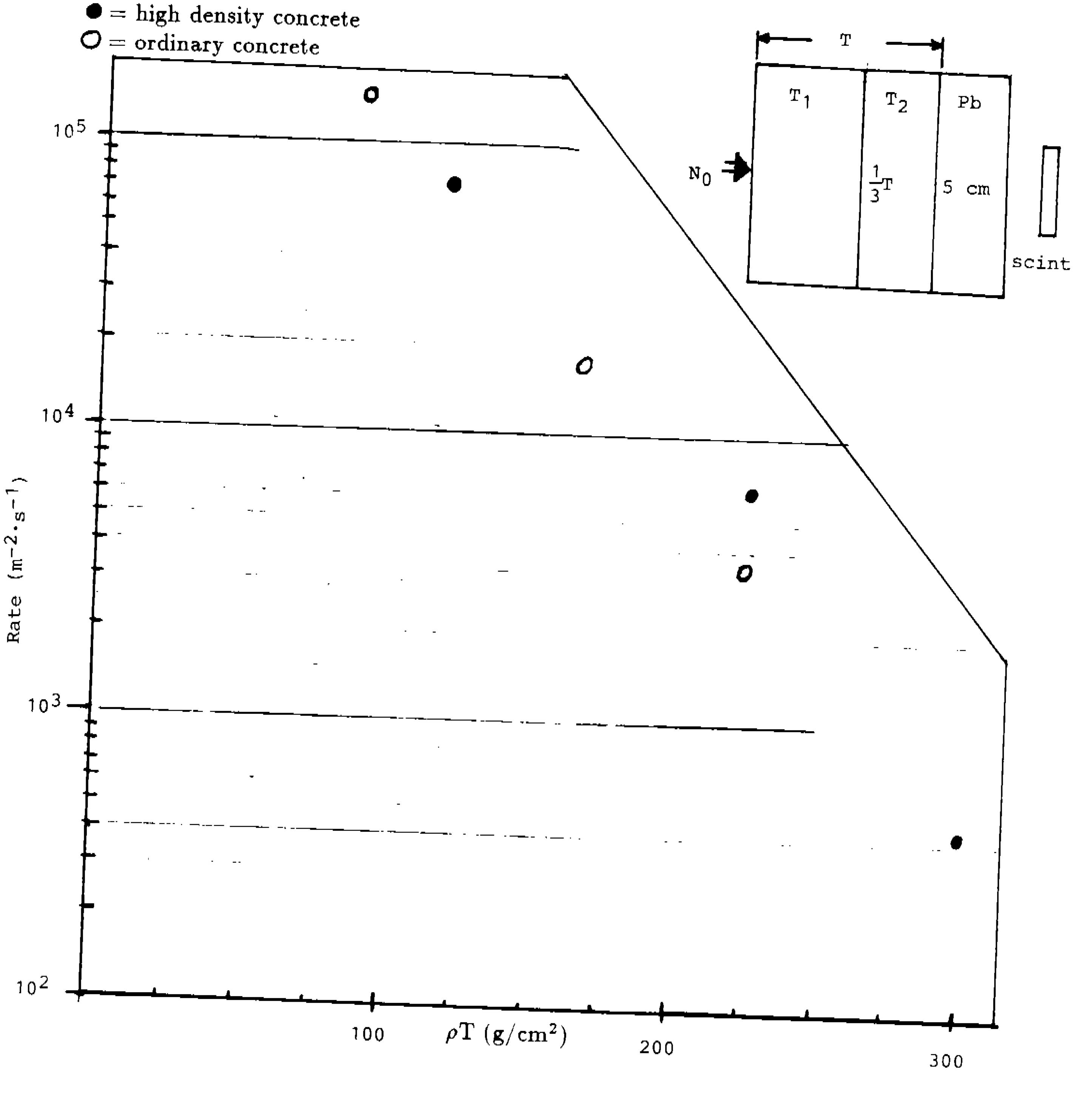
The contribution of neutron induced photons to the rate is negligible compared to the rate in the scintillator due to transmitted neutrons. For a 0.32 cm thick CH_2 slab the probability that a 100 KeV gamma ray interacts is about 5% and at 8 MeV this drops to 0.8% [6]. For T = 80cm, T_2 = 20 cm, ordinary concrete, $T_\gamma = 4.8\times 10^{-4}$ for the whole spectrum. The maximum gamma trigger rate in the 1 m^2 scintillator is then

$$R_\gamma^{tot} \leq \frac{1}{32} 3 \times 10^8 \times 0.05 \times 4.8 \times 10^{-4} = 225 s^{-1}.$$

The neutron induced rate under these conditions is about 15K s^{-1}. Therefore the extra cost to make T_2 larger than about 5 cm is not warranted by a reduction in background rate due to neutron induced photons.

