Environmental Protection from Ionising Contaminants (EPIC)

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Internal and External Dose Models

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To date, the protection of the environment from radiation is based on the premise that if Man is protected from harm, then all other components of the ecosystem will not be at risk. However, this has been increasingly questioned on the basis that it is not always true, it is inconsistent with environmental protection standards for other hazardous materials and conflicts with the recommendations of some international advisory bodies. The aim of the EPIC project is to develop a methodology for the protection of natural populations of organisms in Arctic ecosystems from radiation. This will be achieved by derivation of dose limits for different biota. The project therefore aims to (i) collate information relating to the environmental transfer and fate of selected radionuclides through aquatic and terrestrial ecosystems in the Arctic; (ii) identify reference Arctic biota that can be used to evaluate potential dose rates to biota in different terrestrial, freshwater and marine environments; (iii) model the uptake of a suite of radionuclides to reference Arctic biota; (iv) develop a reference set of dose models for reference Arctic biota; (v) compile data on dose-effects relationships and assessments of potential radiological consequences for reference Arctic biota; (vi) and integrate assessments of the environmental impact from radioactive contamination with those for other contaminants.

The EPIC project is funded under the EC Inco-Copernicus research programme and is co-ordinated by the Norwegian Radiation Protection Authority; project partners:

- Centre for Ecology & Hydrology, CEH-Merlewood, Grange-over-Sands, UK.
- Institute of Radiation Hygiene, St Petersburg, Russia.
- Scientific Production Association TYPHOON, Obninsk, Russia.

For further information on the EPIC project contact Dr. Per Strand (per.strand@nrpa.no).

EXECUTIVE SUMMARY

This deliverable describes the dosimetric models that enable the assessment of exposures to a broad range of target organisms due to both internal and external exposure. Input quantities for the assessment are measured or calculated activity concentrations in biota or in environmental media such as soil, water or sediments. Nuclide-specific dose conversion factors (DCFs) are derived taking into account habitat, target size and exposure route (internal and external exposure). The following points were considered:

- *Selection of radionuclides and reference organisms.* The DCFs were derived for a sub-set of radionuclides of fifteen elements that are considered to be most relevant in case of radioactive releases from nuclear installations and for natural radiation background. Due to the enormous variability of species and habitats it is impossible to consider all species explicitly. Therefore, for both the terrestrial and the aquatic environment a set of Arctic reference organisms, differing in size and habitat were defined for further detailed consideration.
- *Definition of geometry.* Here, instead of 3D mathematical phantoms for DCF calculation, probability distributions of chords/segments lengths (1D array) inside the organisms, from external or internal sources, were used. The developed method, describing the phantoms, allows DCF values to be calculated for organisms of any size or form, as long as input data concerning organism shape are available. If such data are not available, it is possible to use approximation with simplified objects (ellipsoids, cylinders, etc.).
- *Calculations of DCFs for monoenergetic sources.* For the assessment of internal dose the fraction of energy which is absorbed within the organism was estimated. For the assessment of external dose, formulae are used for (i) dose in an infinite or semi-infinite absorbing medium or (ii) kerma calculations at the air/soil, sediment/water interface.
- *The DCFs values were derived using the following assumptions*:
    - DCFs for external exposure were calculated for γ-emitters in all used geometries of exposure. The exposure from β-emitters was taken into account only at an exposure in infinite media (soil, water). Due to the short range of α-radiation the external exposure from α-particles was assumed to be negligible.
    - For the calculations of DCF for species living in the soil, a uniformly contaminated volume source was assumed for natural radionuclides and planar isotropic source located at a depth of 0.5 $g \cdot cm^{-2}$ in soil for artificial radionuclides.
    - For the derivation of DCF values for species living on the ground a planar isotropic source located at a depth of 0.5 $g \cdot cm^{-2}$ in soil and semi - infinite volume source for artificial and natural radionuclides, respectively, were assumed.
    - For the derivation of DCF values for aquatic species at the sediment/water interface, a volume source with a depth of 5 cm and a semi - infinite volume source for artificial and natural radionuclides, respectively, were assumed.
- *Calculations of nuclide-specific dose conversion coefficients.* From the DCFs for monoenergetic radiation sources, nuclide-specific DCFs were derived for external and internal exposure taking into account the type of radiation as well as energy and intensity of emission. The DCFs values were calculated separately

for α- β- and γ- emitters. For internal exposure, DCFs were derived assuming a homogeneous distribution of the radionuclide in the organism. As an example,DCFs were calculated for seal, both for external and for internal exposure not only for the whole organism but also for separate organs. These data are summarized in Appendix 1.

