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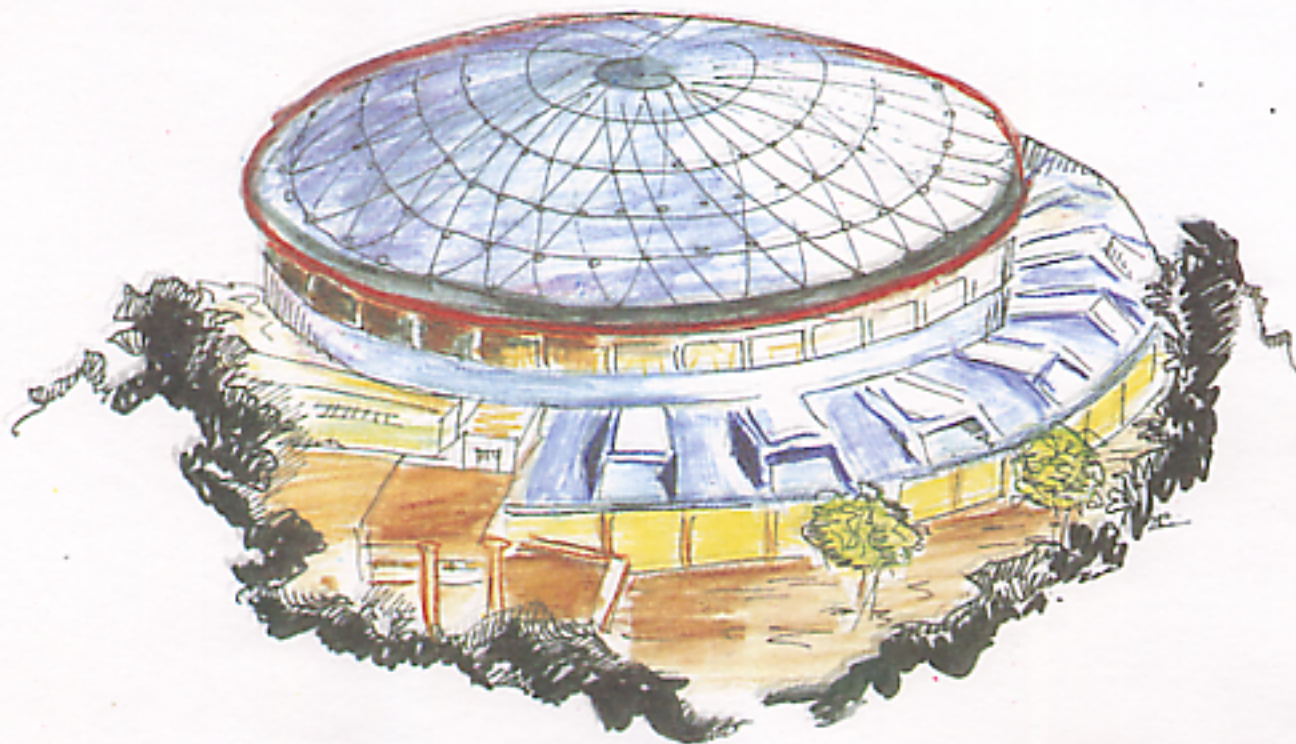
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DOSE EQUIVALENTS FOR MONOENERGETIC ELECTRONS INCIDENT ON THE ICRU SPHERE

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Dose equivalents for monoenergetic electrons incident on the ICRU sphere

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Abstract

Dose equivalents per unit of fluence at 0.07 mm, 3 mm, 10 mm and maximum dose equivalent per unit fluence along the principal axis of the ICRU sphere have been calculated by the FLUKA Monte Carlo code for broad parallel beam of monoenergetic electrons incident normal to the surface. Calculations were performed for kinetic energy ranging from 70 keV to 10 GeV. The results are compared with other published calculations, whenever available. In the energy range where dose equivalents are almost constant, suitable average values are suggested to be used for practical purposes.

Introduction

Although electron or beta-ray hazards exist in several applications (nuclear power industry, processing of radioactive ores, accelerators, radioactive isotopes, etc.), there are relatively few calculations regarding the radiological quantities of interest in radiation protection for these particles. In particular dose equivalent distributions in the ICRU sphere are lacking or incomplete, as claimed in authoritative documents (for instance ICRP Publication 51 [1] and ICRU Report 47 [2]).

According to their energy, electrons can be considered as weakly or strongly penetrating radiation. In the first case the International Commissions agree that the dose equivalents of radiological interest shall be determined at 0.07 mm and 3 mm depths.

