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Dosimetry and Shielding Factors Relevant to the Design of Iron Beam Dumps

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Introduction:

In an early TM, Awschalom et al. used Monte Carlo-generated neutron spectra penetrating various shields to derive quantities of interest for radiation protection.[1] The spectra dealt with were those expected outside a thick soil shield, and outside a thin iron-pulse-heavy-concrete shield. This is a correction and extension of that work.

In Awschalom's work, the thin iron-plus-heavy-concrete spectrum was erroneously labelled as being that expected outside a thin shield of just iron. Such a spectrum, which would be generated whenever beam strikes a magnet or collimator, is considered here, along with the spectrum expected outside a much thicker (>1m) iron shield. What makes both of these spectra interesting is their abundance of intermediate energy neutrons (0.01 to 1 MeV), as compared to the smoother, roughly 1/E spectra expected outside soil or concrete shields. The presence of these intermediate energy neutrons significantly affects the spectra's quality factors, flux to dose conversion factors, and the response of some detectors exposed to them.

Spectra Outside Iron Shields

The "thin iron shield" spectrum considered here was calculated by Armstrong and Alsmiller,[2] and is shown as the solid line in Fig. 1. It is the spectrum expected outside an iron shield of radius 160 gm/cm^2 when struck by a beam of 200 GeV protons. Also shown in this Figure is the smoother spectrum outside an iron-plus-heavy-concrete shield, as used in Ref. 1.

The abundance of intermediate energy neutrons in the "thin iron shield" spectrum is of course the result of the well-known "hole" in the iron non-elastic cross section below about 1 MeV. The greater the thickness of the iron shield, the more pronounced is the excess of intermediate energy neutrons over the high energy ones. To explore the effects that this phenomenon might have in the extreme limit, a spectrum was constructed to represent the neutrons outside a "thick iron shield". The low energy (<1 MeV) part of this spectrum was taken from a shielding calculation for neutrons produced by 400 MeV electrons on copper.[3] This low energy spectrum was spliced onto the high energy part (E > 50 MeV) of the spectrum of Armstrong and Alsmiller,[2] i.e., the high energy portions of the "thin" and "thick" iron spectra were identical. The two spectra being spliced were consistent between 1 and 50 MeV; this region was used for relative normalization. The composite spectrum is shown in Fig. 2.

The "thin" and "thick iron shield" spectra were integrated in a manner identical to that of Ref. 1 to obtain the neutron flux, dose and dose-equivalent per incident proton. Flux-to-dose and flux-to-dose-equivalent conversion factors were taken directly from Ref. 1.

Results for these spectra are given in Table 1 along with the comparable quantities from Ref. 1 for a spectrum outside a thick soil shield. Note that the abundance of intermediate energy neutrons in the "thin iron shield" spectrum raises the quality factor by more than 50% over these for the more common spectra outside hydrogenous shields. However, this geometry does not have enough iron to yield an equilibrium spectrum. Such an equilibrium spectrum does occur at much larger radii (Fig. 2); at which point the ratio of intermediate to high energy neutrons has increased by another two orders of magnitude, and the portion below 10 keV is again roughly 1/E. The net effect of these changes is to reduce the quality factor to 5.4, which is comparable to the quality factor for a thick soil shield.

Detector Response

To aid in understanding the responses of detectors whose efficiencies vary with neutron energy, the curves shown in Figs. 3 and 4 were prepared. They show, for the "thin" and "thick" iron shields, the fraction of the flux, dose and dose-equivalent due to neutrons with energies below a specified energy. The intermediate energy "hump" of Fig. 1 results in the "shoulders" at those energies in Fig. 3. This effect is exaggerated even further for the "thick iron shield", for which essentially all the neutron flux, dose and dose-equivalent are due to neutrons below 1 MeV, as shown in Fig. 4. These curves may be compared with Figs. 6 (iron plus heavy concrete, but mislabelled) and 7 (soil) of Ref. 1, or Figs. VI-8 to VI-13 of Ref. 4.

Dose Calculations from Hadron Star Densities

High energy Monte Carlo hadron cascade programs such as Van Ginneken's CASIM[4] usually have a low energy of momentum cutoff, below which hadrons are not followed. Only particles above this cutoff are allowed to interact and form "stars". In CASIM the cutoff for nucleous is usually P_{min} = 300 MeV/c, corresponding to E_{min} = 47 MeV. As can be seen from Figs. 3 and 4, only a small fraction of the dose in these particular spectra is due to neutrons above the 47 MeV cutoff. Thus a substantial correction must be made in going from the "hadron cascade star density" to neutron flux, dose, and dose-equivalent.

