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NEUTRON DOSIMETRY: EXPECTED NEUTRON SPECTRA & DIFFERENTIAL & INTEGRAL DOSE AND DOSE EQUIVALENT-VS-NEUTRON ENERGY

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INTRODUCTION

The purpose of this note is to present the dose and dose equivalent outside a 200 g/cm^2 iron shield which roughly corresponds to the return legs plus copper of the 200 GeV synchrotron magnets as well as for neutrons outside a 1500 g/cm^2 soil shield. These results can then be used to determine the fraction of the total dose and dose equivalent detected by personnel neutron monitors.

NEUTRON FLUX

The neutron flux outside a thick shield was obtained from several different sources. Armstrong[3] has calculated the neutron spectrum for a 200 GeV/c primary proton beam grazing an iron shield. A "straight ahead" approximation was used in which the radial part of the cascade was developed only for secondaries with energies of less than 3 GeV and scattering angle greater than three degrees. The leakage neutron spectrum outside 220 g/cm^2 (11 in) of iron is shown by the solid curve in

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Figure 1. The curve is normalized to a beam loss rate of 1 proton/cm.

K. O'Brien has also calculated the neutron spectrum outside a thick iron shield[4]. Neutron production in the accelerator structure is related to the flux through the shielding by matching boundary conditions. These arise from a straight ahead transport calculation[5] and expansion of the angular neutron flux in Legendre polynomials[6]. The spectrum outside a 220 g/cm^2 iron shield is shown by the dashed curve in Figure 1.

The neutron spectrum was also calculated using the nucleon-meson cascade computer code TRANSK[7]. For this calculation a straight ahead approximation is not necessary since the computer code directly follows the radial development of the cascade for all particles. The program is easily adaptable to a line source. However, the absolute normalization is difficult to achieve because of the small statistics at large radii. The results are still useful since they can be used to give the slope at the high energy portion of the spectrum. Thus, for our purposes the TRANSK data were matched to the Armstrong spectrum at about 100 MeV and used exclusively for extropolating to 200 GeV (see Figure 1). Table I gives the flux in tabular form.

The same approach was used for the neutron flux outside a 1500 g/cm^2 soil shield. The energy spectrum from a calculation of K. O'Brien and TRANSK is shown in Figure 2, and tabulated in Table I. O'Brien approximates soil as a mixture of aluminum and hydrogen. Water concentration is related to the hydrogen density. TRANSK uses the actual elemental composition but ignores the hydrogen content.

FLUX TO DOSE CONVERSION FACTORS

The flux to absorbed dose and flux to dose equivalent coefficients-vs-energy are shown in Figure 3a-c and listed in Table II. In all cases the values were taken at depths where the dose or dose equivalent reach their maximum values for normally incident neutrons.

CALCULATIONS

Given the flux and flux to dose conversion coefficients the absorbed dose (rad) and dose equivalent (rem) within any energy region are given by

$$D = \text{Absorbed Dose (rad)} = \int_{E_1}^{E_2} KD(E) \quad \Phi(E) \; dE \qquad (1)$$

$$DE = \text{Dose Equivalent (rem)} = \int_{E_1}^{E_2} KDE(E) \quad \Phi(E) \; dE \qquad (2)$$

where KD and KDE are the flux to absorbed dose and dose equivalent coefficients and Φ is the differential neutron flux. The

average absorbed dose and dose equivalent per neutron over any energy range is obtained by

$$\langle D \rangle = \frac{\int_{E_1}^{E_2} KD(E)\ \Phi(E)\ dE}{\int_{E_1}^{E_2} \Phi(E)\ dE} \tag{3}$$

$$\langle DE \rangle = \frac{\int_{E_1}^{E_2} K_{DE}\ \Phi(E)\ dE}{\int_{E_1}^{E_2} \Phi(E)\ dE} \tag{4}$$

Since the energy ranges over many orders of magnitude, the numerical integration was performed using the trapezoidal rule with logarithmic intervals.

$$D = \int_{\log_{10}E_1}^{\log_{10}E_2} K(E)\ \Phi(E)\ E\ d\log_{10}E(\mathrm{MeV})$$

RESULTS

Figures 4 and 5 show the differential absorbed dose and dose equivalent outside the 220 g/cm^2 iron and 1500 g/cm^2 soil respectively. The average values for these quantities over the entire energy range are:

Fe:

$$\langle D \rangle = 6.71 \times 10^{-9}\ \mathrm{rad/neutron\ cm^{-2}\ sec^{-1}}$$

$$\langle DE \rangle = 3.33 \times 10^{-8}\ \mathrm{rem/neutron\ cm^{-2}\ sec^{-1}}$$

Soil:

$$\langle D \rangle = 9.14 \times 10^{-9} \text{ rad/neutron cm}^{-2} \text{ sec}^{-1}$$

$$\langle DE \rangle = 4.87 \times 10^{-8} \text{ rem/neutron cm}^{-2} \text{ sec}^{-1}$$

Figures 6 and 7 show the fraction of the total absorbed dose and dose equivalent for the iron and soil shields respectively.

CONCLUSIONS

These results may be used to evaluate the "efficiency" of personnel neutron film dosimeters. The neutron detection range for Kodak NTA film extends from approximately 1 to 15 MeV. Hence, these film dosimeters would record about one-tenth of the dose and one-fifth of the dose equivalent a person may receive outside a thick shield.

REFERENCES

1. R. L. Lehman, UCRL-9513 (Jan. 1961).
2. J. A. Douglas & M. J. Heard, AERE-R5367 (1967).
3. T. W. Armstrong & R. G. Alsmiller, Calculation of the Residual Photon Dose Rate Around High Energy Accelerators, ORNL-TM-2498 (Feb. 1969).
4. K. O'Brien, U.S.A.E.C. Health and Safety Laboratory New York, N.Y., Private Communication.
5. K. O'Brien & J. E. McLaughlin, Nuclear Instruments and Methods, 60, 129 (1968)
6. K. O'Brien, Transverse Shielding Calculations for the components of a 1/2 TeV Proton Synchrotron for HASL 199, (Aug 1968).
7. J. Ranft & T. Borak, Improved Nuclean-Meson Cascade Calculations: NAL-FN-193, (1969).
8. M. Awschalom, T. Borak & P. Gollon, Chemical Composition of Some Common Shielding Materials, NAL-TM-168 (May 1969).
9. U.S. Dept of Commerce, NBS Handbook 63, Protection Against Neutron Radiation up to 30 MeV (1967).
10. D. C. Irving, R. G. Alsmiller & H. S. Moran, ORNL-4032: UC-41-Health and Safety (1967).
11. R. G. Alsmiller, T. W. Armstrong & W. A. Coleman, ORNL TM-2924 (1970).
12. J. Neufeld, et al, Health Physics 12, 227 (1966).
13. H. A. Wright, et al, Health Physics 16, 13 (1969).

