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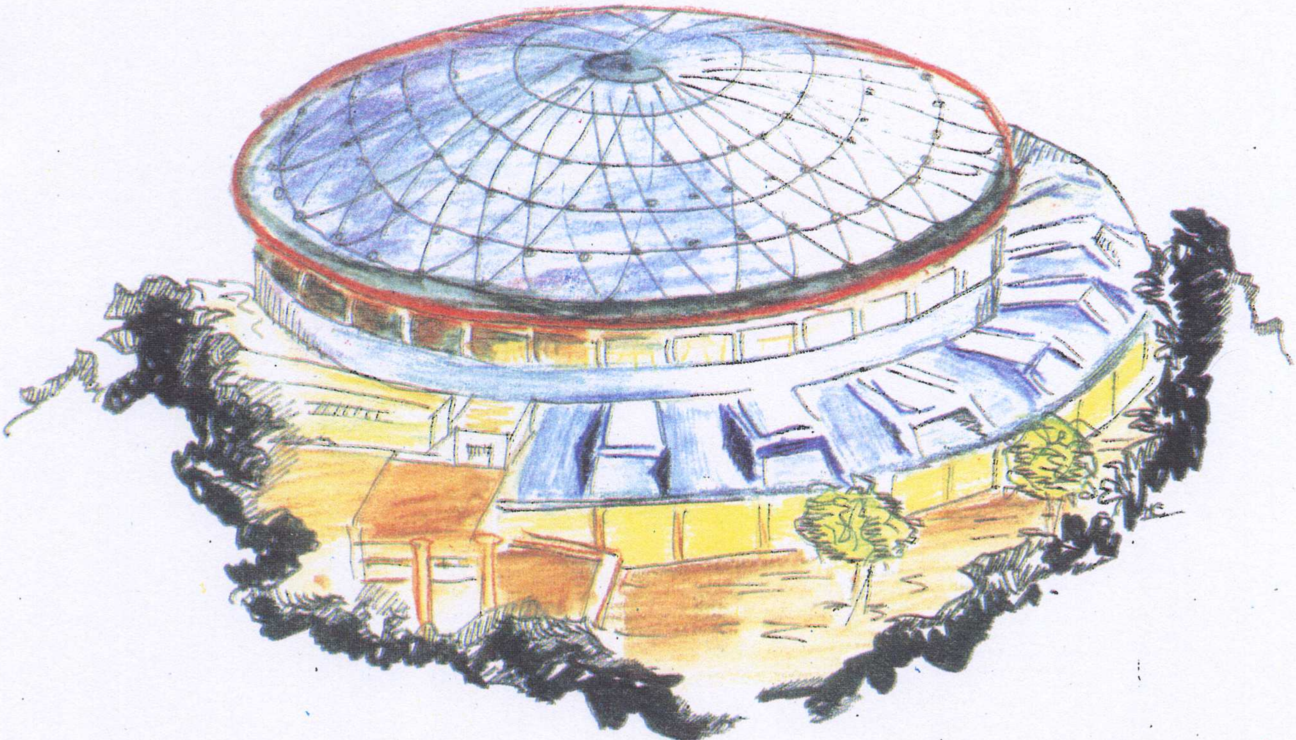

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Bremsstrahlung Source Terms for Intermediate Energy Electron Accelerators

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Abstract

Monte Carlo calculations of bremsstrahlung produced in targets bombarded by electrons with energies between 100 MeV and 1 GeV have been performed with the code FLUKA. The following informations have been obtained: maximum dose equivalent per unit power at 0° and 90°; maximum yield of radioactive gas (^{15}O and ^{13}N) produced in air. Comparisons with experimental data and other Monte Carlo calculations are also included

1 Introduction

Health physicists working at accelerator facilities use to make their evaluations on the basis of "source terms", which are generally derived from simple but very conservative models. As an example, shielding calculations are usually made in the so called model of pointlike sources, in which the beam losses are supposed to occur in a location of the machine considered equivalent to a target of the optimum thickness to maximize the yield of secondaries. Doses can be easily evaluated for a given beam if suitable source terms are available. In this kind of problems source terms are usually expressed as dose equivalent rates or as absorbed dose rates per unit beam power at a distance of one meter from the target (Sv$\cdot$m^2/h$\cdot$kW or Gy$\cdot$ m^2/h$\cdot$ kW).

In principle, a source term of this kind could be used for any other problem of radiation protection, included the estimation of the maximum dose received in case of accidental overexposure.

Another example of field of application of source terms is the evaluation of air activation in the surroundings of electron accelerators, due to photoproduction reactions. In this case, source terms describe the activity of a given radionuclide induced in air by the bremsstrahlung radiation produced by the primary beam. They are expressed per unit distance travelled by photons in air and per unit beam power (Bq/kW$\cdot$m).

The most widely used source terms for electron accelerators are those proposed by W.P.

Swanson in the IAEA Report No.188 [1], both for shielding and air activation estimation. In this report the available experimental data on bremsstrahlung from thick targets at 0° and 90° have been analyzed and summarized in two very practical formulae. However, most of these data concern primary electrons with energy not higher than 100 MeV, while the source terms proposed in the intermediate range (100-1000 MeV) are deduced by extrapolation. Furthermore, the experimental result available at the highest energy (100 MeV) [2] was obtained by means of a target of non optimum thickness for bremsstrahlung production and consequently corrected according to Monte Carlo calculations.