- *Computer program.* On the basis of the developed algorithm, the computer program **DOSES3D** was created. The program allows doses of external (β particles, photons) and internal exposure (α, β particles, photons) in biological objects of the any size and form to be calculated. Doses can be calculated for any radionuclide although, in the present version of the program, an initial data set for 42 radionuclides is used.

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1. Introduction

The EPIC project aims to develop a methodology for the protection of natural populations (and in some cases individuals) of organisms in the Arctic environment from radiation. One of the tasks is the development of a set of dose models for a number of reference flora and fauna. These can be developed to take into account (i) radiation type; (ii) the specific geometry of the target, e.g. the whole body or separate organs of body and (iii) the source of exposure, e.g. radionuclides accumulated in body tissues or distributed in the environment. Clearly, it is not possible to consider all organisms, and there are limitations on the basic data that can be made available as input for the models, e.g. the spatial and temporal distributions of the radionuclides both within the organism and in the external environment. The current "state of art" in wildlife dosimetry therefore involves a high degree of simplification. Some approaches [e.g. USDoE, 2002] assume organisms are simultaneously infinitely large (when calculating internal doses) and infinitely small (when calculating external doses). The approach is therefore likely to be very conservative. In more "realistic" approaches, organisms are represented by simple mathematical figures (sphere, ellipsoid, cylinder) of appropriate dimensions [Woodhead, 2000; Copplestone *et al.,* 2001]. These dimensions define the approximate shape of an average animal or plant. A review of suitable dosimetric models can be found in [Golikov *et al.,* 2003].

The main obstacle to use the current methods has been that results have only been published for a relatively small number of different phantom dimensions. Moreover, to date, attempts of including separate organs inside phantoms representing wild organisms have not been made.

The aim of this report is to present newly developed methodologies and computer code allowing calculation of external and internal absorbed doses to biota with any shape and dimensions to be made.

1.1. Selected Reference Arctic Organisms

In the first stage of this project, reference organisms have been selected and representatives of these generic groups have been identified at the species or family level [Beresford *et al*., 2001]. Further discussions with regards the choice of reference organisms and representatives species/families were held at an EPIC meeting in Oslo in March 2002 (Brown, 2003). Information has been collated on the size and form of these organisms enabling simplified geometries to be constructed. Modifications have been made to the list over time taking account of discussion presented by EPIC participants (see for example, Sazykina *et al*., 2002). The definitive list for the purpose of subsequent dose modelling for terrestrial and marine ecosystems is presented in Table 1.1.

Table 1.1. *Selected for the purpose of dose modelling reference organisms for terrestrial and aquatic ecosystems*

Terrestrial	**Aquatic**
Soil invertebrate (*Collembola spp*.)	Benthic fish (Plaice) [*Pleuronectes platessa*]
Soil invertebrate (Mites)	Small fish (Capelin) [*Mallotus villosus*]
Small herbivorous mammal burrowing (Collared Lemming) [*Lemus Dicrostonyx*]	Large fish (Cod) *[Gadus morhua]*
Small herbivorous mammal burrowing (Vole) *[Microtus spp*]	Bivalve mollusk (Blue mussel) *[Mutilus edulis]*
Large herbivorous mammal (Reindeer) *[Rangifer tarandus*]	Benthic crustacean (Crab) *[Cancer pagurus]*
Herbivorous bird (Willow ptarmigan or willow grouse) [*Lagopus lagopus*]	Pelagic crustacean (Shrimps) *[Pandalus borealis]*
Ground nesting bird egg (Red Grouse) *[Lagopus lagopus scoticus]* egg	Sea mammal (Greenland seal) *[Pagophilus groenlandicus]*
Carnivorous mammal (also burrowing) (Arctic fox) *[Alopex lagopus]*	Seabird (Gull) [*Larus spp.*]
Plant roots (Fine leaved grass) *[Vaccinium myrtillus]*	