Figure 8

Rates in a scintillator 0.32cm×1m² for $N_0=3\times10^8$ n/s on outer hut wall

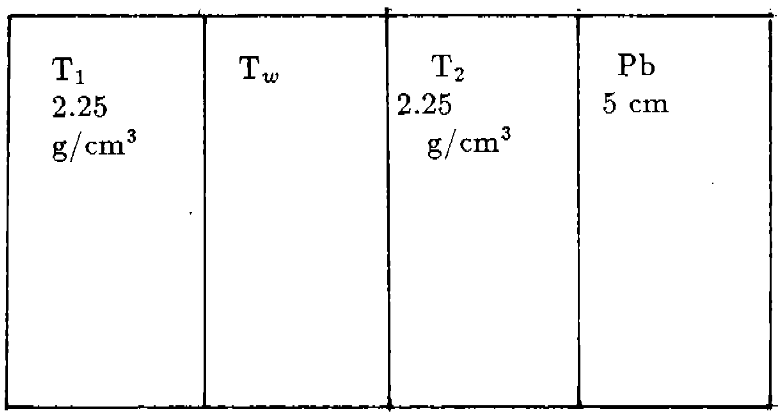


(F) Use of high density wood, water, and borax in shielding

Concerns about the great weight of the shield house (total weight of shield house and gantry is about 2.1×10^6 lbs for 100cm thick ordinary concrete) led us to consider alternate materials. Firstly, if we drop the wall thickness to 80 cm of ordinary concrete the total weight goes to about 1.79×10^6 lbs(as per calculations by Fred Harrel). A suggestion was made (Oscar Rondon, hall A users' meeting, June,1991) to incorporate high density ($\rho \approx 1.25$ g/cm^3) wood in the shield design. The use of hydrogenous material before the boron doped concrete should result in more effective neutron absorption. A series of calculations was performed using the geometry shown in figure 9 where T_w is a thickness of hardwood(C=56.1%,O=37.5%,H=6.74%) or water.

Figure 9

Composite shield wall construction, T_2=20cm, 1%B, 5cm Pb



A substantial reduction in the total neutron transmission can be realized by the use of the composite construction. The results of the study are tabulated in table 5. A comparison of table 4 (T=80 cm concrete) and table 5 for T=80 cm concrete reveals a decrease in total neutron flux by around a factor of 15. This is better than the factor of five one obtains with an extra 20cm of concrete(T=100 cm concrete). A special case of T_1=75 cm ordinary concrete followed by 25 cm of borax(ρ=0.9 g/cm^3, H = 5.25 %, B=11.33%,O = 71.32%, Na = 12.1%) followed by 5 cm of Pb was run and gave $T_n = (3.0\pm0.35)\times10^{-4}$.

Table 5

T_n for T_2=20 cm(1%B), ordinary concrete, isotropic model neutron spectrum, N_{inc}=1,250,000 ,using a composite construction of hardwood or water.

T_1 (cm)	T_w (cm)	T_n wood	T_n water
40	40	$(1.9\pm0.19)\times10^{-4}$	$(1.3\pm0.16)\times10^{-4}$
50	30	$(1.7\pm0.17)\times10^{-4}$	$(1.1\pm0.14)\times10^{-4}$
60	20	$(2.2\pm0.19)\times10^{-4}$	$(1.6\pm0.16)\times10^{-4}$