The intermediate-energy range is particularly interesting for a new generation of storage rings, dedicated to the Φ-factories. One of these machines (DAΦNE) is under construction at the National Laboratory of Frascati (LNF), Italy. DAΦNE will operate with electron and positron beams of 510 MeV, with the possibility of reaching 700 MeV in a later stage.

It is thus worthwhile to better investigate the validity of the extrapolated source-terms in the range 100-1000 MeV by means of Monte Carlo simulations. Calculations of this kind are already available in the literature [3, 4, 5], and sometimes their results have been compared with the formulae of the IAEA Report, but they do not seem to be exhaustive. In one case [4], the calculation concerned energies higher than about 1 GeV. In other cases [3, 5] the authors were not interested in optimizing the target geometry in order to get the maximum yield.

2 Calculations

In this work, all calculations have been performed by the FLUKA program [6] in its most recent version, which includes major modifications to the original one [7, 8, 9]. In particular, the treatment of bremsstrahlung is completely new, as photon yield and spectra are now based on the tabulations of Seltzer and Berger [10], and the photon angular distributions are accurately described.

Since the results are expressed in terms of physical quantities (particle fluences), they have to be converted to quantities in use in radiation protection by means of an appropriate set of conversion coefficients. It must be pointed out that all the available sets refer to broad parallel beam irradiation, whereas in our case the photon beam is confined to a very narrow cone. Moreover, the frequent changes introduced in this matter by ICRU and ICRP made the situation very unclear. In the calculation presented here, the set recommended by ICRP in the Publication 21 [11] has been chosen, because it is still the most widely used and it was in force when the measurements and calculations here quoted were performed.

However also the conversion coefficients calculated by Rogers [12] have been considered. According to this author the values used by ICRP for photons with energies below 10 MeV would give a significant underestimate of the dose equivalent, especially near 100 keV, since based on a collision kerma-to water approximation to the maximal dose equivalent. Conversely, at higher energies the coefficients recommended by ICRP are more conservative.

The geometry considered in the calculations is very simple: a cylindrical target of given radius (r) and thickness (s) of a certain material is perpendicularly hit by a pencil electron beam. Scoring is performed by detectors placed at a distance of one metre from the target. Their dimensions have been varied according to the different source terms investigated. Iron, tungsten and copper targets have been considered. Their dimensions have been optimized at each beam energy to obtain the maximum value of the quantity of interest.

Of course, the optimum target geometry resulted to be strongly dependent on the problem considered: for a lateral shielding problem, which depends mostly on the radiation emitted at 90°, the maximum dose is obtained with thick targets of small section (see fig. 1); on the contrary, when one is interested in the radiation emitted at 0°, targets must be thin (fig 2); for air activation, which is produced by photons emitted in any direction with energy higher than the photoproduction thresholds (the lowest being 10.55 MeV), the optimum can be achieved with medium-thickness targets (fig. 3).

The examples reported in fig.1, 2 and 3 all refer to a 510 MeV incident electron beam, and show the behaviour of the yield as a function of the target thickness for different values of the target radius. Photon scoring has been performed in the angular range $85° - 95°$ in the case of fig.1 and between 0° and $+2°$ in the case of fig.2.

3 Results and discussion

3.1 Source term at 90°

Photons emitted at 90° have been actually scored by a detector covering the angular range $85° - 95°$. This allowed to obtain results still representative of the dose at 90° with good statistics. At each energy, by means of graphs like that of fig.1, we have found the target of optimum geometry (see table 1) and we have assumed its yield as source term at 90°.

A typical photon spectrum at 90° is shown in fig.4. It has been obtained with an iron optimum target (s=16 cm) and a primary beam of 510 MeV. It can be noticed that the contribution of 511 keV photons coming from positron annihilation dominates over the bremsstrahlung one.

The behaviour of the 90° source term as a function of beam energy is shown in fig.5. As it can be observed, the source term results to be completely independent from the beam energy, at least in the energy range considered here, and can be assumed equal to:

$$\dot{D} = 51.3 \tag{1}$$

where $\dot{D}$ is in Sv·m^2/h·kW.

This value agrees very well with that proposed in the IAEA Report No.188 (50 Sv·m^2/h·kW) as an extrapolation from data obtained at energies below 100 MeV.

The present results is not consistent with those of [4], where calculations made with EGS resulted in a source term with a mean value of 40 Sv·m^2/h·kW and growing with beam energy.

3.2 Source term at 0°

In studying the 0° source term one has to cope with the difficult problem of the choice of the detector dimensions or, equivalently, of its angular coverage.

Obviously, the dimensions of the scoring area should depend on the incident beam energy, because the angular distribution of bremsstrahlung radiation depends on it. An exceedingly large detector would lead to saturation effects and unreliable results, while a very small detector would heavily affect the statistics.

On the other hand, one could argue that the determination of the dose due to photons emitted within a very small cone has no practical interest in radiation protection, as the fundamental quantity in radiation protection doctrine is the organ dose (par. 24 of the ICRP Publication 60) [13] and the smallest surface of an organ to be considered is 1 cm^2 for the skin (par. 173-193). Unfortunately, however, this prescription on the irradiated surface does not translate into a useful recipe for the scoring cone in the calculations because the irradiation can occur at a quite large distance from the source. Moreover, in literature the attention has been devoted to smaller surfaces also, like in the case of the so called "hot particles" (see for instance [14, 15]).

