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Environmental Dosimetry – Measurements and Calculations

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1. Introduction

According to UNSCEAR (2008) the largest contribution to external exposure comes from naturally occurring, gamma-emitting, radioactive elements in the ground. Apart from ^{40}K, these elements are members of the decay chains starting with ^{238}U and ^{232}Th, respectively. Both of these radionuclides have half-lives comparable to the age of the earth and have been present in the earth's crust since its formation. The half-life of ^{40}K is of the same order of magnitude. However, nuclear weapons fallout and debris from accidents at nuclear facilities may at some sites contribute even more to the exposure.
Calculation of the external dose rate from field gamma spectrometric measurements requires knowledge of how the primary fluence rate, *i.e.* the number of unscattered photons per unit area and time, from different distributions of radioactive elements, at or in the ground, affects the detector response. Likewise, determination of external dose rate based on gamma spectrometry of soil samples must include a calculation of the primary fluence rate from the actual soil inventory.
The main topic of this chapter is to describe, and compare, some of the methods that can be used to estimate external dose rate from environmental sources of ionizing radiation from radioactive elements. The external dose rate from radioactive sources at or below ground may be estimated in several ways. One method is to simply measure the dose rate with a properly calibrated intensimeter or other type of dose meter (*e.g.* ionization chamber or thermoluminescent dosimeter, TLD). Another method is to calculate the dose rate based on gamma spectrometric measurements, *e.g.* field gamma spectrometry or soil sampling. However, due to assumptions of the relation between primary and scattered radiation, as well as calibration requirements, the dose rate estimations from these methods seldom agree in practical situations. The topics mentioned above will be exemplified with reference to actual measurements by field gamma spectrometry and intensimeter, as well as model calculations of fluence rates from different environmental geometries.

2. Primary fluence rate from different source geometries

The quantity fluence has been defined by the International Commission on Radiation Units and Measurements, ICRU, (ICRU, 1998) as $\Phi = \mathrm{d}N/\mathrm{d}a$, *i.e.* the number of particles per unit area. According to the definition, dN is the number of particles (here photons) incident on

the area da, which should be the cross-sectional area of a sphere. This definition of the area is chosen because the definition of fluence should be independent of the direction of the radiation field. The fluence rate is defined in terms of the increment of the fluence, dΦ, during the time interval dt as dΦ/ dt.
Photons emitted from a radioactive source in a medium may undergo different kinds of interactions. Some of the photons pass through the medium without interacting and these will constitute the primary fluence at the detector position. Other photons, originally not directed towards the detector, may undergo Compton scattering and hit the detector. These latter photons, or scattered radiation, will also contribute to the detector signal. The relation between primary and scattered radiation is given by the build-up factor, which depends on several parameters (*e.g.* photon energy and material between source and detector) and must be determined by experiments or Monte Carlo-simulations.

2.1 Volume source

Figure 1 shows the geometry used for calculating the fluence rate at a reference point outside the active volume. In this case we consider a homogeneously distributed source in the ground, as an example. The number of photons emitted per unit time from a volume element dV at the depth z in the ground is given by $S_V(z,r,\eta)\cdot$dV, where dV equals d$r\cdot$d$R\cdot$dρ.

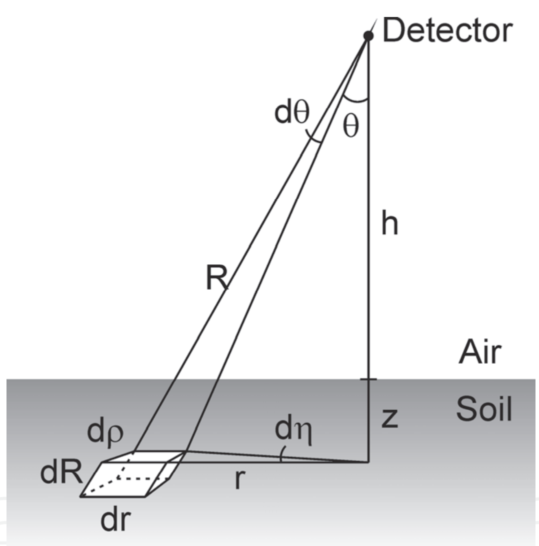

Fig. 1. The geometry used for calculating the primary fluence rate at the position of the detector, from a volume element in the ground. The volume element is considered as a point source.

The differential (primary) photon fluence rate at the detector position, taking into account self-attenuation in soil (μ_s) and attenuation in air (μ_a) is given by

$$d\dot{\phi}_p = \frac{S_V\, dV \cdot e^{-\mu_s(R-h/\cos\theta)-\mu_a \cdot h/\cos\theta}}{4\pi R^2} \tag{1}$$

The contribution from the volume element dV is thus simply treated as the primary fluence rate from a point source at the distance of R from the detector. The exponential function accounts for the attenuation in the materials between the source and the detector (soil and air). The source strength, S_V, is related to the activity, A, through the relation $S_V \cdot dV = A \cdot \Sigma f_i$, where f is the probability for emission of a photon (gamma-ray) of a certain energy in each decay of the radionuclide.

The total primary photon fluence rate can now be determined by integrating the differential fluence rate over the whole volume, *i.e.* summing the contributions from each volume element dV. Changing to spherical coordinates will facilitate the integration and dV is then expressed as $dV = dr \cdot dR \cdot d\rho = R^2 \cdot \sin\theta \cdot d\theta \cdot d\eta \cdot dR$. The primary photon fluence is thus given by

$$\dot{\phi}_p = \int_0^{2\pi} \int_{h/\cos\theta}^{\infty} \int_0^{\pi/2} \frac{S_V \cdot R^2 \cdot \sin\theta \cdot e^{-\mu_s (R - h/\cos\theta) - \mu_a \cdot h/\cos\theta}}{4\pi R^2} d\eta \, dR \, d\theta \qquad (2)$$

The above expression can be calculated analytically for a few cases of distributions and these will be exemplified by two kinds of homogeneous distributions: an infinite volume source and an infinite slab source.

2.1.1 Infinite volume source

An infinite volume source can often be assumed when considering naturally occurring radionuclides in the ground. These are the members of the uranium and thorium decay chains, together with ^{40}K. Since the mean free path of photons from naturally occurring radionuclides is about 10 cm (based on 3 MeV photons and a soil density of 1.5 $g \cdot cm^{-3}$) a soil volume of this thickness may be considered as an infinite source.

Integrating Eq. 2, we find that

$$\int_0^{2\pi} d\eta = [\eta]_0^{2\pi} = 2\pi \qquad (3)$$

and

$$\int_{h/\cos\theta}^{\infty} e^{-\mu_s \cdot (R - h/\cos\theta)} dR = e^{\mu_s \cdot h/\cos\theta} \cdot \left[-\frac{1}{\mu_s} \cdot e^{-\mu_s \cdot R} \right]_{h/\cos\theta}^{\infty} = \frac{1}{\mu_s} \qquad (4)$$

The expression for the primary fluence rate then reduces to

$$\dot{\phi}_p = \frac{S_V}{2\mu_s} \int_0^{\pi/2} \sin\theta \cdot e^{-\mu_a \cdot h/\cos\theta} d\theta \qquad (5)$$

This integral can be solved by variable substitution and by using the properties of the exponential integrals, $E_n(x)$, defined as

$$E_n(x) = x^{n-1} \int_x^{\infty} \frac{e^{-t}}{t^n} dt \qquad (6)$$

The substitution $t = \mu_a \cdot h/\cos\theta$ enables us to rewrite Eq. 5 as

$$\dot{\phi}_p = \int_0^{\pi/2} \frac{S_V \cdot \sin\theta \cdot e^{-\mu_a \cdot h/\cos\theta}}{2\cdot\mu_s} d\theta = \frac{S_V}{2\cdot\mu_s} \int_{\mu_a \cdot h/\cos 0}^{\mu_a \cdot h/\cos(\pi/2)} \sin\theta \cdot e^{-t} \cdot \frac{\cos^2\theta}{\mu_a \cdot h \cdot \sin\theta} dt =$$
$$= \frac{S_V}{2\cdot\mu_s} \cdot \mu_a \cdot h \int_{\mu_a \cdot h}^{\infty} \sin\theta \cdot e^{-t} \cdot \frac{\cos^2\theta}{(\mu_a \cdot h)^2 \cdot \sin\theta} dt = \frac{S_V}{2\cdot\mu_s} \mu_a \cdot h \int_{\mu_a \cdot h}^{\infty} \frac{e^{-t}}{t^2} dt \tag{7}$$