(G) Vendors and material cost quotations

high density concrete

contact - May 7,1991 , Mr. Manjit S. Chopra, (602) 748-9364
Nuclear Shielding Supplies and Service,Tucson ,Arizona 85714
cost $500/yd^3 for 200 lb/ft^3 high density concrete installed
see appendix for vendor information sheet

boron

contact - April 18,1991, Elizabeth A. Davis (203) 966-9999
Wacker Chemicals (USA) Inc., 50 Locust Ave,New Canaan, CT 06840
B_4C 12 mesh and finer, 78% B content ,12000 lb at $16/lb
see appendix for vendor information sheet

contact - April 1991, Gary Asbach, Washington Mills Co., (716) 278-6736
dust collector finds, 120μ, 70% boron content 200 lb drums $11-$12/lb

contact - April 12,1991, James N. Barker, (708) 971-0644
Chi-Vit Corporation, 1430 Branding Lane, Suite 115, Downers Grove Illinois 60515
boron frit, 16% boron content $194/100lb bag
see appendix for vendor information sheet

contact - April 18,1991, Dean White, (408) 745-6770
Reactor Experiments, Inc. 1275 Hammerwood Ave, Sunnyvale, CA 94089 -2231
5% boron-polyethylene sheet 48"×48"×2" at $970 per sheet
see appendix for vendor information sheet

contact - April 19,1991, Rod O'Connor, (201) 391-8600
U.S. Borax Corp.,60 Craig Road, Montvale, NJ, 07645
borax $231/ton bulk or $276/ton as 100 lb bags
see appendix for vendor information sheet

(H) Summary

With an ordinary concrete wall of thickness 75 cm plus a 5 cm ordinary concrete wall doped with boron to 1%, the neutron induced count rate in a $1m^2 \times 0.32$cm scintillator will be about 15K s^{-1} for the extreme case of running 200μA on a thick target at forward angles. A substantial reduction in the neutron transmission can be achieved by using an intervening hydrogenous material between the ordinary concrete and the boron doped concrete. However, it is not likely that the added expense and complexity of incorporating a water or wood interlayer is justified in the likelyhood of a total rate of 1 MHz transmitted through the spectrometer itself. The top and backwalls of the hut should be made from high density concrete(with a 5cm layer of boron doped (0.74%) high density concrete) with a total thickness of 40 cm. A layer of Pb, 5 cm thick, should line the inside of the hut. With a hut constructed as outlined above the total weight of the hut plus gantry is 85% of the maximum weight to be supported by the bogies.

References

(1) CEBAF Technical Note, TN0138, July 1989, G.Stapleton "Radiation Source Terms for the End Stations"

(2) ORNL /TM-10036 , August,1986, T.A.Gabriel,R.A.Little,B.L. Bishop "Shielding Considerations for the 750 MeV Electron Accelerator at the University of Illinois"

(3) Nucl. Phys **B2** 669(1967), G.Bathow, E.Freytag, K. Tesch

(4) MCNP 3B - Monte Carlo Neutron and Photon Transport Code System RSIC Code Collection, CCC-200, LA-7396-M,Rev.2, Sept,1986, Los Alamos National Laboratory, Judith F. Briesmeister, Editor

(5) CEBAF Technical Note, TN-91-024, March 1991, K.A. Aniol, V.Punjabi "Hall A Line of Sight Shielding"

(6) Int. J. Appl. Radiat. Isot. **33** 1269(1982), J.H.Hubbel

Appendix of Vendor Quotes

NUCLEAR SHIELDING SUPPLIES AND SERVICE

4565 SOUTH PALO VERDE, SUITE 203
TUCSON, ARIZONA 85714
TELEPHONE: (602) 748-9362
TELEX: 165550
FAX: (602) 748-9364

ROYAL PALM TOWERS 1, SUITE 400
1700 SOUTH DIXIE HIGHWAY
BOCA RATON, FLORIDA 33432
TELEPHONE: (407) 392-2025
TELEX: 568661
FAX: (407) 393-6165

1079 CHAMBLY ROAD, SUITE 201
LONGUEUIL, QUEBEC J4H 3M7
TELEPHONE: (514) 670-6412
TELEX: 05-25448
FAX: (514) 677-6336

TO: CEBAF, Newport News, VA   Date: May 7, 1991

ATTN: Mr. Suresh Chandra, Plant Engineer

FROM: Mr. Manjit S. Chopra

FAX#: 804/249-7559

Dear Mr. Chandra,

As desired by you we have worked out the following mix proportions for concretes of unit weights of 200 pcf, 225 pcf and 240 pcf.