14. M. Weinstein, F. Hajnal, J. McLaughlin & K. O'Brien, Neutron Dose Equivalents form Mullisphere Accelerator Leakage Spectrum, HASL-223 (March 1970).

TABLE I

Neutron flux emerging from 200 g/cm^2 Fe and 1500 g/cm^2 soil shield for one 200 GeV/c proton interacting per cm.

Energy	Neutrons. MeV^{-1}. cm^{-2}. sec^{-1}	
MeV	Fe	Soil
1.00E-07	9.58E+05	1.74E-02
1.58E-07	5.85E+05	1.11E-02
2.51E-07	3.58E+05	7.12E-03
3.98E-07	2.18E+05	4.55E-03
6.31E-07	1.33E+05	2.91E-03
1.00E-06	8.15E+04	1.86E-03
1.59E-06	4.98E+04	1.19E-03
2.51E-06	3.04E+04	7.62E-04
3.98E-06	1.86E+04	4.88E-04
6.31E-06	1.14E+04	3.12E-04
1.00E-05	6.94E+03	2.00E-04
1.59E-05	4.24E+03	1.28E-04
2.51E-05	2.59E+03	8.16E-05
3.98E-05	1.58E+03	5.22E-05
6.32E-05	9.66E+02	3.34E-05
1.00E-04	5.90E+02	2.14E-05
1.59E-04	3.60E+02	1.37E-05
2.51E-04	2.20E+02	8.75E-06
3.99E-04	1.35E+02	5.59E-06
6.32E-04	8.22E+01	3.58E-06
1.00E-03	5.02E+01	2.29E-06
1.59E-03	3.07E+01	1.46E-06
2.52E-03	1.87E+01	9.37E-07
3.99E-03	1.14E+01	5.99E-07
6.32E-03	6.99E+00	3.83E-07
1.00E-02	4.27E+00	2.54E-07
1.59E-02	2.61E+00	1.65E-07
2.52E-02	1.59E+00	1.16E-07
3.99E-02	1.09E+00	8.63E-08
6.32E-02	8.24E-01	6.72E-08
1.00E-01	6.23E-01	5.39E-08
1.59E-01	4.70E-01	4.41E-08
2.52E-01	3.55E-01	3.63E-08
3.99E-01	2.68E-01	2.98E-08
6.32E-01	2.02E-01	2.43E-08
1.00E+00	1.53E-01	1.95E-08
1.59E+00	1.15E-01	1.53E-08
2.52E+00	6.57E-02	1.18E-08
3.99E+00	3.43E-02	8.91E-09
6.33E+00	2.04E-02	6.58E-09

TABLE I (continued)

Energy	Neutrons. MeV^{-1}. cm^{-2}. sec^{-1}	
MeV	Fe	Soil
1.00E+01	1.37E-02	4.78E-09
1.59E+01	1.03E-02	3.42E-09
2.52E+01	8.20E-03	2.43E-09
3.99E+01	6.63E-03	1.73E-09
6.33E+01	5.05E-03	1.24E-09
1.00E+02	3.33E-03	9.07E-10
1.59E+02	1.72E-03	6.87E-10
2.52E+02	6.01E-04	1.63E-10
3.99E+02	2.18E-04	4.36E-11
6.33E+02	7.93E-05	1.17E-11
1.00E+03	2.88E-05	3.13E-12
1.59E+03	1.04E-05	8.37E-13
2.52E+03	3.79E-06	2.24E-13
4.00E+03	1.38E-06	6.01E-14
6.33E+03	5.00E-07	1.61E-14
1.00E+04	1.81E-07	4.31E-15
1.59E+04	6.59E-08	1.15E-15
2.52E+04	2.39E-08	3.09E-16
4.00E+04	8.68E-09	8.29E-17
6.33E+04	3.15E-09	2.22E-17
1.00E+05	1.14E-09	5.95E-18
1.59E+05	4.15E-10	1.59E-18
2.52E+05	1.51E-10	4.27E-19

TABLE II

Flux to dose (rad/n/cm^2) and flux to dose equivalent (rem/n 1cm^2) us neutron energy for normally incident flux.

ENERGY (MEV)	K(D)	K(DE)
1.00E-07	3.69E-10	1.06E-09
1.58E-07	3.84E-10	1.07E-09
2.51E-07	4.01E-10	1.09E-09
3.98E-07	4.18E-10	1.11E-09
6.31E-07	4.36E-10	1.13E-09
1.00E-06	4.54E-10	1.15E-09
1.59E-06	4.74E-10	1.18E-09
2.51E-06	4.94E-10	1.20E-09
3.98E-06	5.15E-10	1.22E-09
6.31E-06	5.37E-10	1.24E-09
1.00E-05	5.60E-10	1.26E-09
1.59E-05	5.84E-10	1.29E-09
2.51E-05	6.09E-10	1.31E-09
3.98E-05	6.35E-10	1.33E-09
6.32E-05	6.62E-10	1.36E-09
1.00E-04	6.90E-10	1.38E-09
1.59E-04	6.75E-10	1.36E-09
2.51E-04	6.61E-10	1.34E-09
3.99E-04	6.47E-10	1.33E-09
6.32E-04	6.33E-10	1.31E-09
1.00E-03	6.20E-10	1.29E-09
1.59E-03	6.07E-10	1.27E-09
2.52E-03	5.94E-10	1.26E-09
3.99E-03	5.81E-10	1.24E-09
6.32E-03	5.74E-10	1.39E-09
1.00E-02	5.68E-10	1.75E-09
1.59E-02	5.63E-10	2.22E-09
2.52E-02	6.08E-10	2.97E-09
3.99E-02	7.18E-10	4.20E-09
6.32E-02	9.54E-10	5.94E-09
1.00E-01	1.12E-09	8.00E-09
1.59E-01	1.40E-09	1.11E-08
2.52E-01	1.72E-09	1.55E-08
3.99E-01	2.20E-09	2.22E-08
6.32E-01	2.70E-09	3.40E-08
1.00E+00	3.78E-09	3.60E-08
1.59E+00	4.10E-09	3.80E-08
2.52E+00	4.50E-09	3.70E-08
3.99E+00	5.30E-09	3.90E-08
6.33E+00	6.40E-09	4.10E-08

TABLE II (continued)

ENERGY (MeV)	K(D)	K(DE)
1.00E+01	7.00E-09	4.20E-08
1.59E+01	8.84E-09	5.48E-08
2.52E+01	9.52E-09	7.20E-08
3.99E+01	9.87E-09	7.80E-08
6.33E+01	1.00E-08	5.50E-08
1.00E+02	1.10E-08	5.00E-08
1.59E+02	1.25E-08	5.24E-08
2.52E+02	1.65E-08	5.80E-08
3.99E+02	2.25E-08	6.80E-08
6.33E+02	3.30E-08	8.50E-08
1.00E+03	4.20E-08	1.15E-07
1.59E+03	5.70E-08	1.42E-07
2.52E+03	8.00E-08	1.80E-07
4.00E+03	1.12E-07	2.25E-07
6.33E+03	1.50E-07	2.83E-07
1.00E+04	2.15E-07	3.53E-07
1.59E+04	2.93E-07	4.50E-07
2.52E+04	4.00E-07	5.60E-07
4.00E+04	5.50E-07	7.10E-07
6.33E+04	7.50E-07	8.80E-07
1.00E+05	1.05E-06	1.11E-06
1.59E+05	1.45E-06	1.41E-06
2.52E+05	2.00E-06	1.80E-06