Though the question of the most appropriate depth for the control of the exposure to the skin is still under discussion, ICRP in fact, in its 1990 recommendations [3], recommended an annual limit of 500 mSv/y at a nominal depth of 7 mg·cm^{-2}, averaged over any 1 cm^2, regardless of the area exposed,

in order to prevent deterministic effects. The limit recommended for the lens of eyes, conventionally located at 3 mm depth, was 150 mSv/y, aiming to prevent cataract.

ICRU recommended the determination of the dose equivalents at the same depths, 0.07 mm and 3 mm, for purposes of area and individual monitoring [2].

For electron energies greater than about 2.5 MeV a depth of 10 mm is also frequently employed. The 10 mm dose equivalent is usually considered as an useful estimator of the organ doses. Furthermore it should give a conservative estimate of the effective dose.

At very high energies ($E \geq 100$ MeV), when the maximum of the depth-curves does not occur near 10 mm, it becomes necessary to consider also dose equivalents at greater depths. No guidance is provided in this respect by the International Commissions. However, it is common practice by health physicists to make use of fluence to maximal dose equivalent conversion coefficients.

In consideration of the aforementioned lacks of informations, and of the dispersion of available data, the dose equivalent at 0.07 mm, 3 mm, 10 mm and the maximum dose equivalent along the principal axis of the ICRU sphere have been calculated in a consistent manner, for monoenergetic electrons of energy from 70 keV to 10 GeV, using the Monte Carlo code FLUKA in its most recent version [4, 5, 6]. The results are presented in this note.

Monte Carlo calculations

The geometry considered in these calculations was very simple. A 30 cm diameter sphere of unit density tissue, as defined by ICRU (H, 10.1% by weight; C, 11.1%; N, 2.6%; O, 76.2%), was exposed in vacuo to a parallel electron beam expanded throughout its volume.

The details about the version of the FLUKA code used, as well as its physics improvements and its ability to simulate electron-photon transport have been discussed elsewhere [5, 6, 7].

Doses at 0.07 mm, 3 mm and 10 mm, have been derived from the calculated energy deposition in regions of radius 0.5 cm and depths between 0.07 and 0.10 mm, 2.5 mm and 3.5 mm, 0.9 mm and 1.1 mm respectively, along the radius of the ICRU sphere opposing the direction of the parallel beam. The first region was bounded by the surfaces of the spheres of radius 0.07 mm and 0.10 mm respectively. The other two regions had a cylindrical structure. When the electron energy was lower than 0.3 MeV the dose at 0.07 mm has been calculated between 0.065 mm and 0.075 mm and with a radius of 0.1 cm rather than of 0.5 cm. Maximum dose equivalent has been determined, for electron energies higher than 2.5 MeV, scoring the energy deposition as a function of depth and radius in a R-Z binning cylindrical structure along the principal axis. Different grids have been selected according to the depth: 0.2 cm longitudinal bins have been used up to 2 cm, 1 cm ones for larger depths. The radial bin has been taken to be 1 cm. The dimensions of the binning regions have been fixed on the basis of the electron range in tissue and CPU time considerations. The contributions of secondary electrons and bremsstrahlung generated in the phantom have been also taken into account. The cut-off energy was 1 keV for photons and 50 keV for electrons (10 keV for primary energy below 0.3 MeV).

A special algorithm, described in ref. [8], has been used when generating the primary electrons to "concentrate" artificially the incident particles on the sphere axis in order to improve statistics.

The statistical uncertainties have been estimated by doing all calculations in several batches and computing the standard error of the average. The total number of histories was large enough to keep the standard error on the computed dose equivalents below few %.

Results

The present results are quoted in terms of dose equivalents per unit of electron fluence, for normal incidence. They are summarized in tab. 1 over the energy range 70 keV to 10 GeV. Standard errors (in %) are given in brackets.

The dose equivalent per unit fluence at 0.07 mm, H'(0.07), appears practically constant above about 3 MeV. Its mean value can be assumed equal to 274 ± 7 pSv·cm^2. Dose equivalents per unit fluence at 3 mm, H'(3), and at 10 mm, H*(10), have a similar behaviour from about 10 MeV. Their mean values can be assumed equal to 302 ± 5 pSv·cm^2 and 317 ± 7 pSv·cm^2 respectively. From 10 MeV to 100 MeV the maximum dose equivalent too appears approximately constant with a mean value of 355 ± 16 pSv·cm^2.