	200 pcf	220 pcf	240 pcf
Cement	517 lb/yd^3	611 lb/yd^3	611 lb/yd^3
Water	280	320	280
Coarse local aggregate	1400	235	-
Coarse H.D. Aggregate	-	3100	3500
Fine H.D. Aggregate	3370	2040	2270
Admixture	Water reducer/ superplasticizer sufficient doze to get 3" (max) slump.	-	Water reducer/ superplasticizer sufficient doze to get 3" (max) slump.
Unit weight (fresh) calculated	206 pcf	233 pcf	247 pcf
Unit weight (dry) expected	202 pcf	228 pcf	243 pcf
Compressive Strength (min) psi	4000	4000	5000

Data Sheets on the high density aggregates are sent herewith.

The above range of concrete densities will enable the physicist to calculate the barrier thicknesses for anticipated radiation intensity.

The mass of high density concrete will attenuate the gamma radiation and the hydrogen in the concrete (hydrolysed cement) will attenuate neutrons. To further attenuate the neutrons, boron in the form of Boron Carbide can be incorporated in the concrete during its manufacture.

Current price of high density aggregates is $135.00 to $140.00/NT depending upon the quantity. Prices are F.O.B. our stockpiles in Montreal, Canada, Jeffersonville, IN and Houston, TX. We are inquiring into the transportation cost to Newport News from these locations and will revert to you with the best option.

We anticipate the cost of in-place high density concrete will be approximately \$500.00/yd^3 for 200 pcf concrete to approximately \$800.00/yd^3 for 240 pcf concrete.

As mentioned during our conversation, we can sell the high density aggregates to CEBAF or a concrete contractor of your choice.

We are sending you our brochures by mail together with hard copy of this letter.

We very much appreciate your inquiry and look forward to working with you on this project. Should you have any questions, please contact us at your convenience.

Yours very truly,

Manjit S. Chopra

/ae

A DIVISION OF:
MINERALS RESEARCH & RECOVERY, INC.
3100 WESLAYAN, SUITE 300
HOUSTON, TEXAS 77027

NUCLEAR SHIELDING SUPPLIES AND SERVICE

4565 SOUTH PALO VERDE, SUITE 203
TUCSON, ARIZONA 85714
TELEPHONE: (602) 748-8362
TELEX: 165550
FAX: (602) 748-8364

ROYAL PALM TOWERS 1, SUITE 400
1700 SOUTH DIXIE HIGHWAY
BOCA RATON, FLORIDA 33432
TELEPHONE: (407) 392-2025
TELEX: 568661
FAX: (407) 393-6165

1079 CHAMBLY ROAD, SUITE 201
LONGUEUIL, QUEBEC J4H 3M7
TELEPHONE: (514) 670-6412
TELEX: 05-25448
FAX: (514) 677-6336

DATA SHEET

HEMATITE (BR)

COARSE AGGREGATE

1. SIZE DISTRIBUTION

Percent Passing U.S. Std. Sieve	Typical	Range Of Variation	ASTM C-33 Size 57
2"	100	100	
1½"	100	100	100
1"	98	95 - 100	95 - 100
½"	49	35 - 60	25 - 60
No. 4	12*	10 - 25	0 - 10
No. 8	7*	8 - 20	0 - 5

2. Specific Gravity

2.1 Apparent	4.93	4.9 ± 0.1
2.2 Bulk (SSD Basis)	4.86	4.8 ± 0.1

3. Percent Absorption 0.64

4. Dry Rodded Unit Wt. 185 pcf.

* Does not conform to ASTM Specification C-33. Please see ASTM C-637 for acceptability.

5. CHEMICAL COMPOSITION - Typical

Fe	67.48%
P	0.024%
SiO_2	1.25%
Al_2O_3	1.18%
Mn	0.05%
Loss under heat	0.92%

M.S. Chopra
/ae

September, 1990

NUCLEAR SHIELDING SUPPLIES AND SERVICE

4565 SOUTH PALO VERDE, SUITE 203
TUCSON, ARIZONA 85714
TELEPHONE: (602) 748-8362
TELEX: 165550
FAX: (602) 748-8364

~~ROYAL PALM TOWERS 1, SUITE 400
1700 SOUTH DIXIE HIGHWAY
BOCA RATON, FLORIDA 33432
TELEPHONE: (407) 392-2025
TELEX: 568661
FAX: (407) 393-6165~~