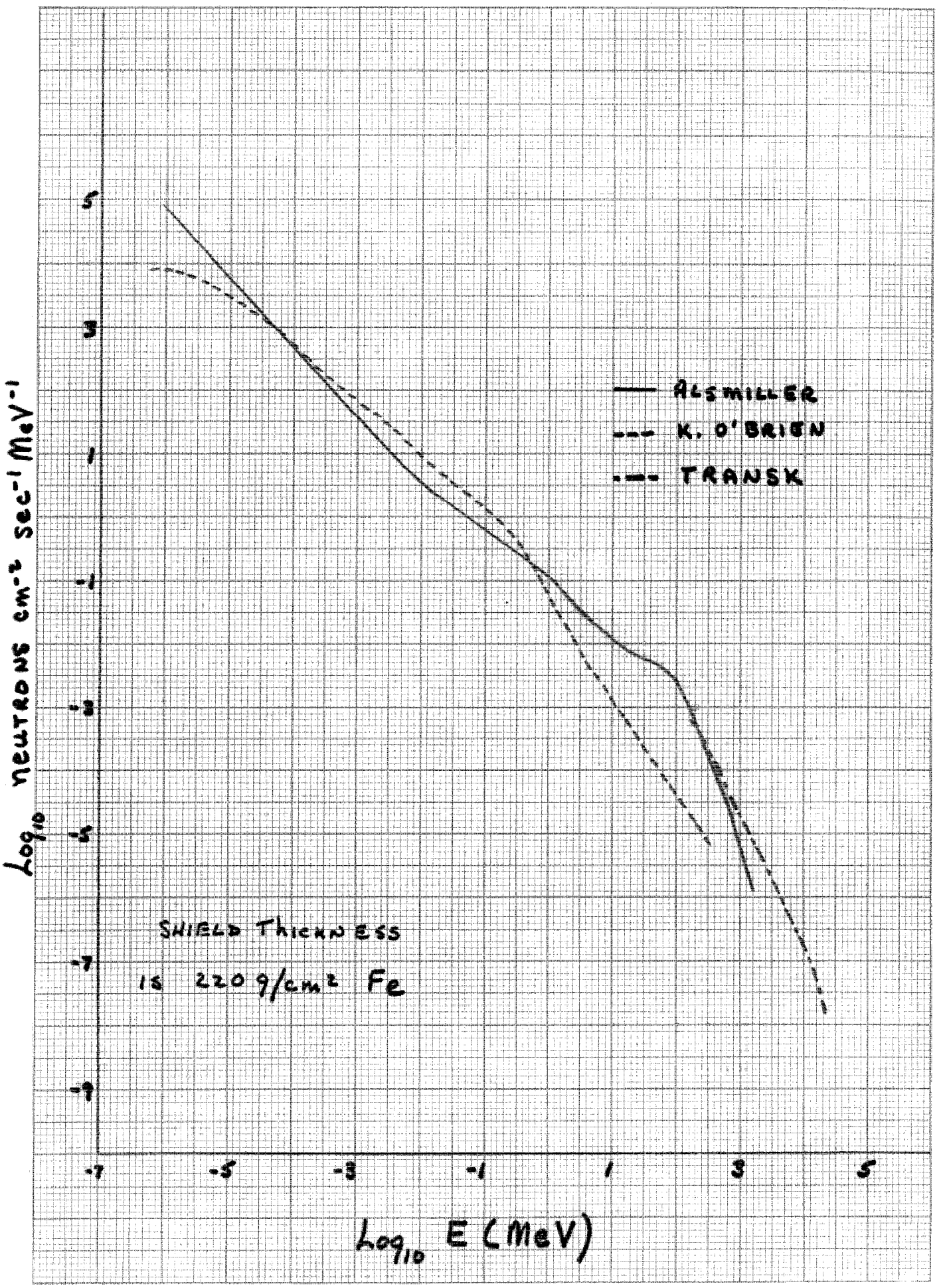

ALSMILLER
K. O'BRIEN
TRANSK
SHIELD THICKNESS
IS 220 g/cm² Fe
Log10 NEUTRONS cm⁻² sec⁻¹ MeV⁻¹
Log10 E (MeV)
5
3
1
-1
-3
-5
-7
-9
-7
-5
-3
-1
1
3
5