It should be noted that the various quantities actually behave as expected on the basis of simple qualitative considerations. The energy imparted to matter becomes in fact roughly constant when interacting electrons approach relativistic velocities. Therefore as soon as the electron velocity is still relativistic at the given depth, the dose equivalent approaches a constant value.

The concept of ambient dose equivalent could be considered significant, although with caution, up to about 100 MeV. In the energy range 4-100 MeV, in fact, it never underestimates the maximum dose equivalent by more than 16%. It is crucial to know the conversion coefficients from fluence to effective dose for a sound conclusion about this question.

At energies higher than about 100 MeV, the dose equivalent at 10 mm diverges from the maximum values as the electron energy increases. Conversion coefficients corresponding to the maximum dose equivalent, should be then conservatively used for radiation protection purposes.

The rise of the maximum dose equivalent at high energies ($E \geq 100$ MeV) can be easily explained by the predominance of the bremsstrahlung and pair production processes in the cascade development, taking into account that the critical energy in tissue equivalent materials is equal to about 90 MeV.

Fig. 1, fig. 2 and fig. 3 show comparisons of the present results with data from other calculations. In particular in fig. 1, the computed values of H'(0.07) and H'(3) are compared with the results of calculations in a water slab [9], reported as in ICRU sphere in the ICRU Report 47. In spite of the different phantoms used, in general the two calculations appear in excellent agreement.

A comparison between our results for dose equivalent at 10 mm, namely the ambient dose equivalent, with the data reported in the ICRU Report 43 [10, 11] and with calculations made by EGS3 for a broad parallel beam of electrons incident on a 30-cm-thick semi-infinite slab of ICRU tissue [12], is presented in fig. 2. As concerns the results of ref. [12] we have considered,

like ICRP did in Publication 51, the values of the dose equivalent in the depth interval 0.8-1.0 cm. Generally all the results presented in fig. 2 agree very well.

Fig. 3 shows a comparison in terms of maximum dose equivalent between the present results and those of ref. [12]. The agreement between the two calculations is satisfactory also in this case. Some differences reflect the influence of the different phantoms and geometry considered and possibly the many improvements of the FLUKA code with respect to the now superseded EGS3 code.

Conclusions

Dose distributions for broad beams of monoenergetic electrons of 70 keV to 10 GeV, incident normally on the ICRU sphere, have been calculated by the FLUKA code.

The values of the dose equivalents at depths significant in radiation protection have been determined and presented in tab. 1. Above certain energies, the values of the various dose equivalents result approximately constant. H'(0.07) results equal to 274 ± 7 pSv·cm^2 from 3 MeV. H'(3) and H*(10) can be assumed equal to 302 ± 5 pSv·cm^2 and 317 ± 7 pSv·cm^2 respectively from 10 MeV. The maximum dose equivalent can be approximated to 355 ± 16 pSv·cm^2 in the energy range from 10 MeV to 100 MeV.

The ambient dose equivalent is likely to provide a reasonable estimate of the effective dose for fast electrons up to about 100 MeV.

For application to β^- emitters problems, the presented results can be easily folded with the β spectrum under investigation.

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Tab. 1 Conversion coefficients from electron fluence to dose equivalent at 0.07 mm, 3 mm, 10 mm and maximum dose equivalent along the principal axis of the ICRU sphere, for monoenergetic electrons incident normal to the surface.