1079 CHAMBLY ROAD, SUITE 201
LONGUEUIL, QUEBEC J4H 3M7
TELEPHONE: (514) 670-6412
TELEX: 05-25448
FAX: (514) 677-6336

DATA SHEET

HEMATITE (SN)

FINE AGGREGATE

1. SIZE DISTRIBUTION

PERCENT PASSING US STD SIEVE NO.	TYPICAL	RANGE OF VARIATION	ASTM C-637 GRADING 1
# 4	100	99 - 100	-
8	99	99 - 100	100
16	98	97 - 99	95 - 100
30	83	82 - 84	55 - 80
50	51	50 - 53	30 - 55
100	20.5	19 - 22	10 - 30
200	4.3	3 - 8	0 - 10

2. FINENESS MODULUS 1.5 1.5 ± 0.2

3. SPECIFIC GRAVITY 5.0 5.0 - 5.1

4. ABSORPTION % 0.2

5. DRY RODDED UNIT WT 209 pcf

6. CHEMICAL COMPOSITION

%	TYPICAL	TOLERANCE LIMITS
Fe	66.3	65.5 - 66.5
Mn	0.018	0.01 - 0.02
SiO_2	5.0	5.0 - 5.5
P	0.009	0.006 - 0.009
S	0.002	0.001 - 0.003
Al_2O_3	0.28	0.25 - 0.32
CaO	0.02	0.004 - 0.03
MgO	0.02	0.015 - 0.025
K_2O	0.011	0.01 - 0.02
Na	0.007	0.007 - 0.03
H_2O	0.05	0.05 - 0.01

M.S. Chopra
/ae

June 1990

ESK Engineered Ceramics
Wacker Chemicals (USA), Inc.
50 Locust Avenue
New Canaan, CT 06840
Phone (203) 966-9999
TWX 643 444
FAX 203-972-0041

April 18, 1991

Mr. Konrad Aniol
Cebaf
Physics Division
12,000 Jefferson Avenue
Newport News, VA 23606

Dear Mr. Aniol:

I am pleased to offer you the following quote for boron carbide powder:

Material	Description	Quantity	Price
B_4C	12 mesh and finer Boron content 78%	12000 lbs	$16.00/lb.

Delivery: 12 weeks

Please refer to RFQ # 910068 with any questions regarding this price structure.

Sincerely,

Elizabeth A. Davis
ESK Engineered Ceramics
Application Engineer

Chi-Vit Research and Development Center
Chi-Vit Corporation 720 South Edgewood Avenue Urbana, Ohio 43078 (513) 652-1341

Data Sheet #475

CV 398-S BORON FRIT FOR RADIATION SHIELDING

DESCRIPTION: Manufactured granular material resulting from quenching (fritting) of molton inorganic glass formulated with high boron oxide, alumina silicates and alkaline earths. Material is inert, non-hygroscopic, virtually insoluble and completely uniform and reproducible from lot to lot.

USE: As an aggregate for incorporating boron into conventional and high-density shielding concretes and mortars. The standard 8 x 30 mesh sizing does not retard set or affect strength at loadings of up to 500 pounds per cubic yard. Twenty-eight day cylinder tests typically average 6-8,000 p.s.i. compressive strength. Does not corrode reinforcing steel. Is not affected by intermittent or continuous exposure to elevated temperatures.

TYPICAL PROPERTIES:

Nominal Composition, w/o:

B_2O_3	51.0
BaO, CaO, Al_2O_3, SiO_2	Balance
Co, Cr, Mn, V, Zn, .	$<$100 ppm

Boron Content, w/o.	16.0
Specific Gravity:	2.62 - 2.72
Bulk Density, lbs./cu.ft., 8 x 30 mesh;	86
Fineness Modulus, ASTM C-136-67, 8 x 30 mesh:	3.7 - 4.1
Relative Solubility, 8 x 30 mesh: (% solids from 4 hr. condensing steam extraction)	1.0

AVAILABILITY: Stock to eight weeks, depending on quantity. Standard sizing is 8 x 30 mesh. Other sizing available on request. Any lot size can be manufactured. Boron content of each lot is certified.