By using Eq. 6 with $x = \mu_a \cdot h$ and $n = 2$, the primary fluence rate can be written

$$\dot{\phi}_p = \frac{S_V}{2\cdot\mu_s} E_2(\mu_a \cdot h) \tag{8}$$

The exponential integral $E_2(x)$ equals 1 for $x = 0$ and decreases monotonically to 0 as x approaches infinity; the value of $E_2(x)$ can be found in standard mathematical tables and graphs. A special case occurs when the reference point (detector) is at the surface of an infinite volume source, *i.e.* $h = 0$. Hence there is no attenuation in air and $\mu_a \cdot h = 0$, giving $E_2(0) = 1$. Eq. 8 then reduces to

$$\dot{\phi}_p = \frac{S_V}{2\cdot\mu_s} \tag{9}$$

2.1.2 Infinite slab source

Ploughing after fallout of radionuclides on arable land may lead to a homogeneous distribution of the radionuclides in the upper part of the soil, whereas the deeper soil may be considered inactive with regard to the radionuclides in the fallout. The fluence rate from such a slab source (of infinite lateral extension) of thickness z can be found by taking the difference between two volume sources: one extending from the ground surface to infinite depth and one extending from depth z to infinity (Fig. 2).

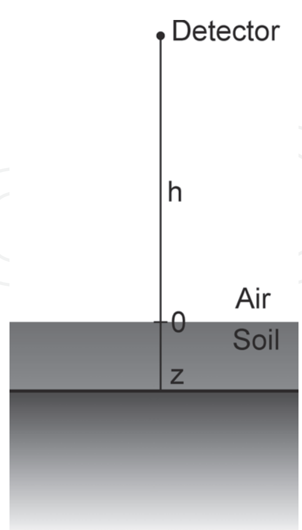

Fig. 2. The geometry of a slab source, extending from the soil surface to depth *z*.

The fluence rate from each of the two volume sources is given by Eq. 8 and the difference is then given by

$$\dot{\phi}_p = \frac{S_V}{2\cdot\mu_s}\left[E_2\left(\mu_a\cdot h\right) - E_2\left(\mu_s\cdot z + \mu_a\cdot h\right)\right] \tag{10}$$

At the surface the attenuation in the air vanishes and Eq. 10 reduces to

$$\dot{\phi}_p = \frac{S_V}{2\cdot\mu_s}\left[1 - E_2\left(\mu_s\cdot z\right)\right] \tag{11}$$

2.2 Plane source

Fresh fallout may be reasonably well described by a plane, or surface, source. The number of photons emitted per unit time from an area element dA at the surface of the ground is given by $S_A(r,\eta)\cdot\mathrm{d}A$, where d$A$ is given by $\mathrm{d}r\cdot\mathrm{d}\rho = \mathrm{d}r\cdot r\cdot\mathrm{d}\eta$. The geometry of the calculations is shown in Figure 3.

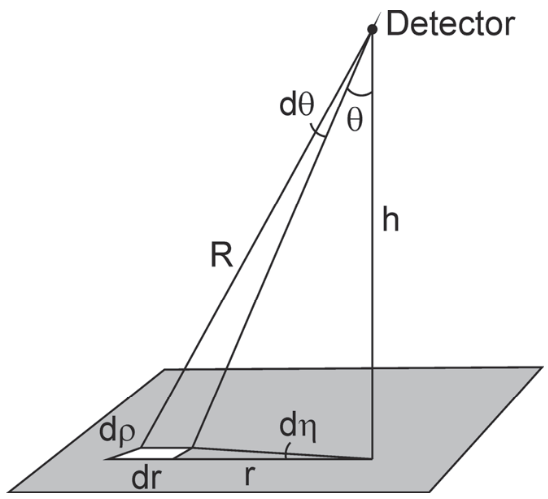

Fig. 3. The geometry used for calculating the primary fluence rate at the position of the detector, from an area element on the ground. The area element is considered as a point source.

The differential (primary) photon fluence rate at the detector position, taking attenuation in air (μ_a) into account is given by

$$d\dot{\phi}_p = \frac{S_A\, dA\cdot e^{-\mu_a\cdot h/\cos\theta}}{4\pi R^2} = \frac{S_A\cdot dr\cdot r\cdot d\eta\cdot e^{-\mu_a\cdot h/\cos\theta}}{4\pi R^2} \tag{12}$$

By integrating over all azimuthal angles, η, from 0 to 2π, according to Eq. 3 we have

$$d\dot{\phi}_p = \frac{S_A\cdot dr\cdot r\cdot e^{-\mu_a\cdot h/\cos\theta}}{2R^2} \tag{13}$$

2.2.1 Infinite plane source

The total primary photon fluence rate will again be found by integrating, this time over the whole plane, which we here will assume is of infinite extent. However, in order to be able to integrate, we need to find a relation between r and R. By looking at Figure 4 we see that $r = R\cdot\sin\theta$ and $\mathrm{d}r\cdot\cos\theta = R\cdot\mathrm{d}\theta$.

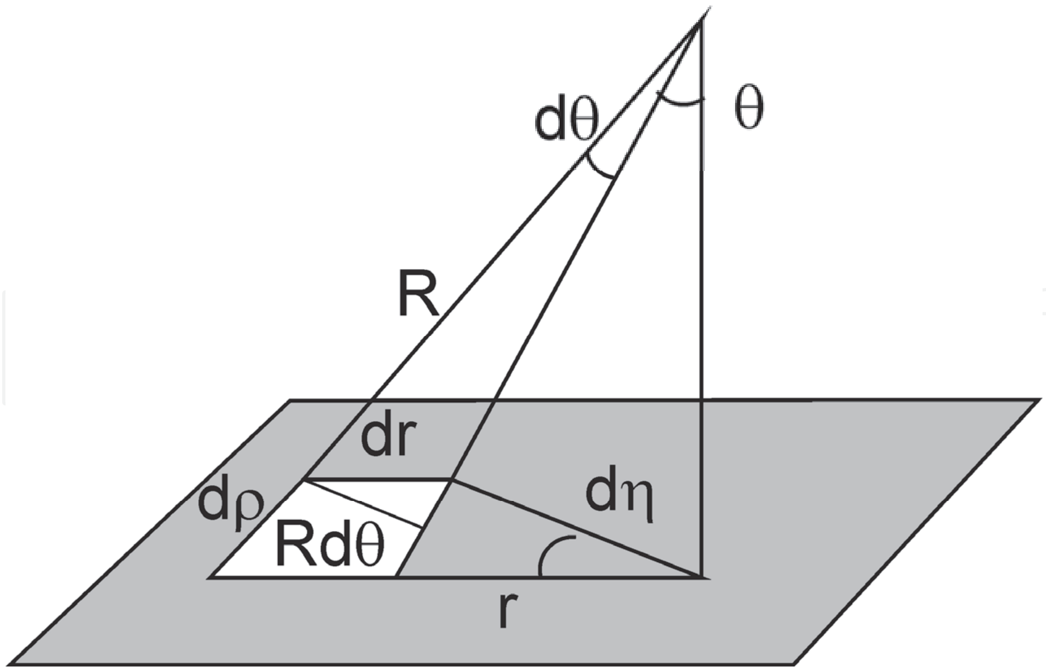

Fig. 4. Relations between distances and angles for the area element.