Due to the exposed considerations, we have studied, for the various targets and energies, the behaviour of the dose equivalent rate as function of the scoring area. This has been made scoring the photons emitted within cones of half-width ranging between 0.0256° and 2°. In a few selected cases we have followed 700000 primary electrons in order to obtain a good statistics also in the smallest detector. All the curves so obtained show a flat plateau, within the statistical uncertainties, followed by a decrease, as shown in fig.6. The curve of fig.6 refers to an iron target 0.5 cm thick and 0.5 cm of radius hit by a 100 MeV electron beam, and the angle reported in abscissa is the half-width of the scoring cone. The uncertainties on photon fluences range from 10.2% in the smallest detector to 0.1% in the largest; the uncertainties on dose are bigger because the folding with conversion coefficients gives a strong weight to the relatively rare high energy photons.

Once determined the general behaviour, we were allowed to choose as optimum size detector for each energy and target the one corresponding to the end of the plateau in the dose vs. angle plot, as reported in table 2.

It can be seen from the values in tab.2 that the width of the plateau decreases with increasing beam energy, as it was expected from the analytical expression of the bremsstrahlung angular distribution, which scales approximately with the critical angle $\theta_c = 1/\gamma$, where $\gamma = E/m_e c^2$

For sake of completeness, fig.7 shows the spectra obtained at the various angles close to 0° with detectors of different sizes from an optimum target bombarded by a 510 MeV electron beam.

As far as the target is concerned, it must be observed that the thickness of the target is not critical, provided that it is small compared to the radiation length. As shown in fig.8, the calculated dose remains constant over a wide range of thicknesses (1 to 5 mm in iron).

We have assumed as source term in the forward direction the value obtained with the target of optimum thickness and size, as summarized in table 2. In all the cases we have followed at least 100000 primary electrons.

The behaviour of the source term as a function of energy is shown in fig.9. It can be approximated with the expression:

$$\dot{D} = 7.16 \cdot 10^{6} \left(\frac{E}{E_0}\right)^{1.5} \qquad (2)$$

where $\dot{D}$ is in Sv·m^2/h·kW, E is the electron energy in GeV and $E_0 = 1$ GeV.

The use of the conversion coefficients suggested by Rogers [12], instead of those recommended by the ICRP in the Publication 21, lowers the doses at most of 20-25% at the highest energies.

Similar calculations have been performed also for tungsten and tin targets, but only at 100 MeV. The resulting source terms for the radiation emitted in the forward direction are similar to those obtained for iron: $2.9 \cdot 10^5$ Sv·m^2/h·kW for tungsten, $2.3 \cdot 10^5$ Sv·m^2/h·kW for tin, in comparison with $2.2 \cdot 10^5$ Sv·m^2/h·kW for iron.

The 0° source terms calculated in this work are quite higher than those proposed in the IAEA Report No.188: for instance, our values are 7 times higher than the IAEA ones at 100 MeV and 22 times at 1000 MeV. Moreover, the dependence on energy seems to follow a power law rather than a linear one.

As already mentioned, the semiempirical formulae proposed in that Report for the dependence of the source term on the energy in the range 100-1000 MeV are obtained as extrapolations from values at lower energies. It was indeed available one experimental result at 100 MeV [2], but the experiment itself was primarily devoted to the measurement of bremsstrahlung from thick targets, not to the determination of the maximum dose. This quantity has been evaluated by correcting the experimental results with a 9.8 factor to take into account the yield dependence on the target thickness. On turn, the correction factor has been estimated from the results of Montecarlo calculations [16] performed at lower energies (maximum 60 MeV) and relative to the total (2π) bremsstrahlung yield. Moreover, since the electron beam used in the experiment of ref [2] was not really pointlike (2 cm at the target face, with a detector to target distance of about 55 cm), the angular resolution of the experiment was, in our opinion, not good enough to determine the yield in the very forward cone. To support this statement, and to test the reliability of the code, we carried out a calculation with a geometry as similar as possible to the experimental. After multiplying our result by the same 9.8 factor used in [2], we obtain for the dose rate the value 2.6 Sv·m^2/h·kW (10% statistical error), in excellent agreement with the value of 2.5 Sv·m^2/h·kW given in ref.[2].

Furthermore, some difference between the result of the experiment in ref. [2] and the estimate of eq. (2) could also arise because of the different geometry of the phantom employed in comparison with those considered to define the conversion coefficients.

We can therefore conclude that the results at 0° in the energy range 100-1000 MeV presented in this paper are a useful complement to those proposed in the IAEA Report, being expecially well suited to the evaluation of dose rate in the very forward zone.

The semiempirical formula proposed in [4] on the base of EGS calculation does not seem acceptable, since the scoring has been performed by a too large detector (covering an angle of 0.6°) with respect to the energies investigated.

It must be also mentioned that other authors [5], on the base of calculation carried out with iron targets 0.2 and 1 cm thick, have proposed source terms which are higher than the IAEA ones, and whose dependence on energy is consistent with that suggested in this work.

The residual discrepancies between these results and ours are due to the larger scoring angles used by these authors and to a non optimum thickness of their targets with respect to the energies investigated.

3.3 Source term for the production of ^{15}O and ^{13}N

For the evaluation of source terms concerning the photoproduction of radionuclides in air only the more prolific reactions have been considered: $^{16}O(\gamma,n)^{15}O$ and $^{14}N(\gamma,n)^{13}N$, whose thresholds are at 15.67 and 10.55 MeV, respectively.

In this case there is no scoring problem since it is sufficient to score all of photons emitted with energy above the thresholds.

The better suited targets for these calculations are those of intermediate thickness, as already illustrated in fig. 3; the values used are listed in table 3.

Obviously, the cross sections for the two reactions considered are needed. For the production of ^{15}O we used up to 25 MeV the values reported in the Atlas of Photoneutron Cross Sections [17]; between 25 and 90 MeV the data of P. Carlos et al. [18]; above 90 MeV, because of the lack of experimental data we assumed a cross section constant and equal to that at 90 MeV.