As a first step in computing this correction, a CASIM-produced spectrum was compared with the high energy end of the Armstrong-Alsmiller spectrum;[2] very good agreement was found. Thus the two calculational techniques give equivalent results in the region in which they overlap. Assuming that total cross sections are constant above 47 MeV (this is true to 10-20%), the flux of nuetrons (cm^{-2}) above this energy is

$$\Phi(E > 47\ \text{MeV}) = S\ \lambda/\rho = 17.2\ S$$

where S is the hadron cascade star density (cm^{-3}) in iron, and λ and ρ are the mean free path (gm cm^{-2}) and density of the shield.

Integrating these two neutron spectra, one finds for the "thin" ("thick") iron shield, the fraction F of neutrons above 47 MeV is only 3.2% (0.018%). Integrals of flux, dose, and dose-equivalent are shown in Figs. 3 and 4.[5] The total neutron flux is then

$$\Phi_{tot} \equiv \frac{\Phi}{F}\ (E > 47\ \text{MeV}) = \frac{\lambda}{\rho F}\ S$$

The entrance dose (rads) and maximum dose-equivalent (rems) per unit star density are then obtained using the appropriate factors from Table 1; results are given in Table 2. These quantities differ drastically from the corresponding quantities in iron quoted by Van Ginneken and Awschalom[4] because a very different soil shield spectrum was used in those calculations.

Also shown for reference in Table 2 are similar quantities (copied directly from Table VI.1 of Ref. 4) for spectra outside concrete and heavy concrete shields. The figures for heavy concrete were obtained by simply correcting ordinary concrete data for the greater density of heavy concrete.

Design of Efficient Transverse Shielding

Given the different shielding characteristics of concrete and iron, how can one obtain the most efficient hadron shield (i.e., providing the smallest dose equivalent) in a limited space? Iron, being much denser than concrete, appears at first glance to be more effective than an equal thickness of concrete. However, iron is nearly transparent to neutrons with energies below 1 MeV, while concrete (or any hydrogen-containing substance) is very effective at shielding these intermediate-energy neutrons. Thus it is advantageous to put a layer of concrete outside the iron shield to attenuate these soft neutrons, even at the expense of giving up an equal thickness of iron with its greater attenuation for higher energy particles. Work by Alsmiller and Barish[3] indicates that about 90 cm of concrete is the minimum thickness needed to filter out the surplus of intermediate energy neutrons. A greater thickness than this is not the most efficient use of the limited space.

CASIM has the capability for multi-media calculations, and the best results for a multi-media geometry will be obtained by making a proper Monte Carlo calculation with the exact geometry. Conversion from hadron cascade star density to dose, etc. can be done properly only if the shape of the lower energy part of the spectrum (not calculated in CASIM) is known. In practice these spectra are known only for equilibrium situations.

It is often not convenient, economical or necessary to do a full Monte Carlo calculation. In those circumstances the following prescription may be used to apply the results of an all-iron Monte Carlo calculation to the two-media case.

1. Replace the outer layer of concrete with a thickness of iron equivalent in hadron attenuation. Rougly, 1 meter of concrete $\simeq$ 40 cm of iron.

2. Determine the star density at the corresponding point in the fictitious all-iron geometry.

3. The star density at the relevant point in the concrete shell will be 0.4 times the star density obtained in step 2.

4. Apply an appropriate radial scaling rule to compensate for the different radial distances of corresponding points in the concrete layer and its iron equivalent.

5. Use the star-to-dose conversion factors appropriate for a concrete shield.

This prescription is reliable only for a concrete layer 90 cm or thicker; thinner layers of concrete are not adequate to filter out the excess neutrons present in the iron equilibrium spectrum.

Acknowledgement

The shielding problem which led to these calculations was raised by Dennis Riley. I would like to thank Miguel Awschalom and R. G. Alsmiller, Jr. for providing helpful information and comments, and Duane Voy for doing the numerical integrations.

References

[1] M. Awschalom, T. Borak and H. Howe, NAL TM-266 (1970).

[2] T. W. Armstrong and R. G. Alsmiller, Jr., ORNL-TM-2498 (1969).

[3] R. G. Alsmiller, Jr. and J. Barish, Particle Accel. 5 155 (1973). The spectrum chosen was that which had the greatest excess of intermediate energy over "fast" neutrons ($E \geq 1$ MeV); this occurred at radii between 800 and 1000 gm/cm^2 in the iron shield.