Substituting these relations into Eq. 13 gives an expression that may be integrated over the vertical angle θ.

$$d\dot{\phi}_p = \frac{S_A \cdot dr \cdot r \cdot e^{-\mu_a \cdot h/\cos\theta}}{2R^2} = \frac{S_A \cdot \sin\theta \cdot e^{-\mu_a \cdot h/\cos\theta}}{2 \cdot \cos\theta} d\theta \tag{14}$$

By making the same variable substitution as for the volume source, $t = \mu_a \cdot h/\cos\theta$, the primary fluence rate may again be expressed as an exponential integral (see Eq. 6).

$$\begin{aligned} \dot{\phi}_p &= \int_0^{\pi/2} \frac{S_A \cdot \sin\theta \cdot e^{-\mu_a \cdot h/\cos\theta}}{2 \cdot \cos\theta} d\theta = \frac{S_A}{2} \int_{\mu_a \cdot h/\cos 0}^{\mu_a \cdot h/\cos(\pi/2)} \frac{\sin\theta}{\cos\theta} \cdot e^{-t} \cdot \frac{\cos^2\theta}{\mu_a \cdot h \cdot \sin\theta} dt = \\ &= \frac{S_A}{2} \int_{\mu_a \cdot h}^{\infty} e^{-t} \cdot \frac{\cos\theta}{\mu_a \cdot h} dt = \frac{S_A}{2} \int_{\mu_a \cdot h}^{\infty} \frac{e^{-t}}{t} dt \end{aligned} \tag{15}$$

The exponential integral in this case is $E_1(\mu_a \cdot h)$ and the final expression for the primary fluence rate from an infinite plane source is

$$\dot{\phi}_p = \frac{S_A}{2} \cdot E_1(\mu_a h) \tag{16}$$

2.2.2 Disc source – Without attenuating media between source and detector

The primary fluence rate from a plane source of limited extent can be calculated by assuming a circular source, see Figure 5. The radionuclide is assumed to be homogeneously distributed over the circular area. The number of photons emitted per unit time from an area element dA is given by $S_A(r,\eta)\cdot$dA, where dA is given by d$r\cdot$dρ = d$r\cdot r\cdot$dη as shown in Figure 3.

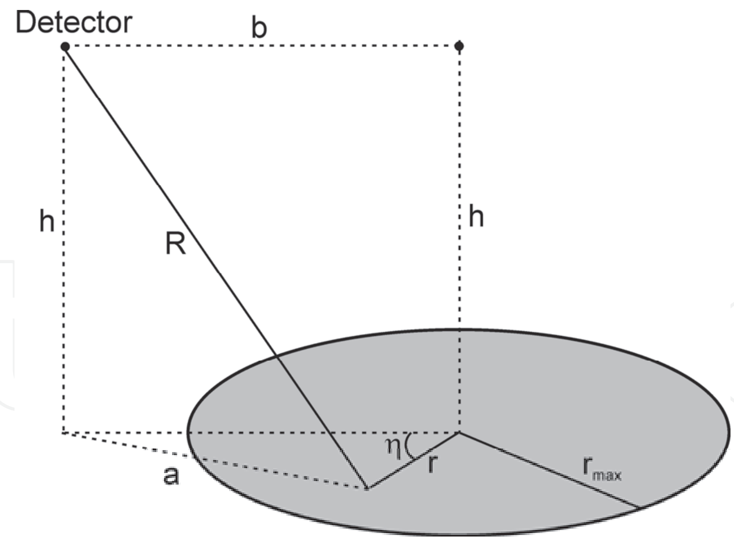

Fig. 5. Geometry for calculating the primary fluence rate from a circular area source of radius $r_{\max}$.

Neglecting attenuation in the air and assuming that the area element acts as a point source, the primary fluence rate at the detector position is given by.

$$d\dot{\phi}_p = \frac{S_A \cdot dA}{4\pi \cdot R^2} \tag{17}$$

In order to carry out the integration to find the primary fluence rate, we need to express the distance R in more "fundamental" parameters. From Figure 5 we find that

$$a^2 = b^2 + r^2 - 2 \cdot r \cdot b \cdot \cos\eta \tag{18}$$

$$R^2 = h^2 + a^2 = h^2 + b^2 + r^2 - 2 \cdot r \cdot b \cdot \cos\eta \tag{19}$$

The expression for the primary fluence rate is then

$$\dot{\phi}_p = \frac{S_A}{4\pi} \int_0^{r_{\max}} \int_0^{2\pi} \frac{r}{h^2 + b^2 + r^2 - 2 \cdot r \cdot b \cdot \cos\eta} dr\, d\eta \tag{20}$$

The integration over η is rather complicated, but could be solved using tables of standard integrals. Recognizing that the integral is of the form

$$\int_0^{2\pi} \frac{d\eta}{\alpha + \beta \cdot \cos\eta} = \frac{2\pi}{\sqrt{\alpha^2 - \beta^2}} \quad (\alpha > \beta \geq 0) \tag{21}$$

Eq. 20 now reduces to

$$\dot{\phi}_p = \frac{S_A}{2} \int_0^{r_{\max}} \frac{r}{\sqrt{\left(h^2 + b^2 + r^2\right)^2 - 4 \cdot r^2 \cdot b^2}} dr \tag{22}$$

The expression within the square root in the denominator could be rewritten as

$$\left(h^2+b^2+r^2\right)^2-4\cdot r^2\cdot b^2=r^4+2r^2h^2-2r^2b^2+2h^2b^2+b^4+h^4 \tag{23}$$

and substituting $t = r^2$ yields

$$\left(h^2+b^2+r^2\right)^2-4\cdot r^2\cdot b^2=t^2+2t\cdot h^2-2t\cdot b^2+2h^2b^2+b^4+h^4 \tag{24}$$

By collecting terms we could write the right hand part of Eq. 24 as

$$t^2+2t\cdot h^2-2t\cdot b^2+2h^2b^2+b^4+h^4=t^2+2t\cdot\left(h^2-b^2\right)+\left(h^2+b^2\right)^2 \tag{25}$$

Now, since $r{\cdot}dr = dt/2$, Eq. 22 is given by

$$\dot{\phi}_p=\frac{S_A}{4}\int_0^{r_{\max}^2}\frac{dr}{\sqrt{t^2+2t\cdot\left(h^2-b^2\right)+\left(h^2+b^2\right)^2}} \tag{26}$$

The denominator is the square root of a polynomial and using standard integral tables we can find a solution since

$$\int\frac{dx}{\sqrt{\alpha x^2+\beta t+\gamma}}=\frac{1}{\sqrt{\alpha}}\ln\left(2\sqrt{\alpha\left(\alpha x^2+\beta t+\gamma\right)}+2\alpha x+\beta\right) \tag{27}$$

Identifying $\alpha = 1$, $\beta = 2(h^2\text{-}b^2)$, $\gamma = (h^2\text{+}b^2)^2$ and $x = t$ the integral in Eq. 26 is evaluated as

$$\begin{aligned}
&\left|\frac{1}{\sqrt{1}}\ln\left(2\sqrt{t^2+2t\cdot\left(h^2-b^2\right)+\left(h^2+b^2\right)^2}+2t+2\left(h^2-b^2\right)\right)\right|_0^{r_{\max}^2}=\\
&=\ln\left(2\sqrt{r_{\max}^4+2r_{\max}^2\cdot\left(h^2-b^2\right)+\left(h^2+b^2\right)^2}+2r_{\max}^2+2\left(h^2-b^2\right)\right)-\ln\left(2\left(h^2+b^2\right)+2\left(h^2-b^2\right)\right)=\\
&=\ln\frac{\sqrt{r_{\max}^4+2r_{\max}^2\cdot\left(h^2-b^2\right)+\left(h^2+b^2\right)^2}+r_{\max}^2+\left(h^2-b^2\right)}{2h^2}
\end{aligned} \tag{28}$$

And finally, the unattenuated fluence rate is given by

$$\dot{\phi}_p=\frac{S_A}{4}\ln\left|\frac{r_{\max}^2+h^2-b^2+\sqrt{\left(r_{\max}^2+h^2-b^2\right)^2+4h^2b^2}}{2h^2}\right| \tag{29}$$