PACKAGING AND SHIPPING: Standard is multi-ply bags, 50 lbs. net, palletized. Other packaging on request. F.O.B. Leesburg, Alabama.

quote 4/12/91 #194/100 lb

DIVISION OF
EAGLE PICHER

Chi-Vit Research and Development Center

Chi-Vit Corporation 720 South Edgewood Avenue Urbana, Ohio 43078 (513) 652-1341

TYPICAL DESIGN MIXES AS USED IN THE FIELD

Mix: Magnetite - Boron (5,000 p.s.i.) - 1 cu.yd.

Cement	658 lbs.
Water	275 lbs.
CV 398-S Boron Frit	500 lbs.
Magnetite (coarse)	3525 lbs.
Magnetite (fine)	1050 lbs.
Water reducing admixture	35 oz.
Air detraining agent	3 oz.

(8,000 p.s.i. - 223 lbs./cu.ft.)

Mix: Sand and Gravel - Boron (5,000 p.s.i.) -1 cu.yd.

Cement	658 lbs.
Water	250 lbs.
CV 398-S Boron Frit	300 lbs.
Gravel	2000 lbs.
Sand	900 lbs.
Water Reducing admixture	35 oz.

(7,500 p.s.i. - 150 lbs./cu.ft.)

Mix: Sand and Gravel - Boron (4,000 p.s.i.) -1 cu.yd.

Cement	425 lbs.
Water	263 lbs.
Fly Ash	105 lbs.
CV 398-S Boron Frit	400 lbs.
Gravel	1720 lbs.
Sand	1060 lbs.
Darex	4.3 oz.

(6,600 p.s.i. - 146 lbs./cu.ft.)

Mix: Sand and Gravel - Boron (5,000 p.s.i.) -1 cu.yd.

Cement	650 lbs.
Water	258 lbs.
CV 398-S Boron Frit	110 lbs.
Gravel (3/4" Aggregates)	1800 lbs.
Sand	1125 lbs.
Protex AEA 6% ± 1%	3.5 oz.
Pozzolith (300N)	26.5 oz.

(6,600 p.s.i. - 148 lbs./cu.ft.)

SOME INSTALLATIONS USING CHI-VIT BORON FRITS:

Tokamak Fusion Test Reactor
Detroit Edison - Enrico-Fermi
Philadelphia Electric
Boeing, Minuteman Missile Silos
Commonwealth Edison, Iowa Electric, Quad Cities
Commonwealth Edison, Zion
E. I. DuPont, Savannah River Plant
Hanford Atomic Products Operation, Richland, Washington
Los Alamos, Weapons Neutron Research Facility
Naval Research Laboratory, Washington, D.C.
Pulse Reactor Facility, Aberdeen Proving Ground
Stanford Linear Accelerator Center

Reactor Experiments, Inc.

1275 HAMMERWOOD AVENUE, SUNNYVALE, CA 94089-2231
(408) 745-6770 • FAX: (408) 745-7013 • TELEX: 34 5505

List A
Effective
December 1, 1990

PRICE LIST - CATALOG NO. 24

All prices are F.O.B., Sunnyvale, California, U.S.A.

NEUTRON/GAMMA SHIELDING

POLYETHYLENE - BASE SHIELDING

Cat. No.	Thickness:	1" Thick			2" Thick				4" Thick	
	Designation: Size: Description	U 24" x 24"	R 48" x 48"	G 48" x 96"	C 4" x 8"	B 24" x 24"	X 48" x 48"	H 48" x 96"	D 24" x 24"	E 36" x 48"
201	5% Boron	$180.00	$485.00	$1085.00	$18.25	$290.00	$ 970.00	$2165.00	$ 530.00	$1810.00
202	1% Boron, 80% Lead	---	---	---	58.25	---	---	---	---	---
206	76% Lead	---	---	---	42.25	---	---	---	---	---
207	0.7% Boron	205.00	565.00	---	21.50	340.00	1130.00	---	615.00	2110.00
210	30% Boron	730.00	2285.00	---	82.50	1310.00	4565.00	---	2565.00	---
213	Pure Polyethylene	165.00	445.00	985.00	16.50	265.00	895.00	1975.00	465.00	1615.00
215	7.5% Lithium	380.00	1480.00	---	52.00	750.00	2940.00	---	1505.00	4450.00

Quantity discounts available. Request Bulletin S-107 for prices on Series-200 Shielding with varied boron loadings from 0.5% to 7%.