| Electron Energy (MeV)	$H'(0.07)/\phi$ (pSv·cm^2)	$H'(3)/\phi$ (pSv·cm^2)	$H^*(10)/\phi$ (pSv·cm^2)	H_{MAX}/ϕ (pSv·cm^2)
0.07	220(1.7)			
0.08	1098(0.7)			
0.09	1538(0.5)			
0.1	1644(0.7)			
0.2	906(0.9)			
0.3	598(0.6)			
0.4	481(0.8)			
0.5	420(1.3)			
0.6	376(0.6)	0.03(21)		
0.7	366(0.5)	8(2.5)		
0.8	349(0.6)	71(0.9)		
0.9	332(0.7)	195(0.9)		
1.0	326(1.2)	316(0.9)		
1.5	300(1.2)	506(0.7)	0.06(31)	
2.0	288(1.0)	472(1.1)	7(5.2)	
2.5	284(0.5)	420(0.9)	160(0.8)	475(0.3)
3.0	278(1.0)	373(0.4)	333(0.9)	462(0.5)
4.0	278(1.2)	339(0.5)	453(0.9)	453(0.7)
5.0	277(0.7)	322(0.8)	421(0.7)	433(0.6)
7.0	275(1.0)	312(0.8)	360(0.8)	
8.0				401(0.6)
10	275(1.7)	305(1.3)	325(1.3)	385(0.7)
20	267(1.5)	305(1.2)	326(0.3)	354(1.2)
30	276(1.0)	305(1.2)	318(1.1)	343(1.9)
40	266(1.9)	294(2.2)	306(1.2)	343(0.9)
50	267(1.9)	295(1.2)	310(1.0)	337(1.8)
70	270(1.4)	303(1.2)	318(1.3)	350(1.1)
100	272(2.0)	300(2.1)	315(1.3)	362(1.5)
200	284(2.8)	303(2.1)	323(1.4)	422(1.8)
500	276(2.0)	306(1.2)	318(1.5)	575(2.2)
1000	260(3.0)	294(3.2)	308(3.5)	675(1.1)
2000	272(2.7)	302(1.7)	317(2.2)	821(1.6)
5000	285(3.7)	304(1.5)	314(1.3)	1007(1.5)
10000	283(2.8)	308(2.5)	328(2.0)	1155(1.1)
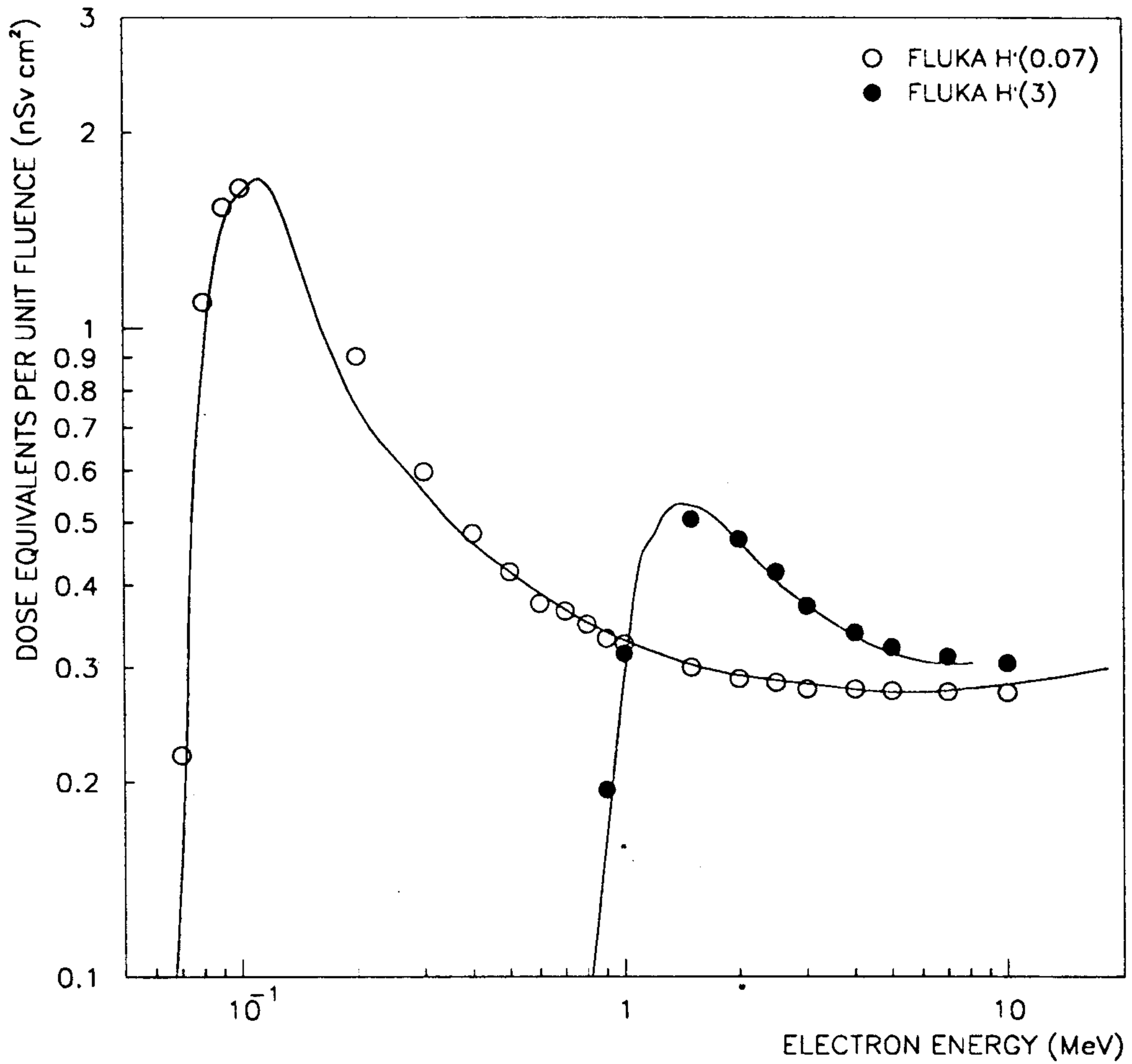