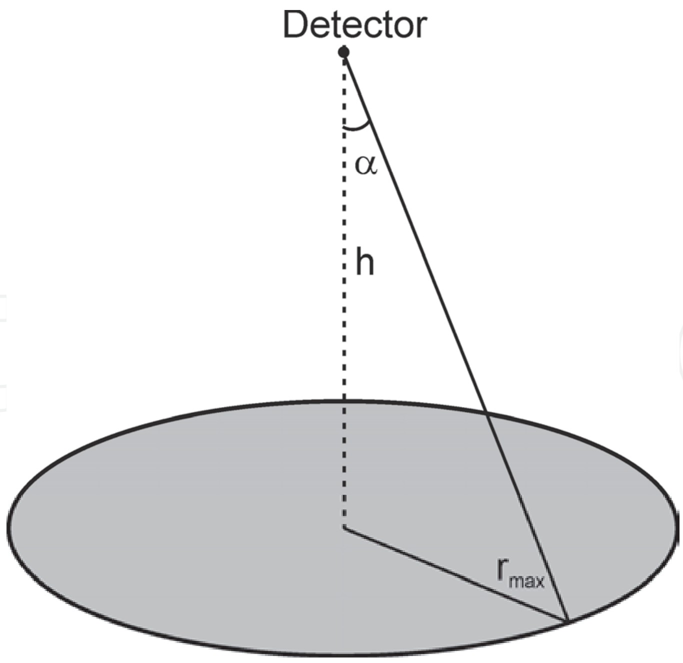

Fig. 6. Geometry for calculating the primary fluence rate at the axis of a circular area source of radius $r_{\max}$.

At a point centrally over the disc (Fig. 6), b equals zero and the expression for the fluence rate simplifies to

$$\dot{\phi}_p = \frac{S_A}{4}\ln\left(\frac{r_{\max}^2 + h^2}{h^2}\right) \tag{30}$$

In some measurements a plane source is approximated by a point source to simplify calculations, especially when trying to make a fast first estimation of the activity of the source. It should be noted that the commonly used "inverse square law", *i.e.* that the fluence rate decreases inversely proportional to the square of the distance between source and detector, is not generally valid for an extended source. The agreement depends on the radius of the source. It is clear, however, that beyond a certain distance an extended plane source may be replaced by a point source in the calculations.

This distance may be found by putting the fluence rate from a point source equal to the fluence rate from a disc source with the same activity (remember that S_A is the activity per unit area):

$$\frac{S_A \cdot \pi \cdot r_{\max}^2}{4\pi \cdot h^2} \approx \frac{S_A}{4}\ln\left(\frac{r_{\max}^2 + h^2}{h^2}\right) \quad \Rightarrow \quad \frac{r_{\max}^2}{h^2} \approx \ln\left(\frac{r_{\max}^2 + h^2}{h^2}\right) \tag{31}$$

A calculation shows that

$$\frac{r_{\max}^2}{h^2} \le 0.2 \quad \Rightarrow \quad \frac{\dfrac{r_{\max}^2}{h^2}}{\ln\left(\dfrac{r_{\max}^2 + h^2}{h^2}\right)} < 1.1 \tag{32}$$

meaning that the error we make is less than 10 % if $r_{max}/h < 0.45$ (since $0.45^2 = 0.2$). The disc source may hence be approximated by a point source if h is larger than 2.2 times the radius of the disc, r_{max}. In short, it is rather safe to make the approximation when the distance from the source is greater than the diameter of the source.

2.2.3 Disc source – With attenuating media between source and detector

If we want to take attenuation in the air into account we have to consider the exponential attenuation factor, which depends on the distance, R, (Fig. 5) and the material between the source and the detector position through the linear attenuation coefficient μ. Eq. 17 is then given by

$$d\dot{\phi}_p = \frac{S_A \cdot dA}{4\pi \cdot R^2} \cdot e^{-\mu \cdot R} \tag{33}$$

and the integral will be complicated to evaluate. However, if we again consider a point centrally over the disc the integral can be evaluated, using the exponential integral, as

$$\dot{\phi}_p = \frac{S_A}{2} \cdot \left[E_1(\mu_a h) - E_1\left(\frac{\mu_a h}{\cos\alpha}\right)\right] \tag{34}$$

where α is given by Figure. 6. If the radius of the source is very large we get, in the limit were $r_{\max}$ approaches infinity, $\cos\alpha = 0$ and hence $1/\cos\alpha \to \infty$. In the limit the exponential integral E_1 will be equal to zero and Eq. 34 reduces to

$$\dot{\phi}_p = \frac{S_A}{2} \cdot E_1(\mu_a h) \tag{35}$$

which is what we found for a plane source of infinite extent (Eq. 16).
A question that may arise is how large a plane source has to be before it can be treated as a source of infinite extent. Calculations with Eq. 34 and 35 for ^{137}Cs, assuming S_A = 2 m^{-2} s^{-1} (giving a unit multiplicative constant), are shown in Table 1. The calculations are made with h = 100 cm and $\mu_a = 9.3 \cdot 10^{-5}$ cm^{-1}, then $\mu_a \cdot h$ equals $9.3 \cdot 10^{-3}$ and $E_1(\mu_a \cdot h) = 4.1$.

α degrees	r_{max} m	E_1 ($\mu_a \cdot h/\cos\alpha$)	$\dot{\phi}_p$ m^{-2} s^{-1}
10	0.18	4.10	0.015
20	0.36	4.05	0.062
30	0.58	3.97	0.14
40	0.84	3.85	0.26
50	1.2	3.67	0.44
60	1.7	3.43	0.68
70	2.7	3.05	1.1
80	5.7	2.40	1.7
89	57	0.52	3.6
89.9	570	$7.8 \cdot 10^{-4}$	4.1
90	∞	0	4.1

Table 1. Calculated primary fluence rate for disc sources of different radii, corresponding to vertical angles of 10° - 90°. The radii of the source for each vertical angle, assuming a detector height of 1 m, are also shown in the table. In this example the source strength S_A = 2 m^{-2} s^{-1}.

The primary fluence rate from a source of infinite extent is thus, in this example, equal to 4.1 m^{-2} s^{-1} and we see that the same value is reached for a limited source with a radius of about 500 metres. The table also shows that 90 % of the photons that reach the detector come from an area within a radius of about 60 metres.

2.3 Spherical source – Dose point inside the sphere

As an example of this geometry we can consider the release of radioactive material in the atmosphere. The radiation dose to a person submerged in a radioactive plume could be estimated using calculations based on this geometry. The same applies for a person surrounded by water containing radioactive elements. Figure 7 depicts the geometry, where the contribution to the primary fluence rate at a detector position in the centre of the sphere is due to a volume element dV. The number of photons emitted per unit time from the volume element dV is given by S_V·dV.

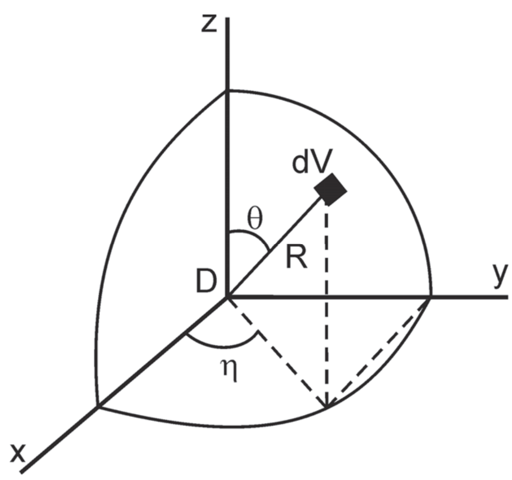

Fig. 7. Geometry for calculating the primary fluence rate in the centre of a spherical volume source. The source extends to the radius $r_{\max}$.