Figure 1

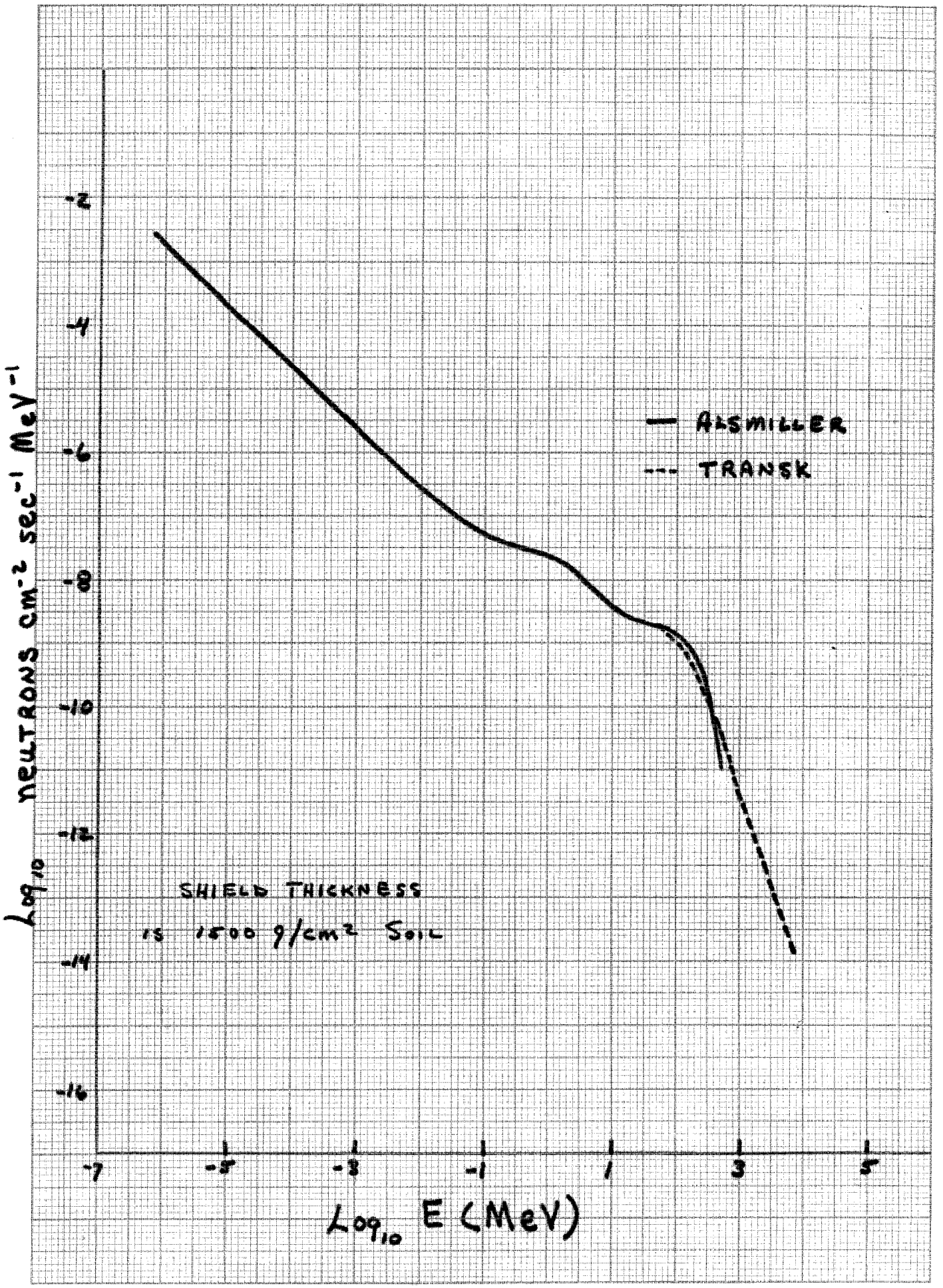

-2
-4
-6
-8
-10
-12
-14
-16
-7
-5
-3
-1
1
3
5
Log10 neutrons cm-2 sec-1 MeV-1
Log10 E (MeV)
— ALSMILLER
--- TRANSK
SHIELD THICKNESS
IS 1500 g/cm2 SOIL

Figure 2

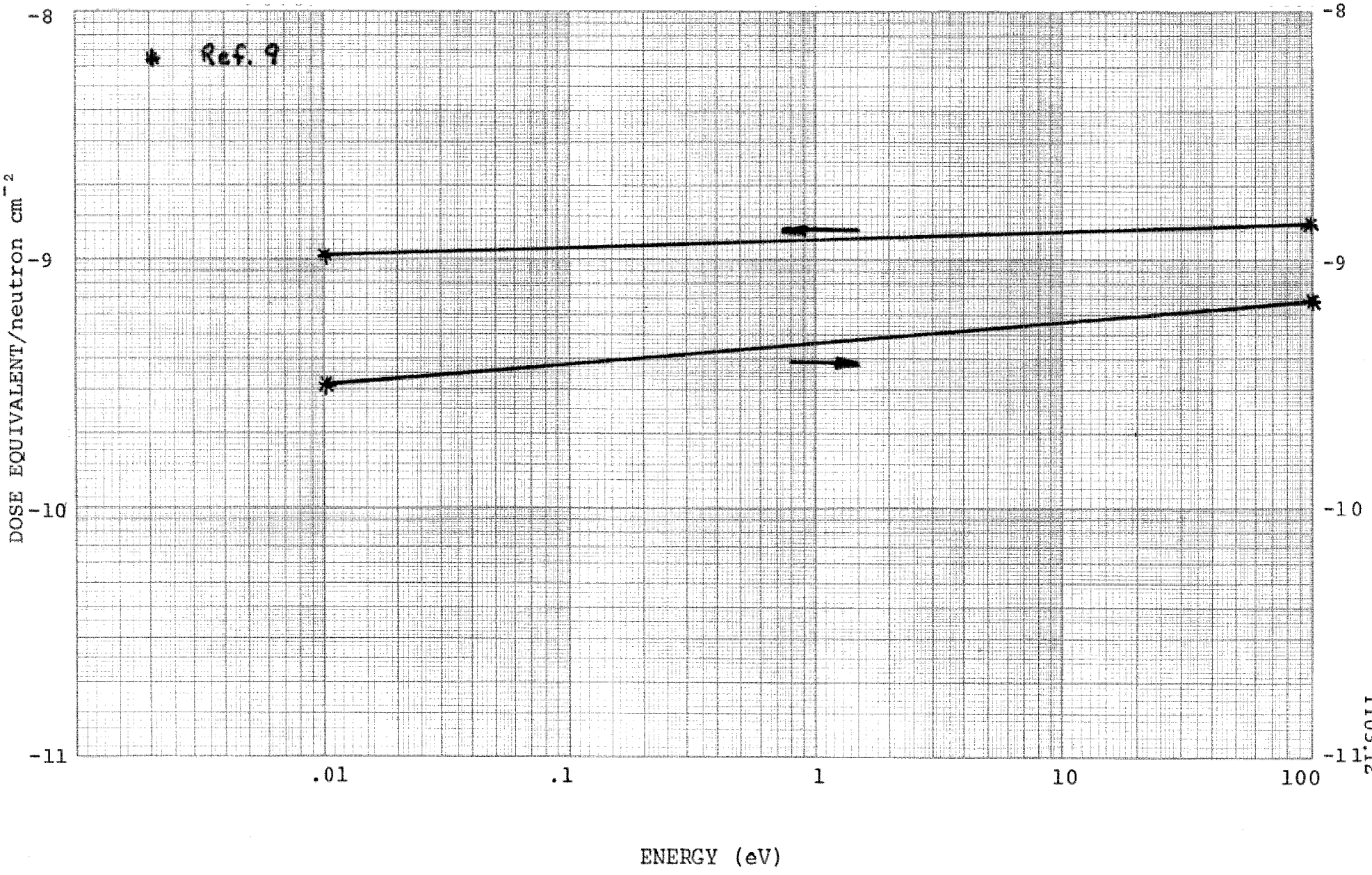

* Ref. 9
DOSE EQUIVALENT/neutron cm^{-2}
DOSE/neutron cm^{-2}
-8
-9
-10
-11
.01
.1
1
10
100
ENERGY (eV)