1.2. Radionuclides Considered

There is a large range of anthropogenic and natural radionuclides which may need to be considered within environmental impact assessments and in this initial consideration of a framework it is not possible to consider them all. Therefore, a sub-set of radionuclides of fifteen elements has been selected: K, Cs, Sr, Tc, Po, Pb, Bi, Pu, Am, I, Ra, H, C, Th and U. These are summarized in Table 1.2 and represent: (i) radionuclides routinely considered in regulatory assessments of waste disposal and releases from different facility types; (ii) a range of environmental mobilities and biological uptake rates; and (iii) both anthropogenic and natural radionuclides. We should consider the full decay series ^{238}U and ^{232}Th (covers all other radionuclides on our original list U, Th, Po, Pb, Bi, Ra).

Table 1.2. Radionuclides selected for consideration within EPIC

Principal radioisotopes	Half–life (a)	Sources
^{3}H	12	Cosmic, fission, activation
^{14}C	5.6E+3	Cosmic, activation
^{40}K	1.3E+9	Primordial
^{90}Sr	28.5	Fission
^{90}Y	7.3E-3	Fission
^{99}Tc	2.13E+5	Fission
^{129}I	1.57E+7	Fission
^{131}I	2.2E-2	Fission
^{134}Cs	2.06	Fission
^{137}Cs	30	Fission
^{210}Po	3.78E-1	^{238}U decay series
^{210}Pb	22	^{238}U decay series
^{210}Bi	1.37E-2	^{238}U decay series
^{224}Ra	1.0E-2	^{232}Th decay series
^{226}Ra	1.6E+3	^{238}U decay series
^{228}Ra	5.75	^{232}Th decay series
^{222}Rn	1.05E-2	^{238}U decay series
^{228}Th	1.91	Natural
^{230}Th	7.7E+4	^{238}U decay series
^{232}Th	1.4E+10	Natural
^{234}Th	6.6E-2	^{238}U decay series
^{234}U	2.45E+5	Natural
^{238}U	4.47E+9	Natural
^{239}Pu	2.4E+4	Activation-neutron capture
^{241}Am	4.32E+2	Activation-neutron capture

The assumptions used in the process of calculating Dose Conversion Factors (DCFs) of the members of these decay chains are the same as those adopted by Amiro (1997). All radionuclides with half-lives greater than 1 day are treated separately and will be presented with their own DCF. But energies from all progeny with half - lives less than 1 day are included within the DCF value of the parent. In cases where decay chains branch (e.g. Bi-212 and Th-234), the DCF value is weighted according to the yield of daughters. Decay chains included in the DCF value of the respective parent are given in Table 1.3.

Table 1.3. Progeny included in DCF values of the parent

Parent radionuclide	Progeny included
^{224}Ra	$^{220}Rn + ^{216}Po + ^{212}Pb + ^{212}Bi + 0.64^{212}Po + 0.36^{208}Tl$
^{228}Ra	^{228}Ac
^{222}Rn	$^{218}Po + ^{214}Pb + ^{214}Bi + ^{214}Po$
^{234}Th	$0.998^{234m}Pa + 0.002^{234}Pa$
^{137}Cs	^{137m}Ba

The considerations of such a range of radionuclides is required to ensure that appropriate reference organisms are selected; those selected on the basis of one radionuclide (or indeed scenario) may not be the same as those selected for others. Subsequently, our framework designed to assess these radionuclides should be readily applicable to the consideration of other radionuclides.