Just as in the previous examples dV is treated as a point source and if we also take the attenuation into account we get

$$d\dot{\phi}_p = \frac{S_V\, dV \cdot e^{-\mu_s R}}{4\pi R^2} \tag{36}$$

where μ_s is the linear attenuation coefficient of the source medium. Recognizing that dV = dη·dR·dθ can be written in spherical coordinates as dV = R^2·sinθ·dη·dR·dθ yields the expression for the total primary fluence rate at the detector position

$$\dot{\phi}_p = \int_0^{2\pi}\int_0^{r_{\max}}\int_0^{\pi} \frac{S_V \cdot R^2 \cdot \sin\theta \cdot e^{-\mu_s R}}{4\pi R^2}\, d\eta\, dR\, d\theta \tag{37}$$

The integral is then evaluated as

$$\dot{\phi}_p = \frac{S_V}{4\pi} \cdot 2\pi \cdot \left| -\frac{1}{\mu_s} e^{-\mu_s R} \right|_0^{r_{\max}} \cdot \left| -\cos\theta \right|_0^{\pi} = \frac{S_V}{\mu_s}\left(1 - e^{-\mu_s r_{\max}}\right) \tag{38}$$

Assume that the source is a cloud or plume of air containing radioactive elements in the form of gasses or particles and the dose point is at the ground surface. Because of symmetry, the primary fluence rate is then given by half the value calculated from Eq. 38. This result is also consistent with what we found for a point at the surface of an infinite volume source, Eq. 9.

It could be interesting to see how large a radioactive plume can be before the primary fluence rate reaches equilibrium. The linear attenuation coefficient for 662 keV (gamma radiation from ^{137}Cs) in air is $9.3 \cdot 10^{-5}$ cm^{-1} and for a plume radius of 495 m the factor within the parenthesis is 0.99. Figure 8 shows the primary fluence rate as a function of plume radius for a spherical source in air and for some different photon energies, as well as the corresponding situation in water. Thus, for a plume of radius greater than about a few hundred metres, approximate calculations may be performed without knowledge of the linear attenuation coefficient for air. In water the radius is instead of the order of a few tens of centimetres.

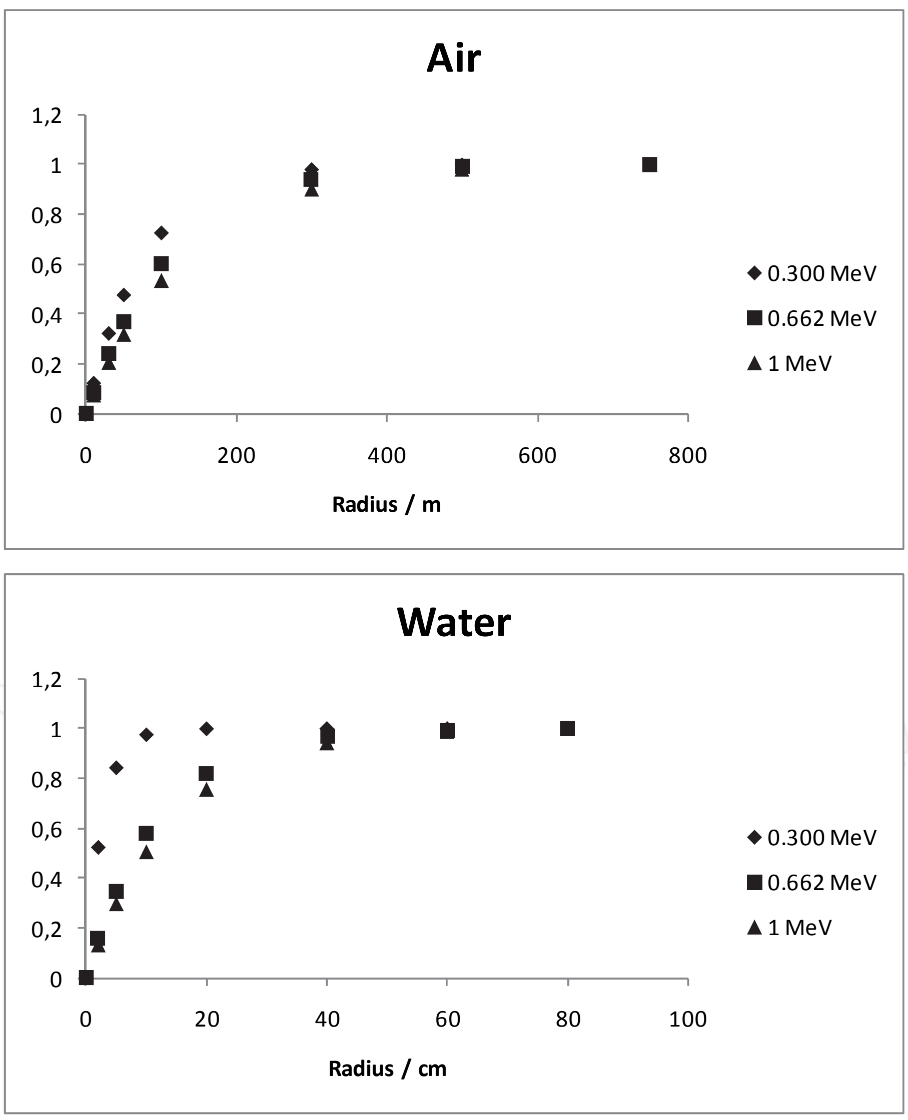

Fig. 8. Primary fluence rate at the centre of a spherical source of different radius, r_{max}, normalized to S_V/μ_s, for air and water, respectively, at some different photon energies.

3. Dose calculations

An important application of the calculations of primary fluence rate is to determine the effective dose to humans or absorbed dose to other biota. These calculations are often simplified by using conversions coefficients available from the literature. The concepts of absorbed dose, kerma and effective dose will be discussed below.

3.1 Absorbed dose rate and air kerma rate

Absorbed dose is defined by the ICRU (ICRU, 1998) and is basically a measure of how much of the energy in the radiation field that is retained in a small volume. The SI-unit of absorbed dose is 1 Gy (gray), which in the fundamental SI-units equals 1 J kg^{-1}. Absorbed dose rate to air in free air can be defined in terms of the fluence rate, photon energy, E_γ, and mass energy-absorption coefficient, μ_{en}/ρ, for air according to Eq. 39. The relation is valid for monoenergetic photons of energy E and if the radiation field consists of photons of different energies the contribution from each occurring photon energy has to be included in the calculation of the absorbed dose. In addition, the requirement of charged particle equilibrium, CPE, has to be fulfilled. This concept is further discussed in several dosimetry books (e.g. Attix, 1991, McParland, 2010).

$$\dot{D}_{p,E} = \dot{\phi}_{p,E} \cdot \left(\frac{\mu_{en}}{\rho}\right)_E \cdot E_\gamma \tag{39}$$

The total dose rate from primary and scattered photons is then given by

$$\dot{D}_{t,E} = \dot{D}_{p,E} + \dot{D}_{s,E} = \dot{D}_{p,E} \cdot B_E \tag{40}$$

where B_E is a build-up factor, which depends on the photon energy, and the distance and material between the source and the detector. Values of B_E can be determined by Monte Carlo-methods, found in tables and graphs, or calculated by analytical approximations (e.g. Shultis & Faw, 2000). The analytical expressions are convenient when the radiation field consists of photons of several energies, such as in environmental measurements. The contribution from each energy can then be integrated to yield the total absorbed dose. These calculations can of course be applied directly on the calculations of primary fluence rate instead.

Calculation of dose rate conversion factors, relating the activity per unit mass in the ground to dose rate at 1 m above ground, have been made by *e.g.* Clouvas *et al.* (2000). These factors can be applied when the activity in the ground has been determined from an *in situ* (field gamma spectrometry) measurement or gamma spectrometric soil sample analysis. As an example of the use of these conversion factors, consider the naturally occurring uranium decay series starting with ^{238}U and ending up with the stable lead isotope ^{206}Pb. To determine the activity of the radioactive elements in the series the bismuth isotope ^{214}Bi is often used due to the easily identified peak at 609.4 keV in the gamma spectrum. For this isotope a factor of 0.05348 nGy h^{-1} per Bq kg^{-1} is given by Clouvas *et al.* (2000). If secular equilibrium can be assumed, the activities of all members of the series are equal and the dose rate from all radioactive elements in the series can be calculated by using the factor 0.38092 nGy h^{-1} per Bq kg^{-1}, using the activity of the measured ^{214}Bi.