[4] A. Van Ginneken and M. Awschalom, High Energy Particle Interactions in Large Targets. I. Hadronic Cascades, Shielding, Energy Deposition. Fermilab (1975).

[5] Similar integrals for dose equivalent only are given in Ref. 3.

SPECTRUM	<QF>	<D> rad/n-cm^2	<DE> rem/n-cm^2
1. THIN iron shield	7.9	2.4×10^{-9}	1.9×10^{-8}
2. THICK iron shield	5.4	0.81×10^{-9}	0.44×10^{-8}
3. Iron and heavy concrete, thin	5.0	6.7×10^{-9}	3.3×10^{-8}
4. All soil or concrete, thick	5.3	9.1×10^{-9}	4.9×10^{-8}

Table 1.

Spectrum averages of quality factor, dose and dose-equivalent for spectra outside three different shields. Data for spectra 3 and 4 comes from Ref. 1. Reference 4 predicts a quality factor of 6 for spectrum 4.

MATERIAL	Density gm/cm^3	Neutron Flux n·cm^2/star-cm^3	Entrance Absorbed Dose rad/star-cm^3	Maximum Dose Equivalent rem/star-cm^3
All iron, thin	7.9	540	1.29×10^{-6}	10.2×10^{-6}
All iron, thick	7.9	95000	$77. \times 10^{-6}$	420×10^{-6}
Concrete	2.4	350	1.5×10^{-6}	9.0×10^{-6}
Heavy Concrete (PPA)	3.85	220	0.9×10^{-6}	5.6×10^{-6}

Table 2.

Shielding characteristics and conversion factors from star densities.