For the production of ^{13}N we used the data of King et al. [19] up to 32 MeV, and assumed again a constant value of the cross section above.

The results, expressed in Bq/kW·m, are shown in fig.10 as a function of the electron beam energy, in the range 100-1000 MeV, and are listed in table 3. They appear practically independent on energy, since the difference between the values at the two extremities of the range considered is of about 37%. Sticking to the most conservative choice, we propose as source terms for the two reactions investigated the values calculated at 100 MeV:

$$A(^{13}N)= 2\cdot 10^{8}\ \mathrm{Bq/kW\cdot m} \qquad A(^{15}O)= 1.3\cdot 10^{8}\ \mathrm{Bq/kW\cdot m}$$

The IAEA Report No.188 suggested the values of $5.2\cdot 10^{8}$ Bq/kW·m for ^{13}N and $5.6\cdot 10^{7}$ Bq/kW·m for ^{15}O. The major discrepancy concerns the ratio between the two values, which is about 10 in the IAEA Report, and about 2 in our calculations. This difference could be probably due to some difference in the cross sections used. The results reported in literature tend to support the ratio found here (see for instance [20, 21]).

An analysis of the angular distribution of the photons emitted with energy higher than the reaction thresholds led to the conclusion that a fraction higher than 99.5% is emitted within 45°. It follows that the radioactive gas production could be easily reduced shielding the forward zone near the locations where beam losses are likely to occur.

4 Conclusion

Eq. (1) and (2) allow to calculate the maximum dose equivalent delivered at 90° and 0° respectively when an electron beam of energy between 100 MeV and 1 GeV hits a target. They can be used in radiation protection practices for many purposes, included shielding design and accidental overexposure estimation.

In an analogue way the source terms suggested in section 3 provide the maximum yield of radioactive gas (^{15}O and ^{13}N) induced in air by the bremsstrahlung emitted from a target bombarded by an electron beam, independently on its energy.

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Tab.1 Results of the simulations and target dimensions for the photon yield at 90°.

E (MeV)	r (cm)	s (cm)	$\dot{H}$ (Sv·m^2/h·kW)
100	1.5	20.0	51.3
250	1.5	16.0	51.3
510	1.5	16.0	51.0
800	2.0	20.0	52.8
1000	1.5	17.4	50.0

Tab.2 Results of the simulations, target dimensions and scoring cones for the photon yield at 0°; θ is the half width of the scoring cone.

E (MeV)	r (cm)	s (cm)	$\theta(deg)$	$\dot{H}$ (Sv·m^2/h·kW)
100	0.5	0.2	0.2	$2.1 \cdot 10^5$
250	0.5	1.0	0.1	$1.0 \cdot 10^6$
510	0.5	2.0	0.05	$2.5 \cdot 10^6$
800	0.5	2.0	0.0256	$5.4 \cdot 10^6$
1000	0.5	2.0	0.0256	$6.7 \cdot 10^6$

Tab.3 Results of the simulation and target dimensions for the production of ^{13}N and ^{15}O.

E (MeV)	r (cm)	s (cm)	^{13}N (Bq/kW·m)	r (cm)	s (cm)	^{15}O (Bq/kW·m)
100	0.5	2.0	$2.0 \cdot 10^8$	0.5	2.0	$1.3 \cdot 10^8$
250	0.5	4.0	$1.5 \cdot 10^8$	0.5	4.0	$9.8 \cdot 10^7$
510	0.5	8.0	$1.3 \cdot 10^8$	0.5	4.0	$8.9 \cdot 10^7$
800	0.5	8.0	$1.3 \cdot 10^8$	1.0	6.0	$8.4 \cdot 10^7$
1000	0.5	8.0	$1.3 \cdot 10^8$	1.0	6.0	$8.2 \cdot 10^7$

FIGURE CAPTIONS

Fig.1 Dose equivalent rate at 90° per unit of beam power at 1 m from iron targets of various radii, bombarded by 510 MeV electrons, as a function of the target thickness.

Fig.2 Dose equivalent rate in the forward direction (±2°) per unit of beam power at 1 m from iron targets of various radii, bombarded by 510 MeV electrons, as a function of the target thickness.

Fig.3 Activity of ^{13}N (black symbols) and ^{15}O (open symbols) induced in air per unit of beam power and of photon path in air as a function of the target thickness. Primary electron energy 510 MeV.

Fig.4 Photon spectrum at 90° at 1 m from an iron target of optimum geometry bombarded by a 510 MeV electron beam.

Fig.5 Source term for the production of bremsstrahlung at 90° as a function of the energy of the electron beam.

Fig.6 Dose equivalent rate in the forward direction per unit of beam power at 1 m from an iron target (s=0.5 cm; r=0.5 cm), bombarded by 100 MeV electrons, as a function of the half width of the scoring cone

Fig.7 Photon spectra within various cones centered around 0° at 1 m from an optimum iron target, bombarded by a 510 MeV electron beam. The spectra emitted at the smallest angles are practically superimposed.

Fig.8 Dose equivalent rate in the forward direction per unit of beam power at 1 m from optimum targets (Fe, W, Sn), bombarded by a 100 MeV electron beam, as a function of the target thickness.

Fig.9 Source term for the production of bremsstrahlung at 0° as a function of the energy of the electron beam.

Fig.10 Source terms for the production in air of ^{13}N and ^{15}O as a function of the energy of the electron beam.