Figure 3a

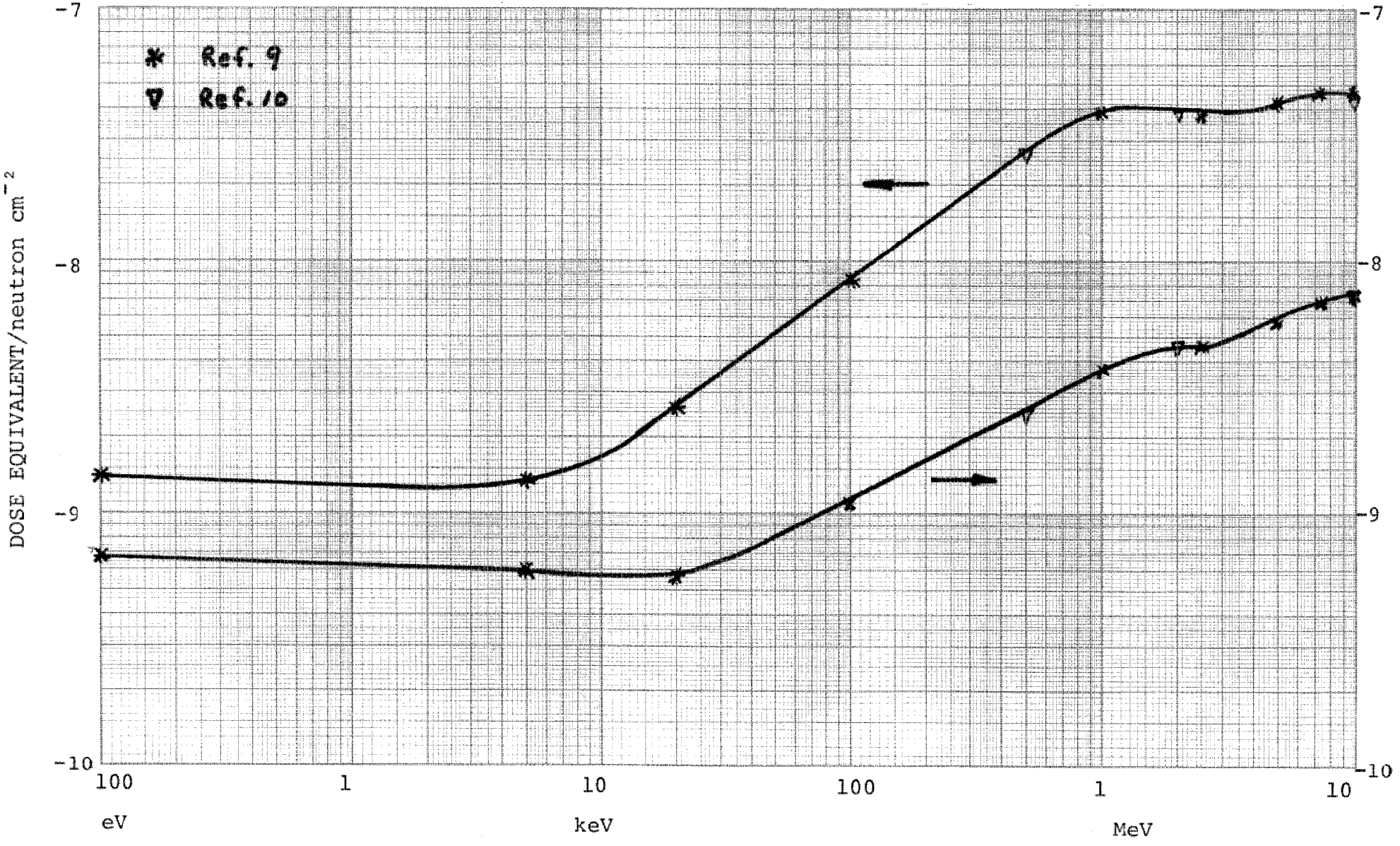

* Ref. 9
▽ Ref. 10
DOSE EQUIVALENT/neutron cm^{-2}
DOSE/neutron cm^{-2}
-7
-8
-9
-10
100
1
10
100
1
10
eV
keV
MeV
ENERGY

Figure 3b

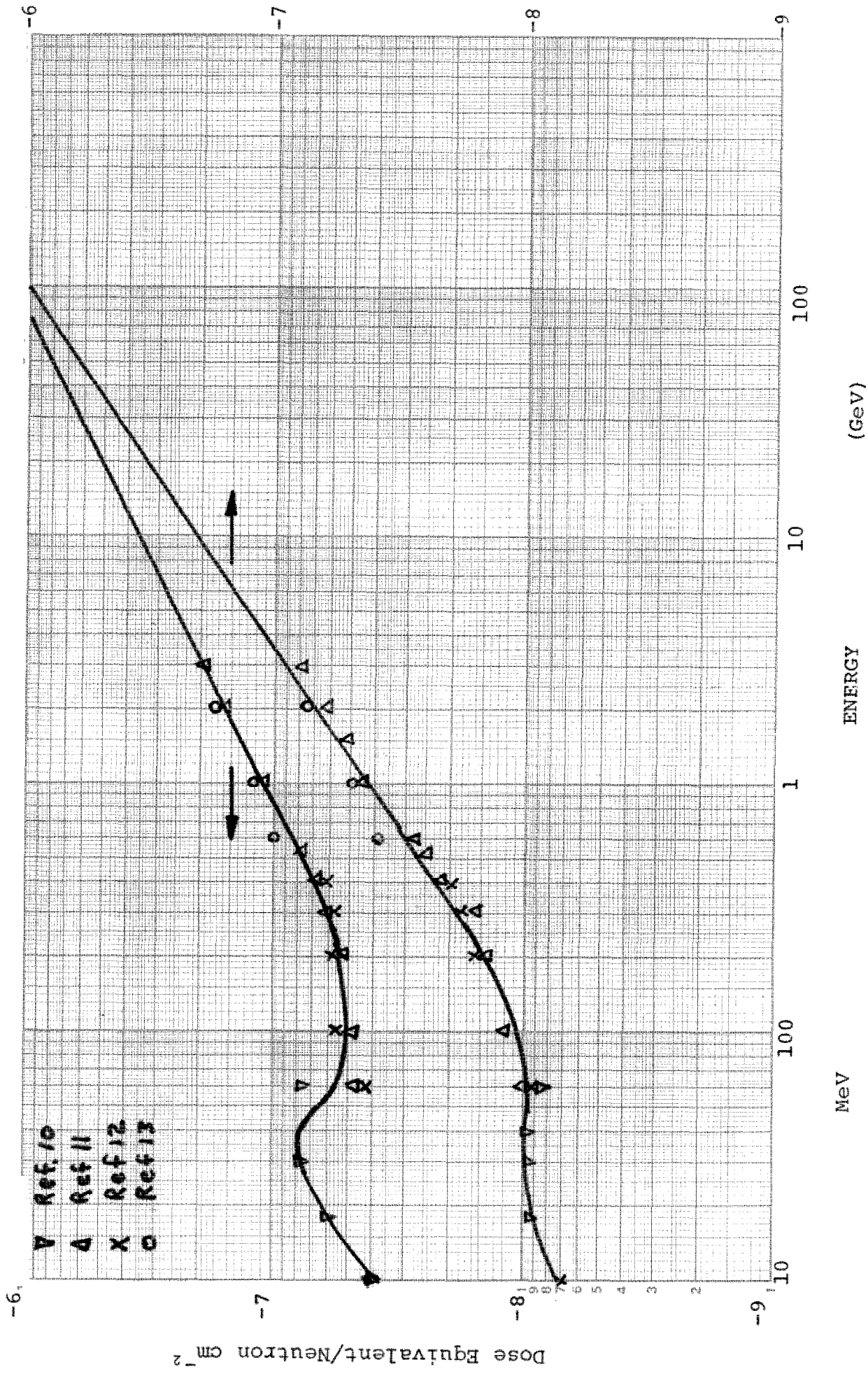

Dose/Neutron cm^{-2}
Dose Equivalent/Neutron cm^{-2}
-6
-7
-8
-9
10
100
1
10
100
MeV
ENERGY
(GeV)
Ref. 10
Ref 11
Ref 12
Ref 13