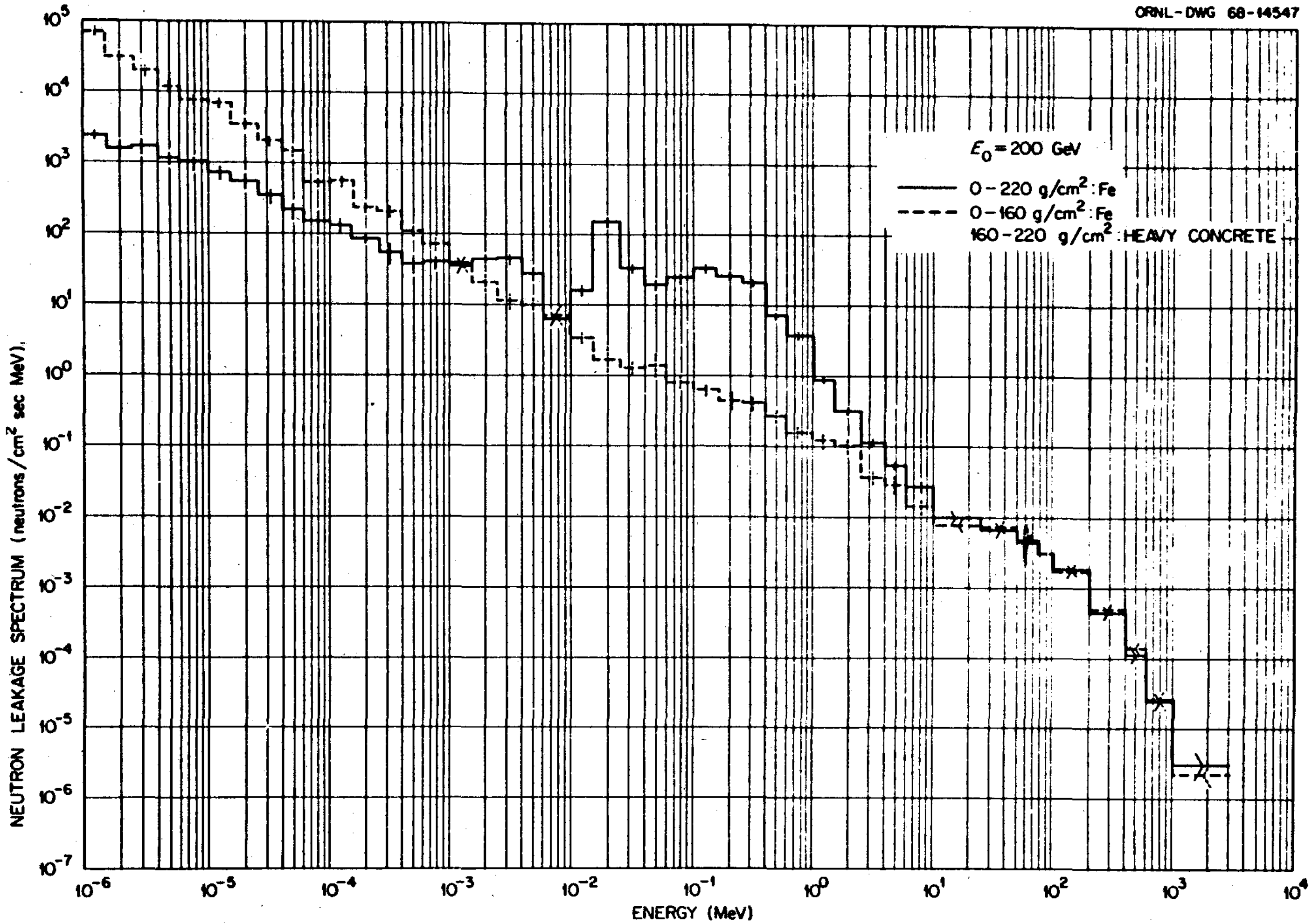

Fig. 1 . Neutron Leakage Spectra at a Radius of 220 g/cm^2 for Iron and Iron Followed by Heavy Concrete.