2. Phantoms for the Reference Arctic Organisms

2.1. General method for phantoms description

A quite simple, but very general approach has been chosen for geometrical modelling of objects. This approach can be divided into two parts: surface and volume description. Any 3D solid object can be approximated *via* a set of points on some 3D lattice inside some bounding rectangular parallelepiped (description as volume) or as an interior of some surface. Formally, a description with such a surface is sufficient, but a 3D lattice allows some specific calculations to be performed simply and quickly. Furthermore the approach allows data about some characteristics of 3D fields inside or around the object (if such information is necessary for particular kind of modeling) to be kept. For description of these surfaces a modern universal approach is used with so-called *triangular meshes*, i.e. solids are approximated using polyhedrons with triangular faces. Such an approach allows us to use the same algorithm of calculations both for analytic objects (like sphere, ellipsoids, cylinders, etc.) and, for that matter, any 3D object, such as those presented by modern systems of 3D design like *AutoCad®*, *3D Studio Max®* or even simple 3D editors for office and Internet applications (VRML). A typical representation of this kind is shown in Figure 1.

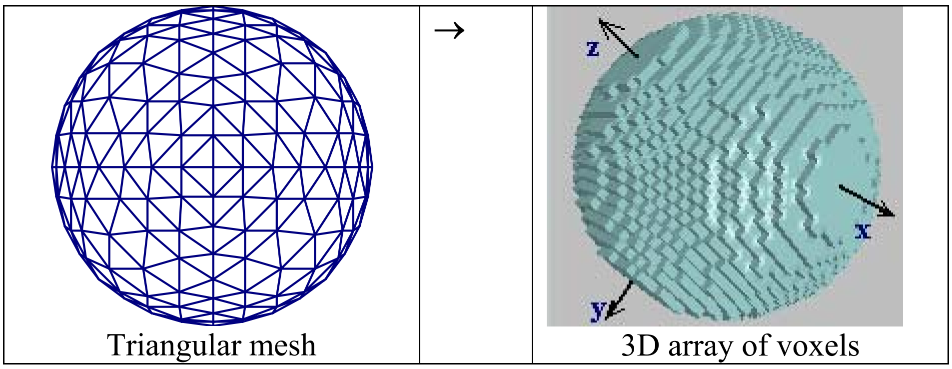


Figure 1. *Representation of 3D solid object*

Because of the universal way of representing 3D data, calculations for biological objects described with arbitrary levels of detail are possible, if there are input data about the object's shape. If such data are not available, it is possible to use approximations using simplified objects (ellipsoids, cylinders, etc.).

For a more detailed description of the object, it is necessary to have the object represented as a triangular mesh. Owing to the fact that such descriptions are now almost standard for 3D objects, there are many ways to prepare or find such types of data, e.g.:

- object prepared with non-professional (often free) editors for creating **`*.wrl`** text format of VRML (format used for representation 3D data for fast Internet application -- currently models used in our calculations may be saved in this format for viewing and checking errors and adequacy in 3D object shape representation);
- many models represented in professional 3D software like *3D Studio Max*®, *Light Wave*®, etc. and saved in **`*.dxf`** text format of *AutoCad*®;
- output of computer program using analytical description of surface.

Meshes are saved in files with extension **`*.mes`**. These text files have the format described below.

Format of mesh files

mesh.Mesh_Name	name of first mesh
N	number of vertexes
x_1 y_1 z_1	coordinates of all vertexes, real numbers.
x_2 y_2 z_2	
...	
x_N y_N z_N	
n	number of faces;
i_1 j_1 k_1	indexes of 3 vertexes for each face, natural numbers [0,…,N-1]
i_2 j_2 k_2	
...	
i_n j_n k_n	

In Figure 2, possible variants that might be used to represent dosimetric phantoms for biota are presented.