One member of the thorium series (^{232}Th to ^{208}Pb) is ^{208}Tl, which also has a convenient gamma line at 583.1 keV. The activity of this radionuclide, however, can not be used in the same straight-forward way as ^{214}Bi in the uranium series. The previous radionuclide in the series, ^{212}Bi, decays both by α (35.9 %) and β-decay (64.1 %) to ^{208}Tl and ^{212}Po, respectively and hence the activity of ^{208}Tl is only 35.9 % of the activity at equilibrium. The thorium series, as well as the uranium series, contains isotopes of radon that easily escape from the ground or from a sample. The degree of equilibrium therefore ought to be checked by measuring the activity of some member of each series, above radon.
Related to absorbed dose is the concept of kerma, *K*. The unit of this quantity is also 1 Gy, but kerma is a measure of how much of the photon energy in the radiation field that is transferred, via interactions, to kinetic energy of charged particles in a small volume (ICRU, 1998). Part of this kinetic energy may be radiated as breaking radiation, thus leaving the volume, and will not be a part of the absorbed dose. To account for this energy loss, kerma is defined in terms of the mass energy-transfer coefficient, μ_{tr}/ρ, insted of μ_{en}/ρ. An expression for air kerma rate in free air can thus be written

$$\dot{K}_{p,E} = \dot{\phi}_{p,E} \cdot \left(\frac{\mu_{tr}}{\rho} \right)_E \cdot E_\gamma \tag{41}$$

For a point source, an air kerma rate constant can be defined, which enables calculation of the air kerma rate from knowledge of the source activity. Such constants can be found in *e.g.* Ninkovic *et al*. (2005). The air kerma rate free in air is a useful concept in environmental dosimetry, since published dose conversion coefficients to determine effective dose are often expressed in this quantity, which will be discussed below.

3.2 Exposure of humans – Effective dose

The quantity absorbed dose is basically a measure of the energy imparted in a small volume due to irradiation. In some applications, such as radiation therapy, absorbed dose is used to determine the biological effect on (tumour) tissue but in radiation protection its use is limited. The effects on tissue depend, apart from the absorbed dose, on the type of radiation, *i.e.* whether the energy is transferred to tissue by α-particles, β-particles, γ-radiation or neutrons. For example, to cause the same degree of biological damage to cells the absorbed dose from γ-radiation has to be twenty times as large as the absorbed dose from α-particles. This dependence is accounted for by multiplying the absorbed dose with a so called radiation weighting factor (ICRP, 2007). The weighted quantity is then given a new name, Equivalent dose, H_T, and a new unit, 1 Sv (sievert). Equivalent dose can be used in regulations to limit, for example, the exposure to the hands and feet in radiological work.
However, in environmental radiation fields a large number of different irradiation geometries may occur and to determine the risk for an exposed individual would require knowledge of the equivalent dose to each exposed organ in the body. Furthermore, risk estimates for all possible combinations of irradiated organs for each possible equivalent dose would be needed. It is obvious that such a table would be quite cumbersome (mildly speaking) and instead ICRP has defined the quantity Effective dose (Jacobi, 1975; ICRP, 1991), with the unit 1 Sv. The effective dose, *E*, is a so called risk related quantity that can be assigned a risk coefficient for different detriments (*e.g.* cancer incidence) and be used for regulatory purposes concerning populations. The quantity is not applicable to individuals.

Effective dose is calculated by multiplying the equivalent dose to each exposed organ by a tissue weighting factor, w_T, and summing the contributions from each organ or tissue, T, according to Eq. 42. The effective dose can thus be described as the dose that, if given uniformly to the whole body, corresponds to the same risk as the individual organ doses together.

$$E = \sum_T w_T \cdot H_T \tag{42}$$

The effective dose, E, has replaced the earlier used quantity effective dose equivalent, H_E (ICRP, 1977; ICRP, 1991). Although the effective dose has been in use for many years, dose conversion factors published before the replacement and hence given in terms of effective dose equivalent are still useful (*e.g*. Jacob *et al*., 1988). Relations between E and H_E has been published by ICRP (1996) and the difference is less than 12 % for all photon energies above 100 keV and for all irradiation geometries (see Fig. 9). For rotational symmetry E/H_E is between 0.95 and 1.0 for photon energies larger than 100 keV. Thus, for environmental applications the two quantities may often be interchangeable.

3.3 Relation between air kerma and effective dose

The effective dose can be related to the physical quantities photon fluence, absorbed dose and kerma by conversion coefficients and ICRP (1996) reports conversion coefficients from both photon fluence, ϕ, and air kerma, K_a, to effective dose. Conversion coefficients derived from measurements in a contaminated environment have also been reported (*e.g.* Golikov et al., 2007). The determination of effective dose from air kerma requires detailed knowledge about the energy deposition in the human body, *i.e.* the absorbed dose to each organ connected to an organ weighting factor. This can be achieved through Monte Carlo-simulations using different kinds of models or body-like phantoms. The effective dose will thus depend on the irradiation geometry and hence the simulations will yield different conversion factors for different irradiation geometries. Since the actual number of geometries can be very large, conversion coefficients are given for some idealised geometries, which approximates real situations (Fig. 9).

The AP & PA geometry approximates the irradiation from a single source in front of or behind the person, respectively and LAT may be used when a single source is placed to the left (or right) of the body. When the source is planar and widely dispersed the ROT geometry will be a good approximation, whereas a body suspended in a cloud of a radioactive gas can be approximated by the ISO geometry. The most usable geometries for environmental applications are ROT and ISO and Figure 10 shows the value of the conversion coefficient E/K_a for these geometries for different photon energies.

According to Figure 10 the conversion coefficient between effective dose rate and air kerma rate in rotational invariant irradiation situations concerning naturally occurring radionuclides is around 0.8 Sv Gy^{-1}, since the mean value of the gamma energy of those is close to 1 MeV. However, Golikov et al. (2007) reports a value of 0.71 Sv Gy^{-1} for adults and 1.05 Sv Gy^{-1} for a 1-year old child, based on phantom measurements in an environment contaminated with ^{137}Cs. Since the conversion coefficient is based on the absorbed dose to several organs in the body it will depend on the size of the body (distance from the source and self-shielding) as well as the energy distribution of the photons from the source. The photon fluence from a surface source will consist mainly of primary photons whereas the contribution from scattered photons (of lower energies) increases when the source is distributed with depth.

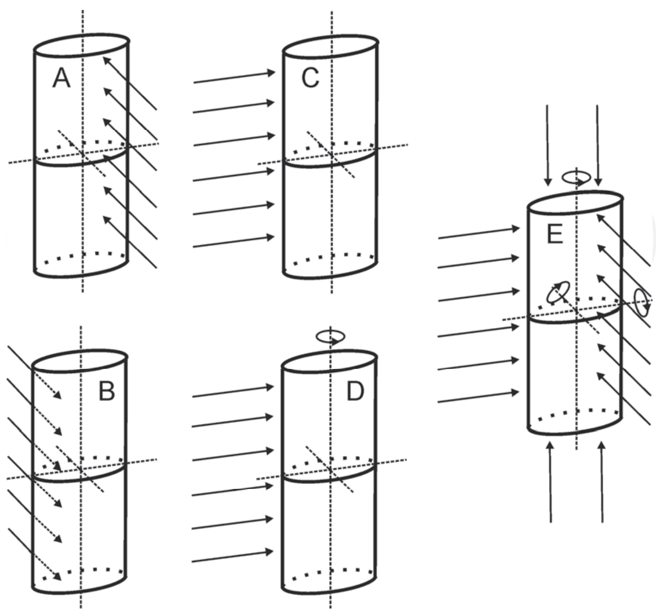

Fig. 9. Irradiation geometries used for simulation of real exposure situations: AP (Anterior-Posterior); B: PA (Posterior-Anterior); C: LAT (Lateral, in some applications specified as RLAT or LLAT depending on the direction of the radiation: from the left or from the right); D: ROT (Rotationally symmetric) and E: ISO (Isotropic radiation field).