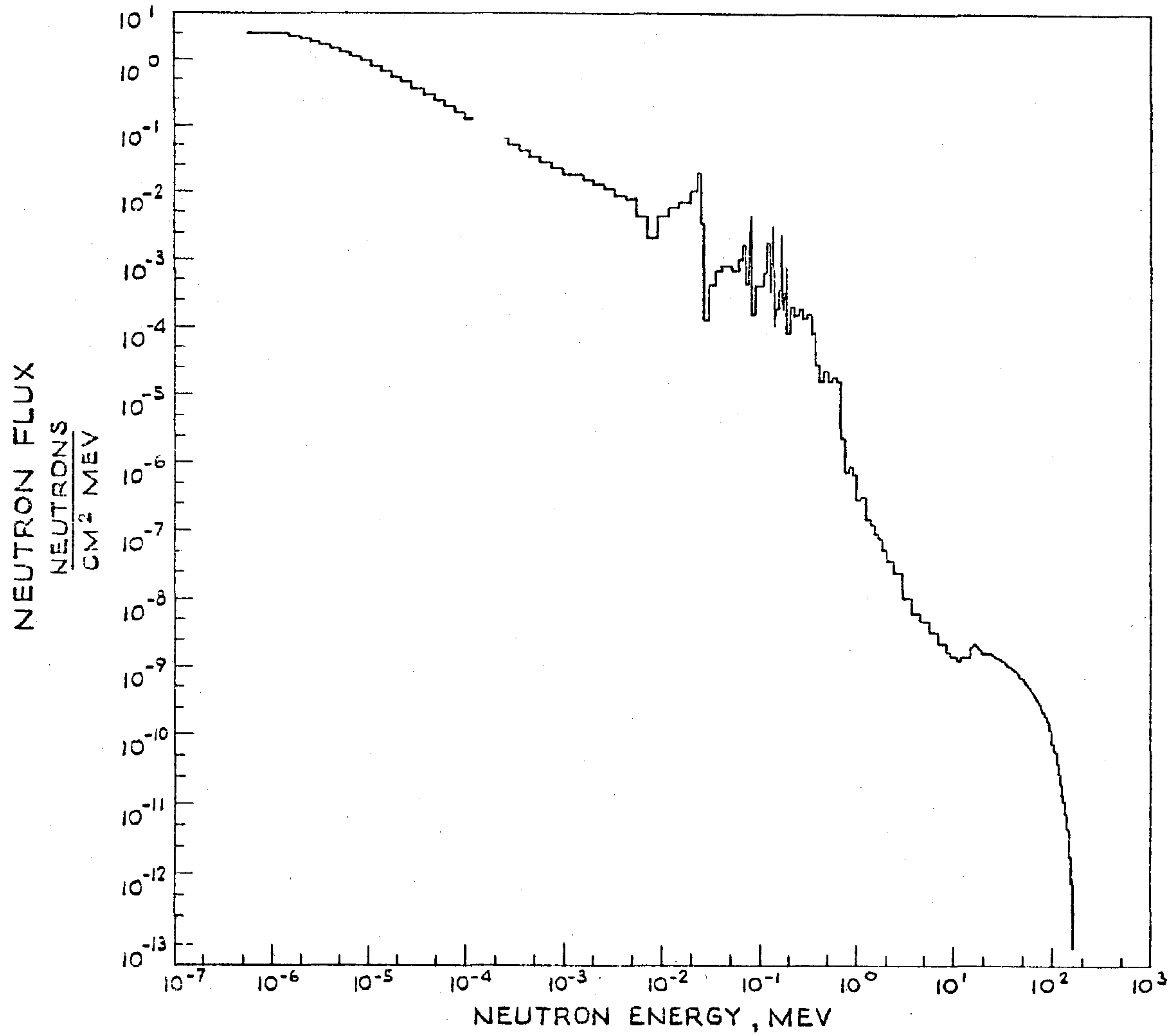

Fig. 2. Spectron outside a thick iron shield, as calculated by Alsmiller and Barish (ref. 3). Note the great abundance of neutrons from 100 keV to 1 MeV, as compared to Fig. 1.

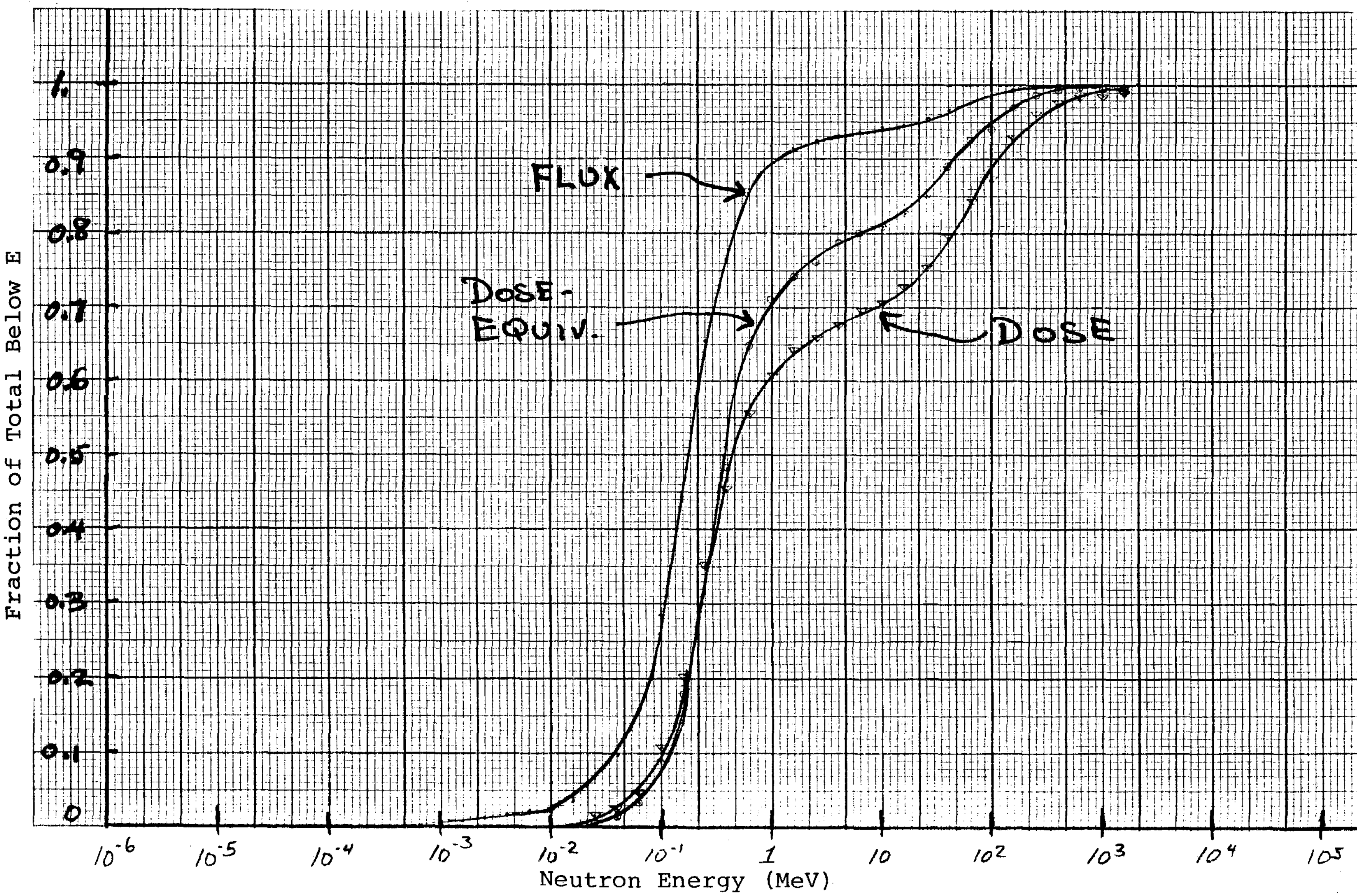

Fig. 3. Fraction of Various Quantities due to Neutrons below given energies, for the "thin iron shield" spectrum shown in Fig. 1.