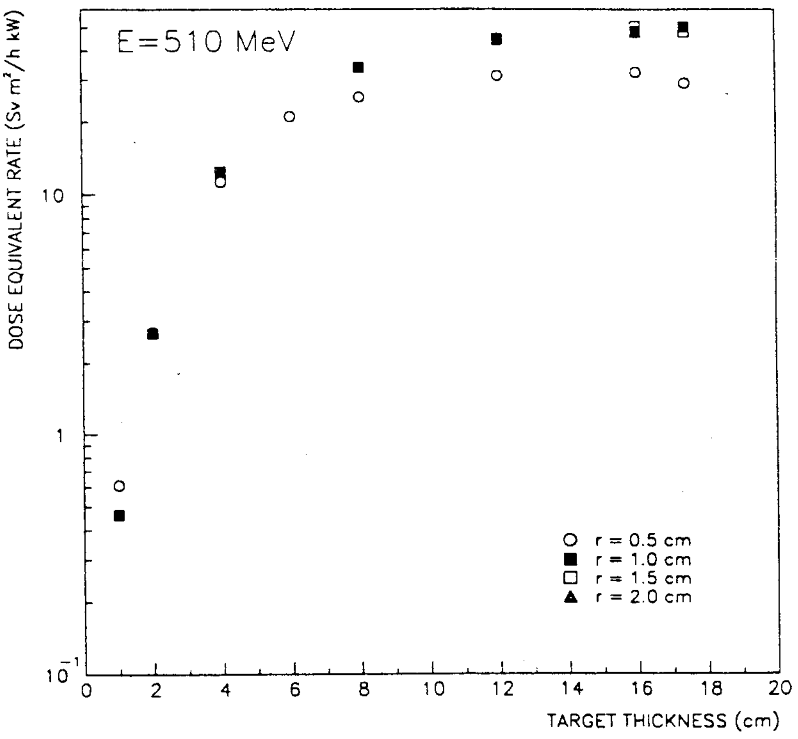
E=510 MeV
DOSE EQUIVALENT RATE (Sv m²/h kW)
TARGET THICKNESS (cm)
10
1
10⁻¹
0
2
4
6
8
10
12
14
16
18
20
○ r = 0.5 cm
■ r = 1.0 cm
□ r = 1.5 cm
▲ r = 2.0 cm

FIG. 1

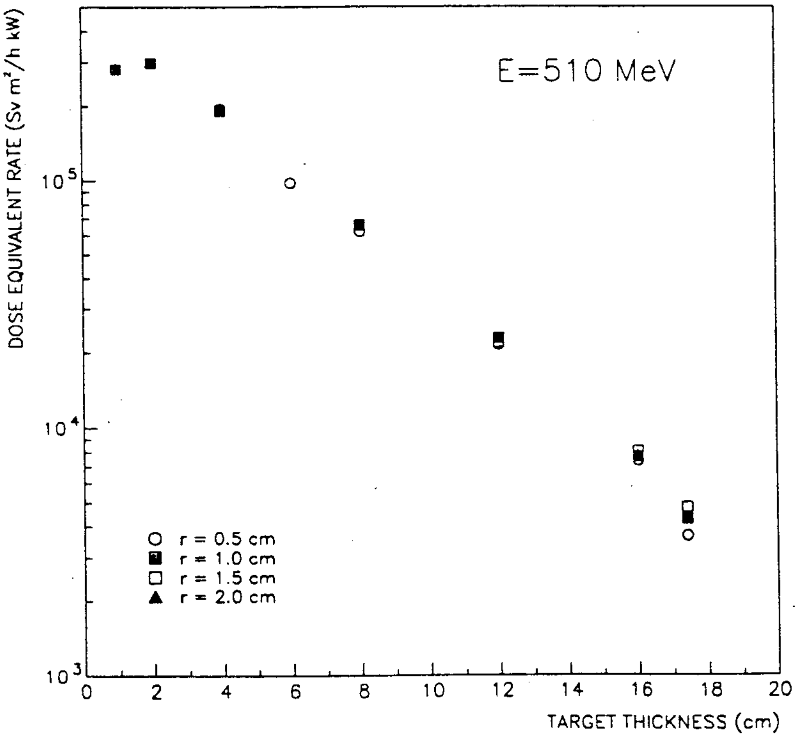
E=510 MeV
DOSE EQUIVALENT RATE (Sv m²/h kW)
TARGET THICKNESS (cm)
10⁵
10⁴
10³
0
2
4
6
8
10
12
14
16
18
20
○ r = 0.5 cm
■ r = 1.0 cm
□ r = 1.5 cm
▲ r = 2.0 cm