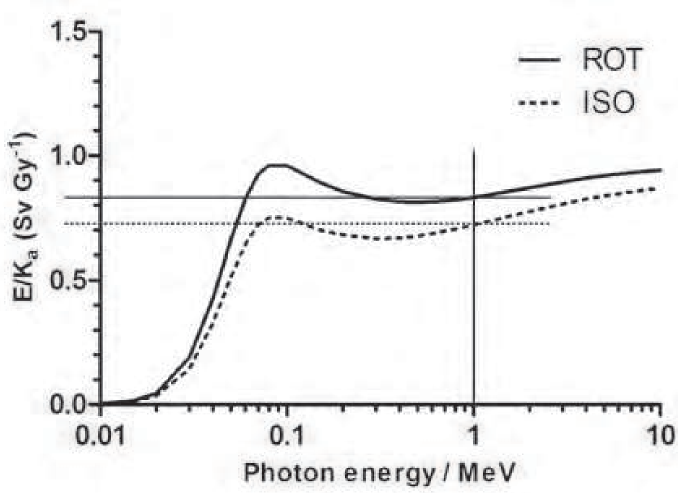

Fig. 10. Effective dose per unit air kerma for irradiation geometries ROT and ISO. Rotational symmetry (ROT) is applicable to a planar and widely dispersed source; isotropic symmetry may be used for a body suspended in a cloud of a radioactive gas. Data from ICRP (1996).

Also the angular distribution of the photons plays a role in this aspect. Figure 11 shows, schematically, the angular distribution of 662-keV photons from two different sources: an infinite volume source and an infinite plane source; the detector is placed one metre above ground. The expressions for the angular distribution of primary photons can be derived from Eq. 5 and Eq. 14, respectively. For angles of incidence less than about 75° the fluence increases with increasing angle of incidence due to the increasing source volume and area, respectively. At larger angles the attenuation in air limits the fluence at the detector and both curves in Figure 11 has a maximum. Detailed calculations for this photon energy show that the maximum for the infinite volume source occurs at 77.91° and the maximum for the infinite plane source at 89.45° (Finck, 1992). Thus most of the primary photons hitting the detector are nearly parallel to the ground surface.

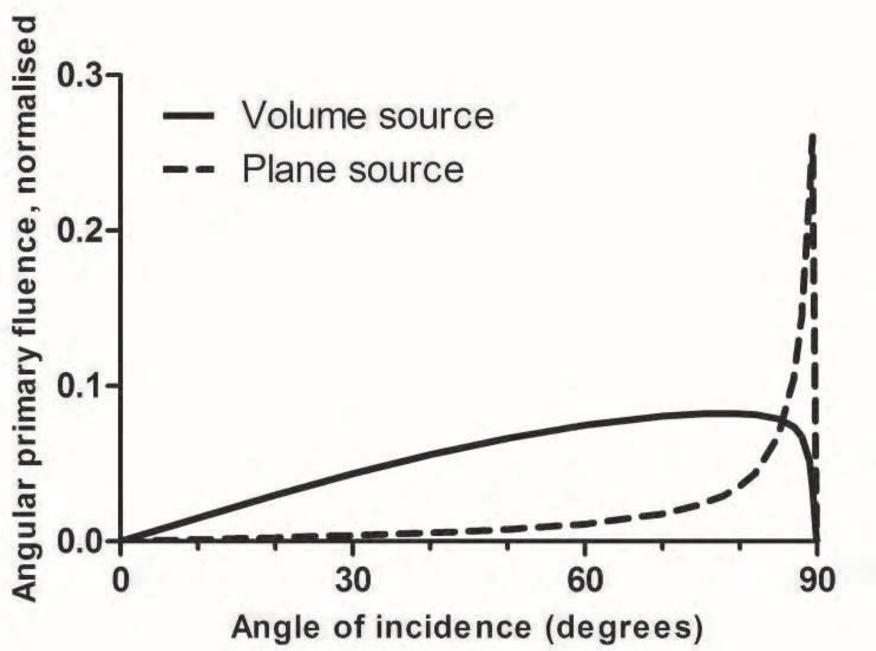

Fig. 11. Angular distribution of primary 662-keV photons from an infinite volume source and an infinite plane source as a function of angle of incidence on a detector placed one metre above ground.

4. Measurements

Since the risk related quantities, *e.g.* effective dose, could not be measured, some measurable quantities need to be defined. These measurable quantities should then be an estimation of the risk related quantities. As an example of the use of data from field gamma spectrometry to estimate the radiation dose, some results from repeated measurements are presented.

4.1 Measurable quantities

The relations between the different categories of quantities, risk related and measurable, are shown in Figure 12. The physical quantities, such as the absorbed dose, can be used to calculate risk related quantities by the use of weighting factors (ICRP 1991; ICRP, 2007), but also by conversion coefficients (*e.g.* ICRP, 1996). Operational quantities are derived from the physical quantities through definitions given by the ICRU (ICRU 1993; ICRU, 2001), for photon as well as for neutron irradiation. These definitions utilises the so called ICRU-sphere – a tissue equivalent sphere of 30 cm diameter – and the absorbed dose at different depths in the sphere. Furthermore, relations between risk related and measurable quantities can be found from data given by the ICRP (ICRP, 1996).

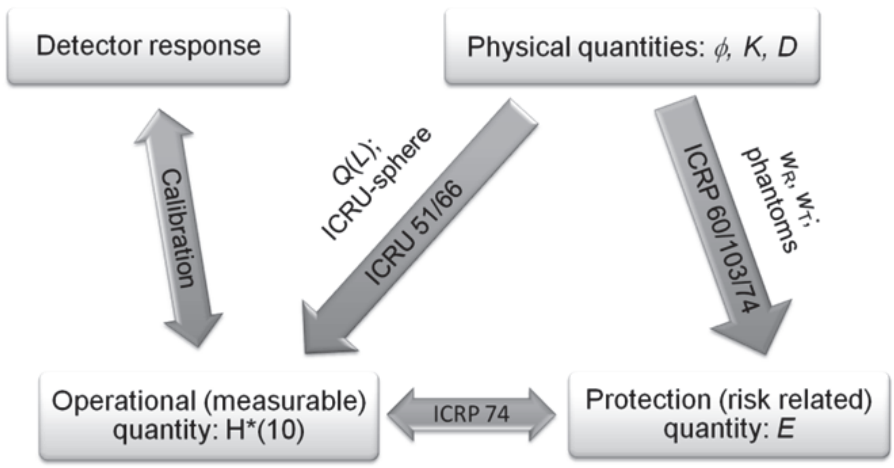

Fig. 12. Relations between the quantities of interest in radiation protection and measurements. Only one of the measurable and risk related quantities, respectively are shown in the figure; several other operational quantities are defined, which are used to monitor the radiation dose to individuals.

Instruments used for radiation protection purposes, *e.g.* intensimeters, are often calibrated to directly show a measurable quantity and guidelines for the calibration of those instruments have been issued by the IAEA (IAEA, 2000). Other types of detectors, *e.g.* high-purity germanium detectors (for determination of activity or fluence rate by field gamma spectrometry) or ionisation chambers (for determination of absorbed dose), can be used to measure a physical quantity. The relationship between detector response and the physical quantity of interest is then found by calibration.

Several measurable quantities have been defined for different purposes. Some are used to monitor personal exposure and others to monitor the radiation environment. The quantity of interest in environmental measurements is often the ambient dose equivalent, $H^*(10)$, since it is an estimate of the effective dose. From Figure 13 it is obvious that an instrument calibrated to show ambient dose equivalent should never underestimate the effective dose. This may cause deviations if effective dose is estimated from field gamma spectrometry and compared to the reading of an intensimeter calibrated to show ambient dose equivalent.

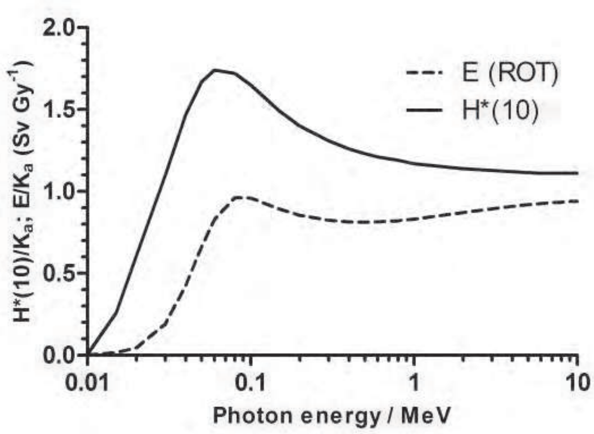

Fig. 13. Effective dose and ambient dose equivalent per unit air kerma, respectively. Data from ICRP (1996).