Figure 1: Dose equivalents per unit of fluence at 0.07 and 3 mm along the principal axis of the ICRU sphere as a function of the energy of an electron beam incident normal to the surface. The solide lines show the data of ICRU Report 47.
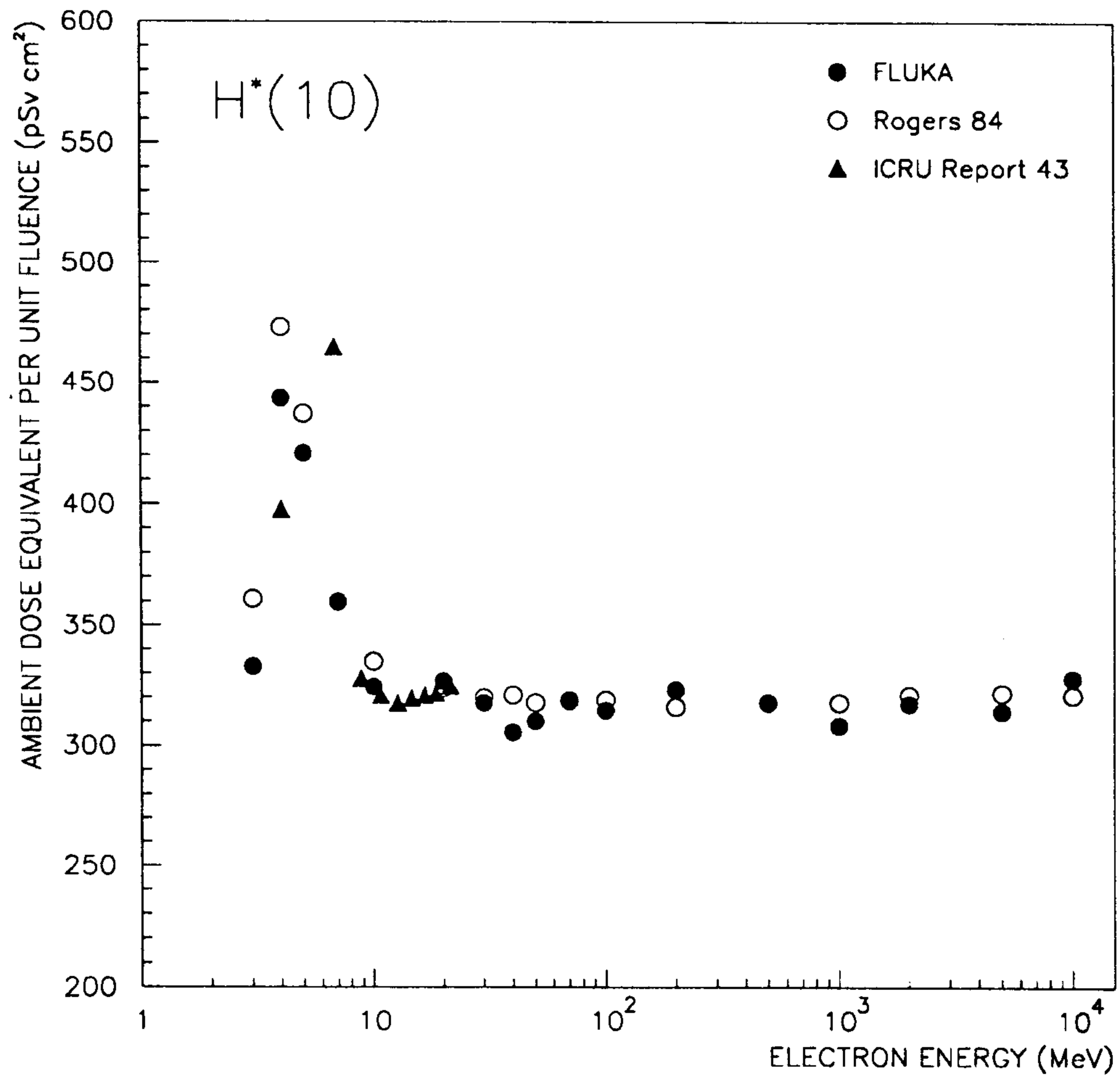
Figure 2: Ambient dose equivalent per unit of fluence as a function of the electron energy.
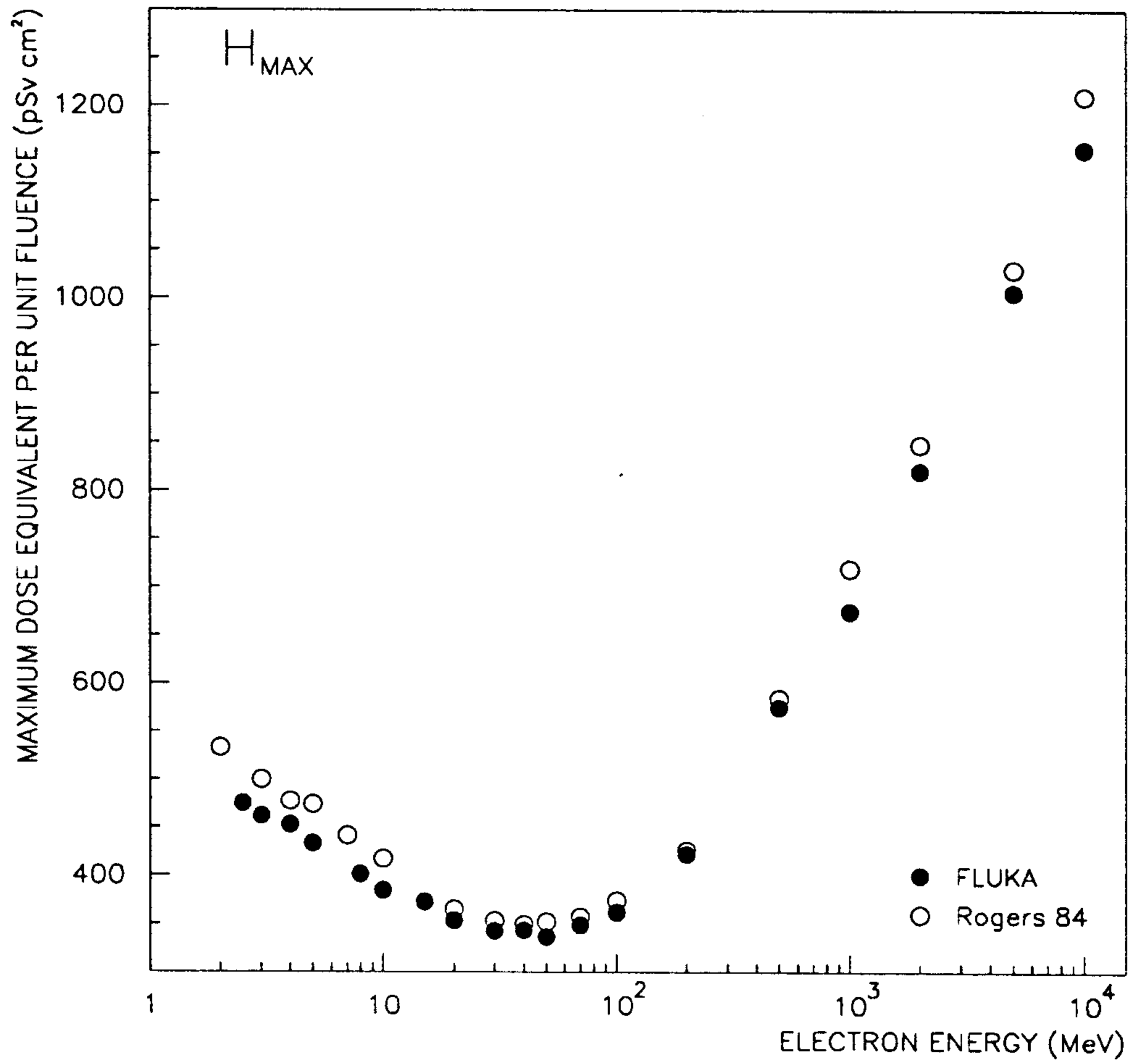
Figure 3: Maximum dose equivalent per unit fluence along the principal axis of the ICRU sphere as a function of the energy of an electron beam incident normal to the surface. A comparison is made with the data of the ref. [12].