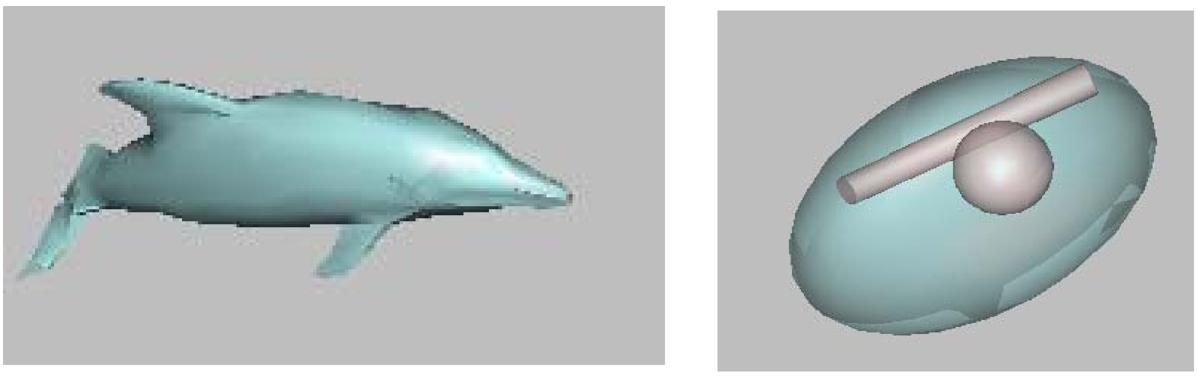


Figure 2. *More realistic phantoms for representatives of biota: a) realistic shape of body of aquatic organism (dolphin); b) ellipsoid with internal organs.*

2.2. Phantoms for Marine and Terrestrial Reference Organisms

Despite the fact that the above-mentioned approach allows phantoms representing actual flora and fauna to be described using a high degree of realism, for the purposes of the present work, we will use simplified geometrical phantoms (sphere, ellipsoid, etc.) for calculations. This is in line with approaches adopted elsewhere (see Pröhl *et al*., 2003). The use of simplified geometries also reflects the lack of systematized data describing realistic shapes (surfaces) of representative flora and fauna. The sizes of geometrical bodies (diameter of a sphere, axes of a ellipsoid) were taken from the literature [IAEA, 1976; IAEA, 1979, IAEA, 1988; NCRP, 1991; Copplestone *et al.* 2001] and systematized in the previous EPIC reports [Beresford *et al*., 2001; EPIC, 2002]. The tissue density has been assumed to be unity. For marine organisms when there were two sets of sizes for the objects- without and with cover (bivalve mollusk, benthic crustacean), internal doses were calculated for the case "without cover" while external doses were estimated for the set "with cover". For birds and mammals, the derived mass of the animal assuming unit density and based on the volume of the organism differed from the actual, observed mass of the organism. This reflected the low density covering of fur/feathers that were included in the volume estimation. The following approach was taken to deal with this situation explicitly. For calculation of internal doses on organisms, the sizes of the effective homogeneous phantoms with a density equal to unity were calculated on the basis of the observed body mass. For calculation of external doses of organisms, the initial sizes of a body that is determined for the heterogeneous phantoms was used. The organisms under discussion along with the dimensions of the phantoms (adopted to represent each of these animals) used in the calculations are given in Tables 2.1 and 2.2.

Table 2.1. *Reference geometry for the marine organisms*

Organism type (Proposed reference organism)	Mass (kg)	Body length (m)	Body width (m)	Body depth (m)	Shape
Bivalve mollusk (blue mussel) *[Mutilus edulis]*	0.016 [1]0.005	0.05 0.032	0.025 0.02	0.025 0.015	ellipsoid ellipsoid
Benthic fish (plaice) [*Pleuronectes platessa*]	0.80	0.25	0.20	0.03	ellipsoid
Sea mammal (Greenland seal) *[Pagophilus groenlandicus]*	160	1.70	0.45	0.40	ellipsoid
Small fish (capelin) [*Mallotus villosus*]	0.035	0.15	0.03	0.015	ellipsoid
Large fish (cod) *[Gadus morhua]*	1.5	0.5	0.1	0.06	ellipsoid
Benthic crustacean (crab) *[Cancer pagurus]*	0.26 [1]0.04	0.1 0.05	0.1 0.05	0.05 0.03	ellipsoid ellipsoid
Pelagic crustacean (shrimps) *[Pandalus borealis]*	[1]0.008	0.07	0.015	0.015	ellipsoid
Seabird (gull) [*Larus spp.*]	[2]0.6	0.15	0.10	0.08	ellipsoid

The biota sizes relate to the adult form for each of the organisms considered.
[1] without cover; [2] without feathers.