When the effective dose is estimated by detectors worn by individuals, special attention ought to be given to how the detector is calibrated. In these measurements the detector is often a TL-dosimeter (Thermo Luminescence Dosimetry, TLD), which is commonly used for monitoring workers at hospitals or in the nuclear industry. These detectors are calibrated to show the personal dose equivalent and if the reading is to be used for estimation of effective dose, the relation between the reading and air kerma must be known. Thereafter the effective dose can be estimated by the relations given above.

4.2 Measurements in western Sweden

We have made repeated field gamma measurements at 34 predetermined sites in western Sweden (Almgren & Isaksson, 2009) and the results are shown here to give an example of the use of these data to estimate the ambient dose equivalent. By a proper calibration of the field gamma detector, the amount of different radioactive elements in the ground can be determined. For the naturally occurring radionuclides with an assumed homogeneous depth distribution the inventory is given as Bq kg^{-1}. However, for ^{137}Cs a plane source is assumed and the activity given as Bq m^{-2}. The latter is a common procedure when the depth distribution is unknown and the reported "equivalent surface deposition" (Finck, 1992) will underestimate the true inventory due to the absorption of photons in the ground. The quantity is, however, still a good measure of the photon fluence rate above the ground.
Using published dose rate conversion factors and the relation between absorbed dose and ambient dose equivalent the field gamma measurements may be compared to intensimeter measurements made in connection to the field gamma measurements. Figure 14 shows the sum of the contribution to the ambient dose equivalent from the radionuclides in the uranium series, the thorium series and ^{40}K, as well as the contribution from ^{137}Cs. The figure also shows the results from intensimeter measurements, corrected for the contribution from cosmic radiation. Although a correction has been made to compensate for the fact that the intensimeter is calibrated for ^{137}Cs (0.662 MeV), whereas the mean energy of the naturally

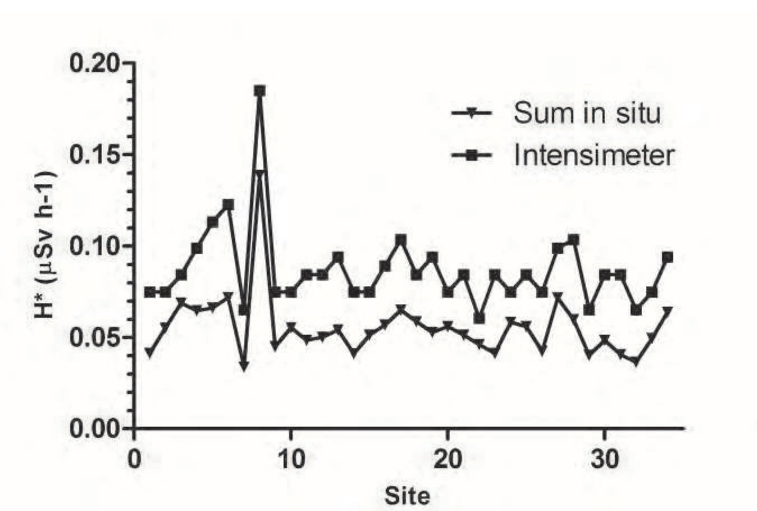

Fig. 14. Ambient dose equivalent rate at 34 reference sites shown as the sum of the contribution from the radionuclides in the uranium series, the thorium series and ^{40}K, as well as the contribution from ^{137}Cs. Also shown are the results from intensimeter measurements, corrected for the contribution from cosmic radiation and photon energy used in the calibration.

occurring radionuclides are slightly higher, a deviation between the results remains. One explanation may be that the measured area differs due to different angular sensitivity of the two measurements systems and that the correction of the intensimeter reading is insufficient. Still there is a good agreement between the two methods to estimate the ambient dose equivalent.
Figure 15 shows the contribution from each of the terms in the sum depicted in Figure 14. The main contributor to the ambient dose equivalent is ^{40}K and the contribution from ^{137}Cs is practically negligible in this area.

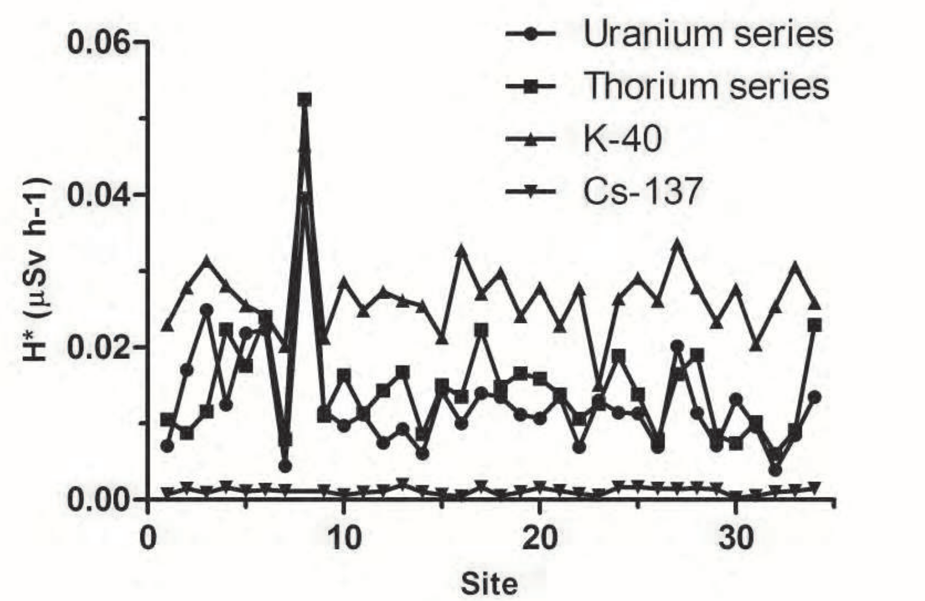

Fig. 15. Ambient dose equivalent rate at 34 reference sites from the radionuclides in the uranium series, the thorium series and ^{40}K, as well as from ^{137}Cs.

5. Conclusion

This chapter includes the basic relations for calculating the primary photon fluence rate from environmental sources of different shapes. Such calculations may be used for calibrating field equipment and also for estimating the exposure to people in the vicinity of the source. The chapter also dealt with practical environmental measurements and the importance to keep in mind the relation between effective dose and ambient dose equivalent. Measurements made by intensimeters tend to overestimate the effective dose due to the calibration requirements.

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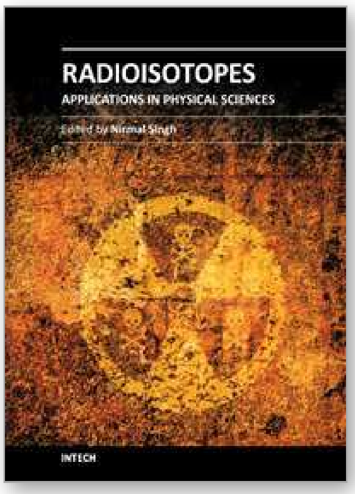

Radioisotopes - Applications in Physical Sciences

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The book Radioisotopes - Applications in Physical Sciences is divided into three sections namely: Radioisotopes and Some Physical Aspects, Radioisotopes in Environment and Radioisotopes in Power System Space Applications. Section I contains nine chapters on radioisotopes and production and their various applications in some physical and chemical processes. In Section II, ten chapters on the applications of radioisotopes in environment have been added. The interesting articles related to soil, water, environmental dosimetry/tracer and composition analyzer etc. are worth reading. Section III has three chapters on the use of radioisotopes in power systems which generate electrical power by converting heat released from the nuclear decay of radioactive isotopes. The system has to be flown in space for space exploration and radioisotopes can be a good alternative for heat-to-electrical energy conversion. The reader will very much benefit from the chapters presented in this section.

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