FIG. 2

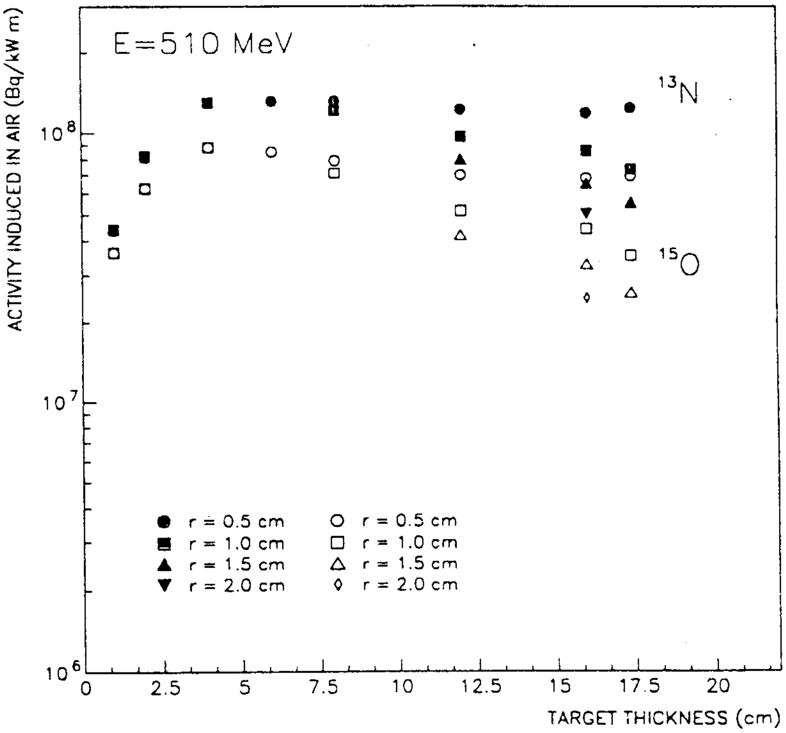
E=510 MeV
^{13}N
^{15}O
ACTIVITY INDUCED IN AIR (Bq/kW m)
10^8
10^7
10^6
● r = 0.5 cm
■ r = 1.0 cm
▲ r = 1.5 cm
▼ r = 2.0 cm
○ r = 0.5 cm
□ r = 1.0 cm
△ r = 1.5 cm
◊ r = 2.0 cm
0
2.5
5
7.5
10
12.5
15
17.5
20
TARGET THICKNESS (cm)

FIG. 3

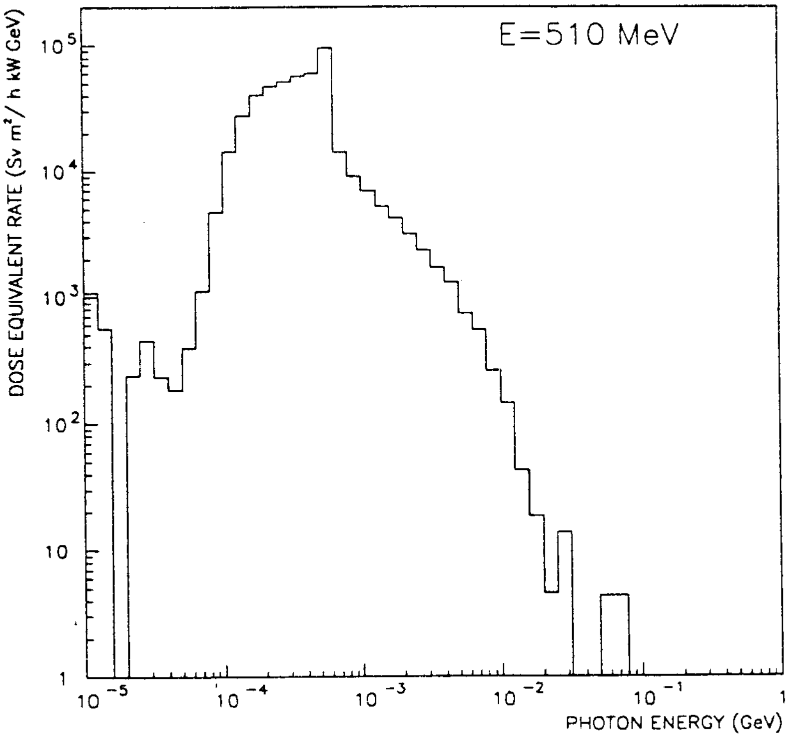
E=510 MeV
DOSE EQUIVALENT RATE (Sv m^2/ h kW GeV)
10^5
10^4
10^3
10^2
10
1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
PHOTON ENERGY (GeV)

FIG. 4

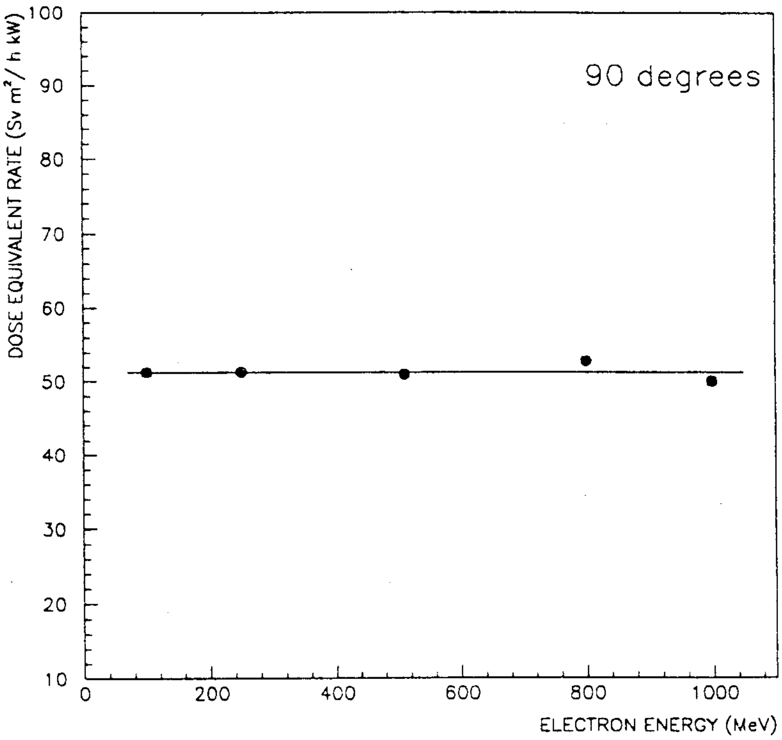
DOSE EQUIVALENT RATE (Sv m^2/ h kW)
100
90
80
70
60
50
40
30
20
10
0
200
400
600
800
1000
ELECTRON ENERGY (MeV)
90 degrees

FIG. 5.