Figure 3c

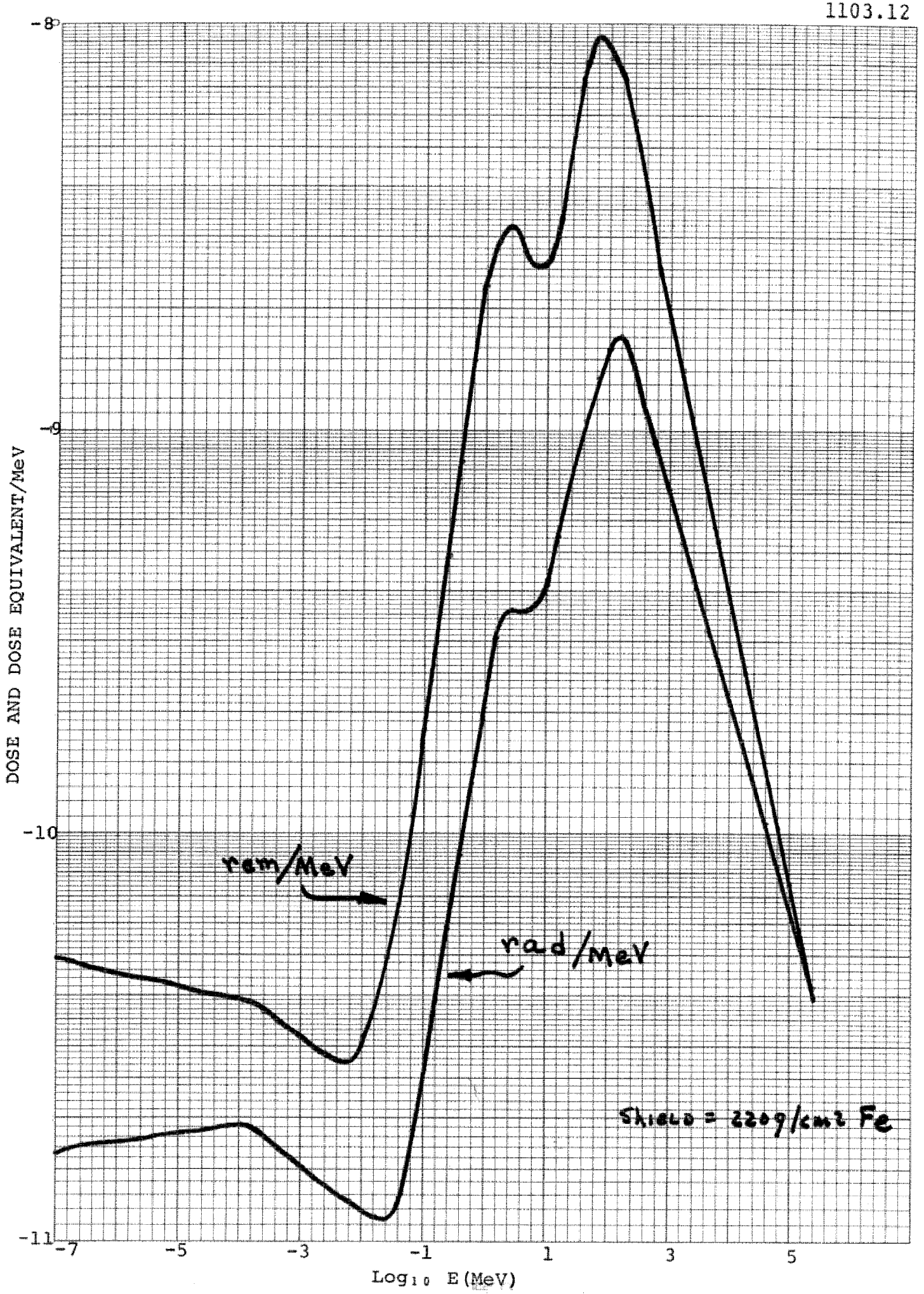