Table 2.2. *Reference geometry for the terrestrial organisms*

Organism type (Proposed reference organism)	Mass (kg)	Body length (m)	Body width (m)	Body depth (m)	Shape
Soil invertebrate (Collembola spp.)	$2.6 \cdot 10^{-6}$	0.005	0.001	0.001	Ellipsoid
Soil invertebrate (Mites)	$1.4 \cdot 10^{-8}$	0.003	0.0004	0	Flattened sphere
Small herbivorous mammal burrowing (Collared Lemming) [*Lemus Dicrostonyx*]	0.06	0.14 [1]0.088	0.055 [1]0.034	0.063 [1]0.039	Ellipsoid
Small herbivorous mammal burrowing (Vole) *[Microtus spp*]	0.03	0.103 [1]0.066	0.04 [1]0.026	0.0494 [1]0.033	Ellipsoid
Large herbivorous mammal (Reindeer) *[Rangifer tarandus*]	64	2	0.19	0.32	Ellipsoid
Herbivorous bird (Willow ptarmigan or willow grouse) [*Lagopus lagopus*]	0.5	0.25 [1]0.14	0.17 [1]0.094	0.13 [1]0.072	Ellipsoid
*Ground nesting bird egg (Red Grouse) *[Lagopus lagopus scoticus]* egg	0.025	0.046	0.032	0.032	Ellipsoid
Carnivorous mammal (also burrowing) (Arctic fox) *[Alopex lagopus]*	5.5	0.54	0.11	0.18	Ellipsoid
Plant roots (Fine leaved grass) *[Vaccinium myrtillus]*	$2.8 \cdot 10^{-7}$	0.29	0.000035	0.000035	Cylinder

The biota sizes relate to the adult form for each of the organisms considered with the exception *. [1]sizes of effective homogeneous ellipsoids.

2.3. Selected Geometry of Exposure

Radiation dose may arise either from radionuclides present in the soil, sediment, water or air surrounding the organism (external dose) or from radionuclides taken up internally by the organism (internal dose).

The general strategy of estimating exposure doses consist of two main tasks:

- development of radionuclide transfer models to estimate the radionuclide content in the environment surrounding the organism and after that in organisms at any time after a radioactive release [Beresford *et al*., 2003];

- development of dosimetric models for evaluation of internal and external exposure of reference organisms. Essentially, this is a time-independent dose coefficient for a given type of exposure (this Deliverable Report).

If one assumes an infinite or semi-infinite volume with a uniform concentration *C(t)* of a radionuclide at time t, then the absorbed dose to biota, D_b, can be expressed as:

$$D_b = d_b \cdot \int C(t)dt, \quad (1)$$

where d_b denotes the time-independent dose coefficient for given type of exposure, $Gy \cdot a^{-1}$ per $Bq \cdot kg^{-1}$.

The coefficient d_b represents the dose per unit time-integrated exposure expressed in terms of the time-integrated concentration of the radionuclide. An alternative interpretation considers d_b to represent the instantaneous dose rate per unit activity concentration of the radionuclide in the environment.

For the assessment of internal dose, it is necessary to estimate the fraction of energy which is absorbed within the organism. For the assessment of external dose formulae are used for dose in an infinite or semi-infinite absorbing medium or kerma calculations at the air/soil, sediment/water interface.

The number of situations of external exposure is enormous; therefore a number of limited and representative situation have been selected for detailed calculations. The following standard models of estimating external exposure were identified:

- exposure of target in infinite (semi-infinite) medium (water, soil) with uniform distribution of β, γ-emitting radionuclides;
- exposure of target on semi-infinite medium (water, soil) with uniform distribution of β, γ-emitting radionuclides;
- exposure of target from contaminated ground surface (infinite in a horizontal direction) or from contaminated slab.