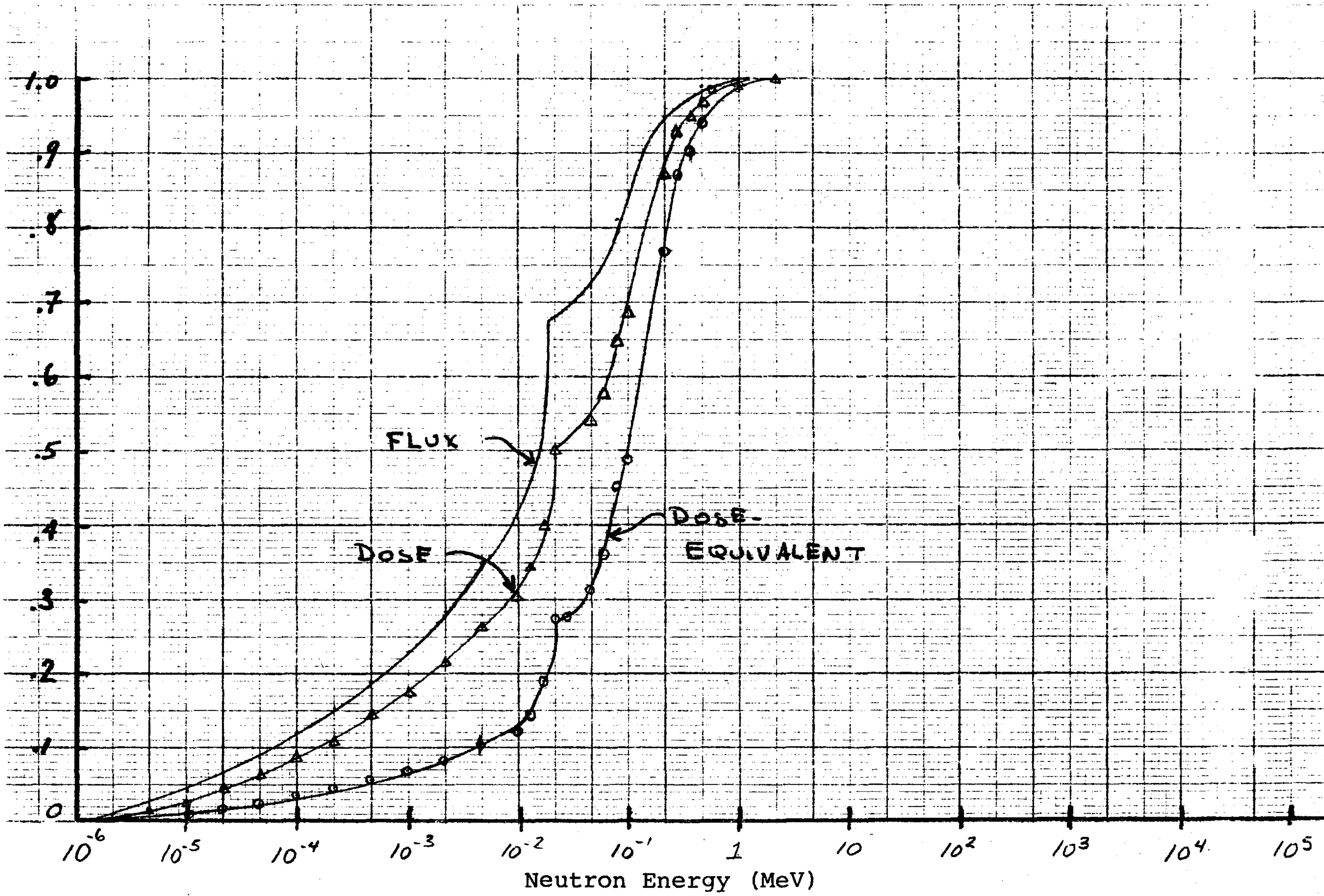

Fig. 4. Fraction of Various Quantities due to Neutrons below given energies, for the "thick iron shield" spectrum shown in Fig. 2.