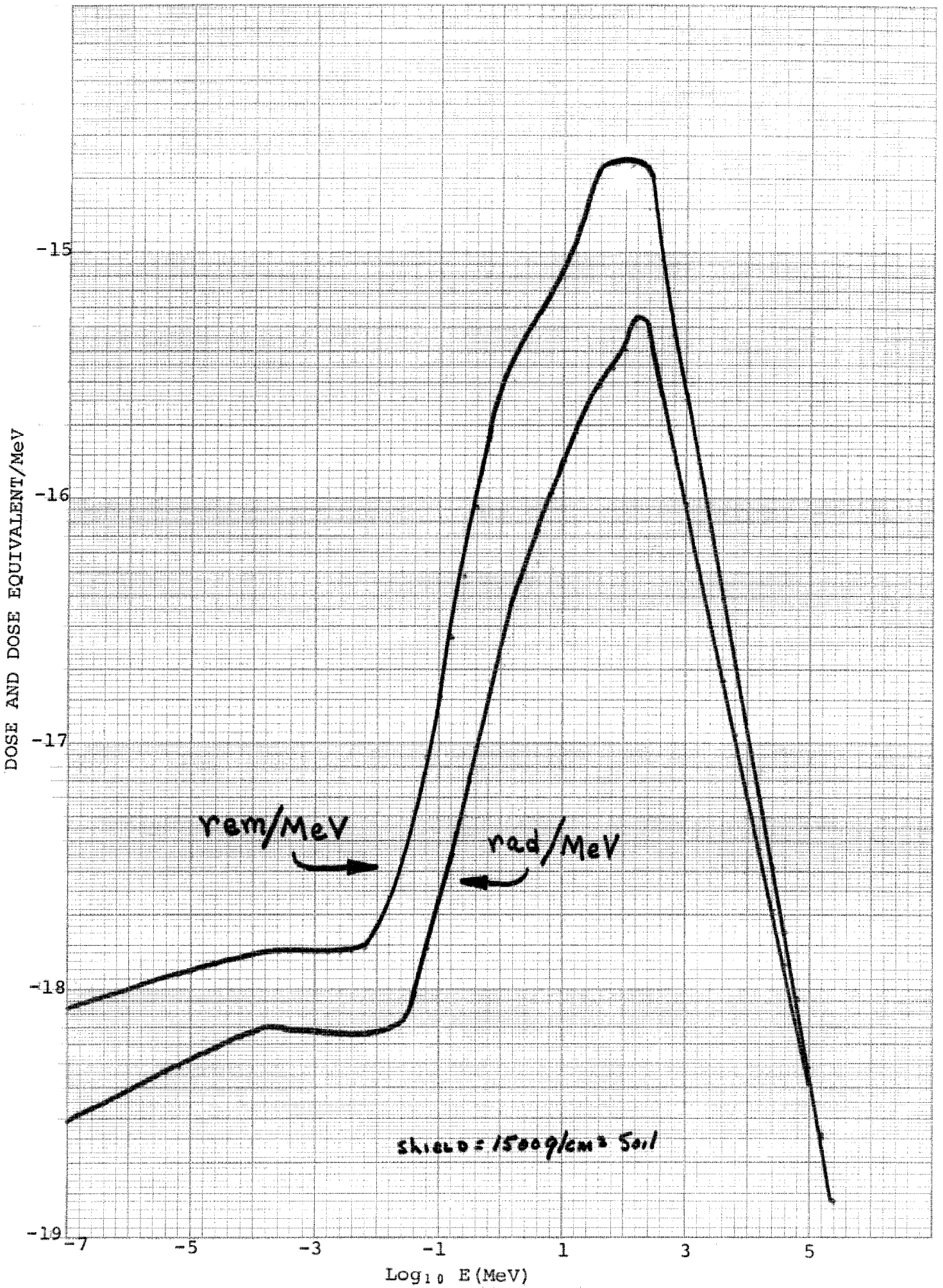
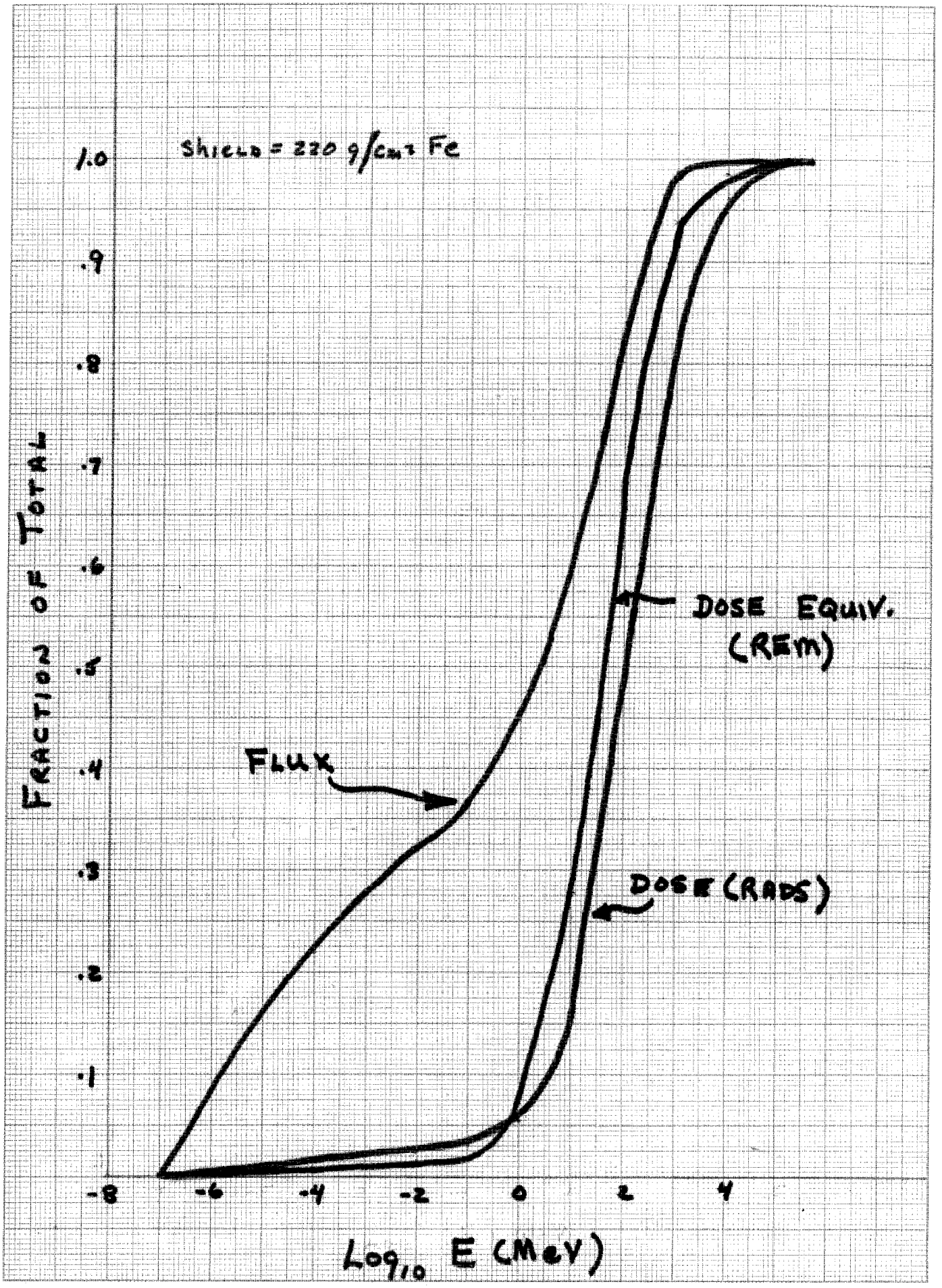