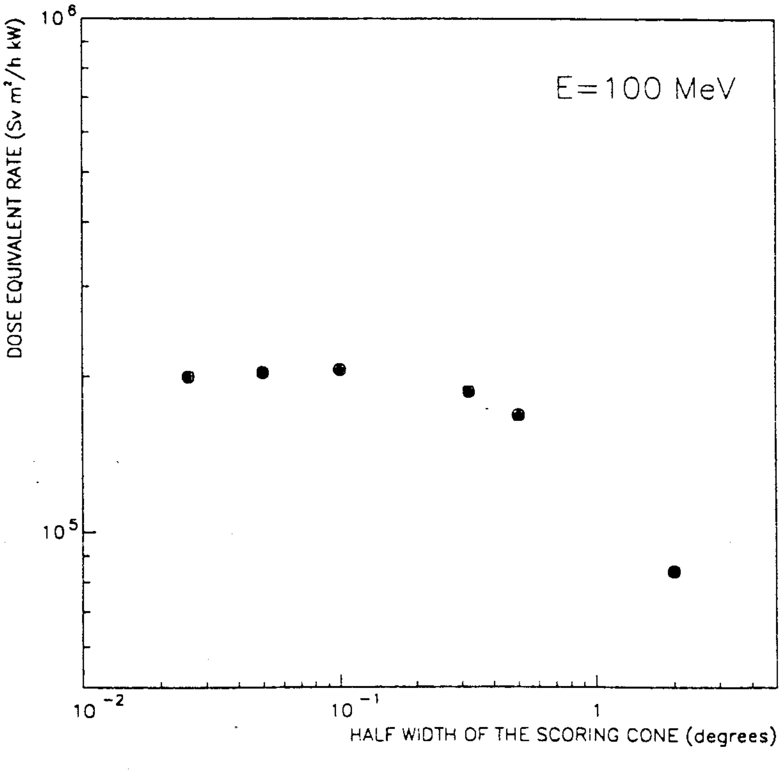
DOSE EQUIVALENT RATE (Sv m^2/h kW)
10^6
10^5
10^{-2}
10^{-1}
1
HALF WIDTH OF THE SCORING CONE (degrees)
E=100 MeV

FIG. 6

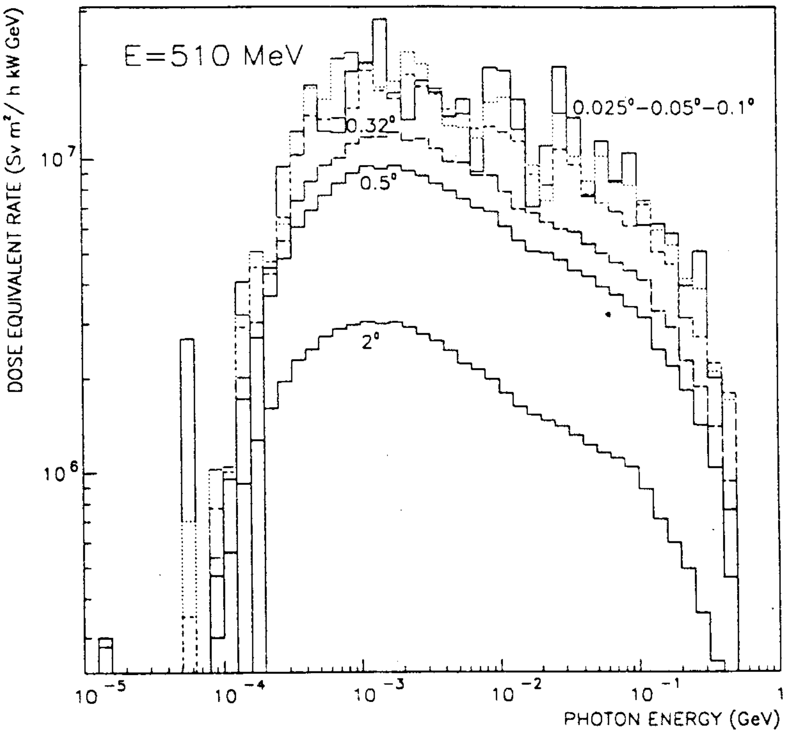
E=510 MeV
DOSE EQUIVALENT RATE (Sv m²/ h kW GeV)
PHOTON ENERGY (GeV)
0.025°-0.05°-0.1°
0.32°
0.5°
2°
10⁷
10⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
1