POLYETHYLENE - BASE RODS

Cat. No.	Description	Diameter:	4"	5"	6"	7"	8"	9"	10"
201	5% Boron	Price	$130.00	$160.00	$195.00	$245.00	$ 325.00	$ 390.00	$ 490.00
202	1% Boron, 80% Lead		455.00	520.00	645.00	815.00	1105.00	1390.00	1680.00
206	76% Lead	per	205.00	225.00	315.00	360.00	610.00	680.00	845.00
207	0.7% Boron		140.00	170.00	205.00	250.00	345.00	410.00	525.00
210	30% Boron	12"	455.00	520.00	665.00	835.00	1120.00	1315.00	1705.00
213	Pure Polyethylene		120.00	145.00	180.00	225.00	300.00	---	---
215	7.5% Lithium	Length	255.00	300.00	380.00	475.00	635.00	750.00	975.00

SHIELDING PELLETS (Minimum Order: 200 lbs)

Cat. No.	Description (Polyethylene-Base)	Price Per Pound			
		200-1,000 lbs	1,001-2,500 lbs	2,501-5,000 lbs	5,001-10,000 lbs
201	5% Boron	$ 4.90	$ 4.35	$ 4.30	$ 4.20
202	1% Boron, 80% Lead	12.05	10.30	9.00	8.35
206	76% Lead	11.55	9.80	8.60	7.95
207	0.7% Boron	5.85	5.55	5.05	4.80
210	30% Boron	26.20	22.65	21.10	19.70
213	Pure Polyethylene	3.50	3.45	3.40	3.35
215	7.5% Lithium	13.25	12.60	11.90	11.30

Discounts for quantities over 10,000 pounds available on request.

BORAX $Na_2B_4O_7 \cdot 10H_2O$

[illegible]

GRANULAR AND POWDERED
TECHNICAL, [illegible] AND SPECIAL QUALITY GRADES

THEORETICAL COMPOSITION

Sodium Oxide (Na_2O) 16.25%
Boric Oxide (B_2O_3) 36.51
Water of Crystallization (H_2O) 47.24
Anhydrous Borax ($Na_2B_4O_7$) 52.76

PHYSICAL and CHEMICAL PROPERTIES

Formula Weight 381.37
Specific Gravity 1.73
Melting Point—Heated in closed space, begins to melt in own water at about .... 62°C (144°F)
Melting Point (Anhydrous Form) .... 742°C ±1° (1367°F)
Heat of Solution—BTU per pound (absorbed) .... —122

Dissolved in water, BORAX hydrolyzes to give a mildly alkaline solution. It is thus capable of neutralizing acids. It also combines with strong alkalies to form compounds of lower pH.

STABILITY: Sodium Tetraborate Decahydrate is stable under ordinary conditions but exposed to dry air or elevated temperatures it tends to lose water of crystallization. The basic chemical composition or properties are not changed thereby. When heated above 144°F BORAX melts in its own water, swells to a frothy mass, and when fully dehydrated at increasing temperatures it fuses to a clear glass.

HYDROGEN ION CONCENTRATION: The pH of a 0.1 molar solution of BORAX, about 3%, at 20°C (68°F) is 9.25. The value increases very slightly with increasing concentration, and diminishes very slightly with increasing temperature. This relatively constant pH of BORAX solutions makes it an excellent buffering agent. (See chart "pH Values of Borate Solutions," at 20°C; Supplementary Data Section)

COMPARATIVE pH OF SOLUTIONS OF SOME COMMON ALKALIES @ 20°C (68°F)

Concentration, weight percent	0.1%	0.5%	1.0%	2.0%	5.0%
Caustic Soda $NaOH$	11.90	12.70	13.10	13.30	13.80
Sodium Metasilicate Na_2SiO_3	11.30	12.10	12.30	12.70	13.10
Trisodium Phosphate $Na_3PO_4 \cdot 12H_2O$	11.50	11.55	11.60	11.70	11.80
Soda Ash Na_2CO_3	10.70	11.30	11.40	11.50	11.60
Sodium Metaborate $Na_2B_2O_4 \cdot 8H_2O$	10.52	10.84	11.00	11.18	11.44
Borax $Na_2B_4O_7 \cdot 10H_2O$	9.26	9.23	9.24	9.24	(9.32*)

*pH @ 4.71% Borax, saturated solution at 20° (68°F).