-8
-9
-10
-11
DOSE AND DOSE EQUIVALENT/MeV
rem/MeV
rad/MeV
Shield = 220g/cm² Fe
-7
-5
-3
-1
1
3
5
Log₁₀ E(MeV)

Figure 5


DOSE AND DOSE EQUIVALENT/MeV
-15
-16
-17
-18
-19
-7
-5
-3
-1
1
3
5
Log10 E(MeV)
rem/MeV
rad/MeV
SHIELD = 1500 g/cm² Soil


Shield = 220 g/cm² Fe
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
Fraction of Total
Dose Equiv. (Rem)
Flux
Dose (Rads)
-8
-6
-4
-2
0
2
4
Log10 E (MeV)

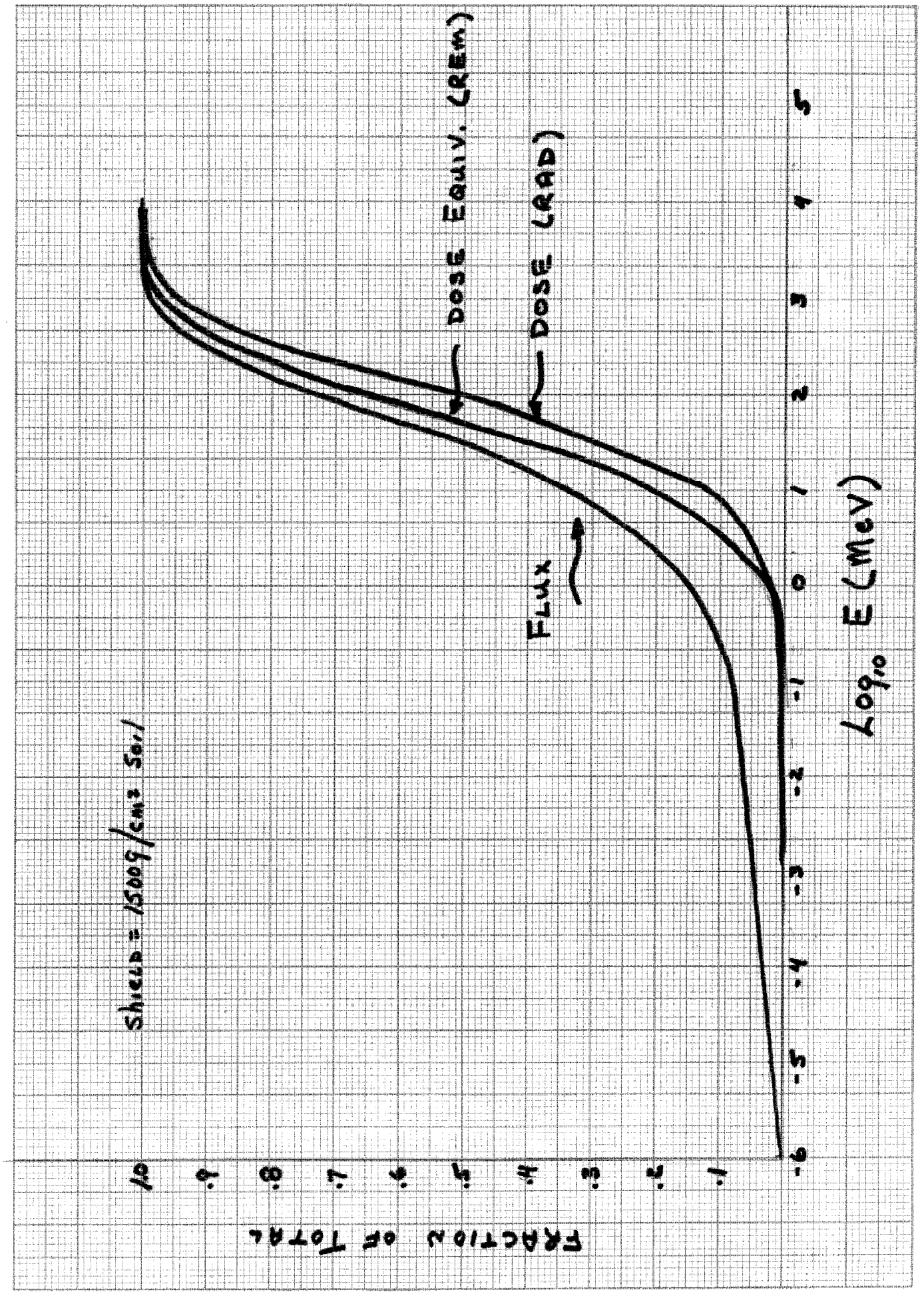

Shield = 1500g/cm² Soil
DOSE EQUIV. (REM)
DOSE (RAD)
FLUX
FRACTION OF TOTAL
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Log10 E (MeV)

Fig. 7

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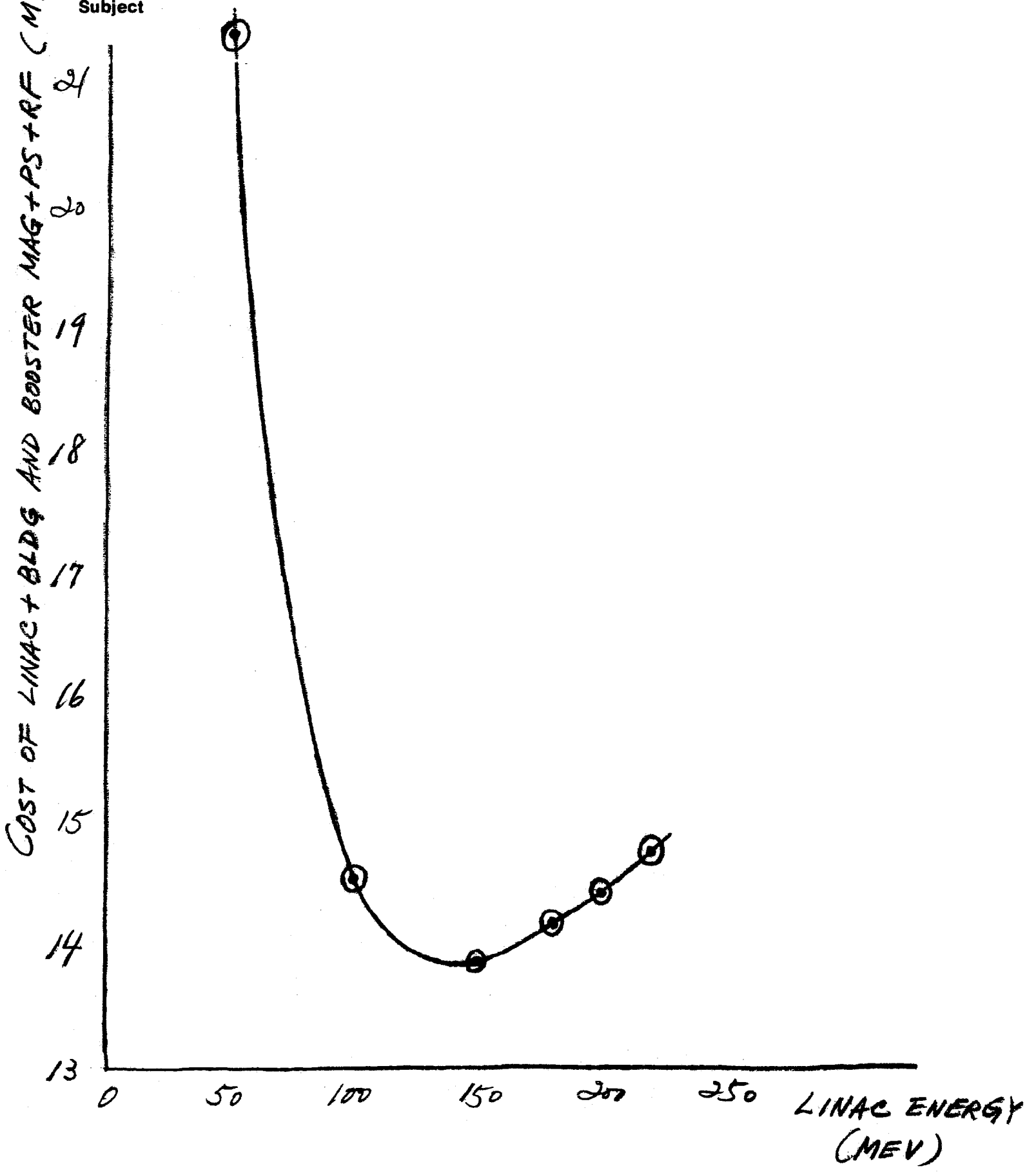
Date	Category	Serial

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