FIG. 7

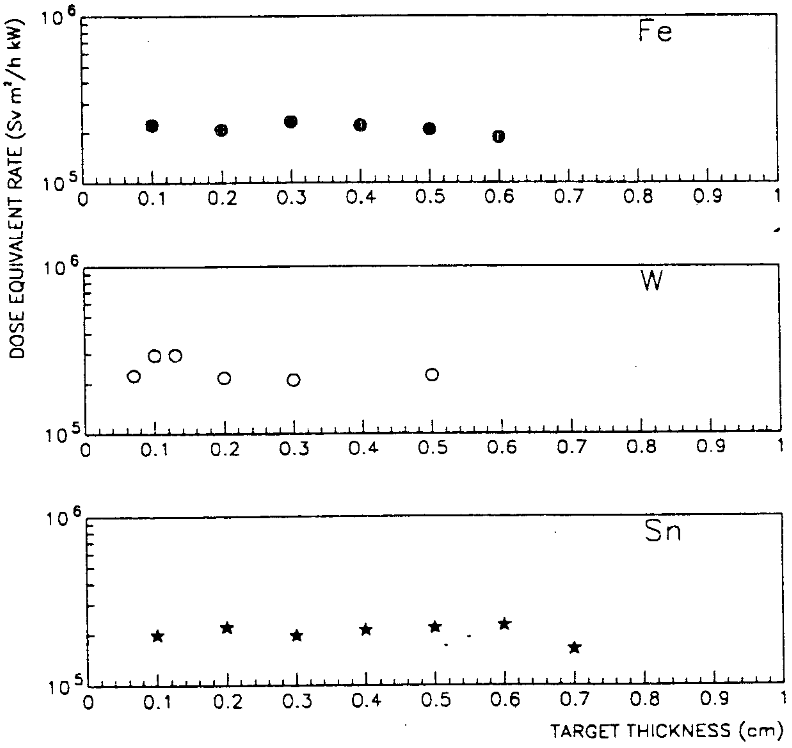
DOSE EQUIVALENT RATE (Sv m²/h kW)
Fe
W
Sn
10⁶
10⁵
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
TARGET THICKNESS (cm)

FIG. 8

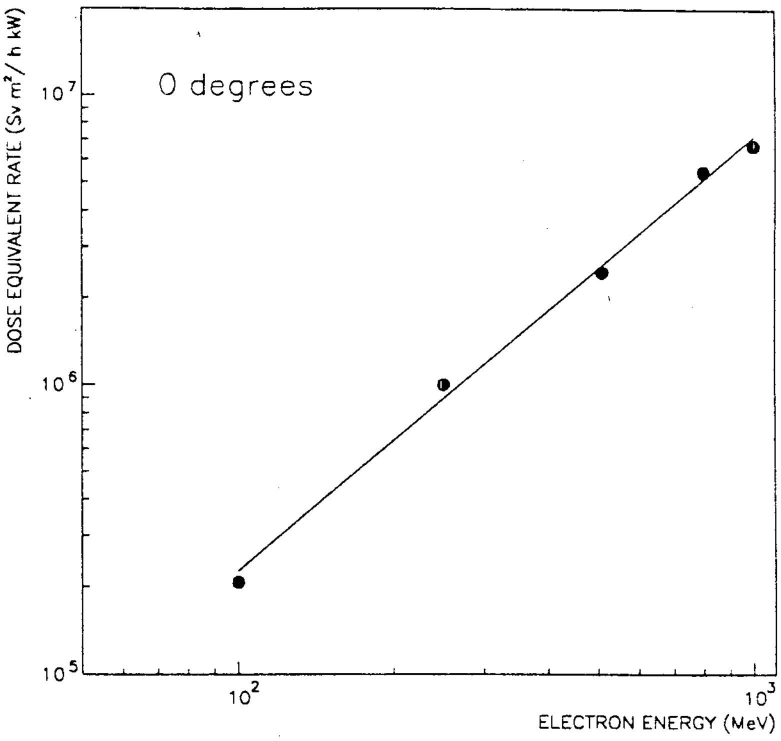
0 degrees
DOSE EQUIVALENT RATE (Sv m^2/ h kW)
10^7
10^6
10^5
10^2
10^3
ELECTRON ENERGY (MeV)

FIG. 9

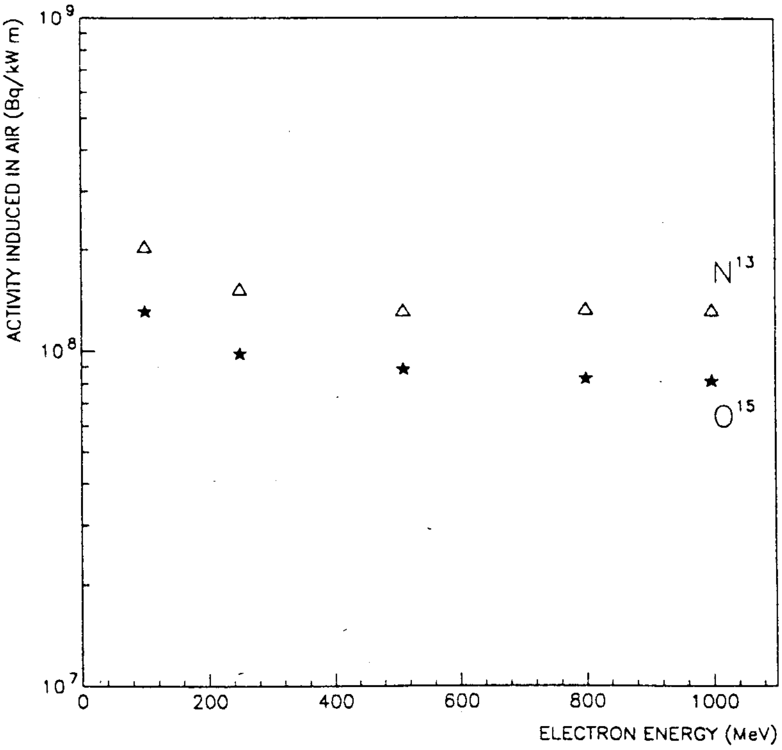
ACTIVITY INDUCED IN AIR (Bq/kW m)
10^9
10^8
10^7
N^{13}
O^{15}
0
200
400
600
800
1000
ELECTRON ENERGY (MeV)

FIG. 10