In the case where the individual (biota) is mobile the characteristics of the radiation field will clearly change as areas with differing contamination levels are traversed and/or occupied. Thus the integrated exposure for an individual biota can be divided into partial exposures. Each of these exposure situations can be describe by individual models including dose coefficients connecting concentration of radionuclides in environmental compartments with the characteristics of the external radiation field. This set of partial exposures situations used in combination with a set of occupancy factors, defined as the part of time spent under each partial exposure situation, defines the common model of external dose formation for the organism.

3. Methods of Calculation of Absorbed Doses

3.1. General description

At present, there are two ‘exact’ methods for calculation of radiation transport through different materials. These are the numeric solution of transport equation and the Monte-Carlo method. The methods have their own advantages and disadvantages. Numeric methods, which can give the results with the necessary precision under an acceptable consumption of computer time, are reasonable to use for one-dimension tasks, for example, for calculation in media, which may be modeled by sets of finite-thickness layers having infinite horizontal sizes (calculations for two-layers media soil-air). If we use complex three-dimensional objects for the model, the Monte-Carlo method of calculation is more appropriate because it allows us to perform the calculations for objects of any geometry. However, huge computer time consumption is a considerable disadvantage of this method.

Alongside the ‘exact’ numeric methods, for the solution of practical tasks dealing with calculation of photons fields in finite-size media, approximate methods of calculation have been developed. For example, in relation to dose distribution calculations and their average values for different organs in humans, the following approach is used. The dose of gamma radiation at any point in the organ of interest can be determined in accordance with an appropriate function of dose attenuation ***D(x),*** where ***‘x’*** is a path length of a particle to the chosen point inside the body. The function ***D(x)*** for the given energy can be calculated with ‘exact’ numerical methods The function of distribution of the path lengths in the organ - ***p(x)dx*** is then calculated. This function defines the probability of the mass element position at a depth between ***x*** and ***x+dx.*** The distribution of the doses inside an organ and the average dose can be thus calculated:

$$\bar{D} = \int_V D(x) \cdot p(x) \cdot dx \Big/ \int_0^\infty p(x) \cdot dx \qquad (2)$$

The distribution function *(chord distribution)* for the given geometry and phantom orientation is calculated using the Monte-Carlo method; the position ***dm*** inside the organ in randomly taken and the process of calculation is repeated up to a point where an acceptable statistical accuracy has been achieved. This method is close to a method described in the literature as a CHORD-method [Jones, 1977], which was used, with some success, to estimate exposure doses for Hiroshima and Nagasaki bomb survivors.

Let us consider this approach for calculation of the average absorbed doses in bodies of various biotic representatives.

At this point, it is useful first to describe some necessary concepts about chord distributions and kinds of randomness relevant to the present investigation. Different kinds of randomness are described in Kellerer [1971] and include :

Mean free path randomness (μ-randomness). A point in Euclidean space and a direction defines a chord. The point and the direction are from independent uniform distributions. This randomness is the result if the convex body is exposed to a uniform, isotropic field of straight infinite tracks. This kind of randomness is rather difficult from a computational perspective and leads to slow computer simulation times. However, chord distributions may be produced also *via* analytical formula using I-randomness as described below.

Interior radiator randomness (I-randomness). A chord is defined by a point in the interior of a given body and a direction. The point and the direction are derived from independent uniform distributions. The distribution really is not applied directly, but may be used as a simple and fast way for producing and checking other distributions.

Interior source randomness (i-randomness). The distribution is produced in a similar way to I-randomness, but instead of a full line only a *half* track is used. This approach corresponds to the actual internal emitter of radiation and is the main focus for the present investigation.

The *mean free path randomness for circular exposure (μ_c-randomness)* has also been considered. A point in Euclidean space and a direction parallel to the X-Y plane defines a chord. The point and the direction are derived from independent uniform distributions. This randomness is a suitable model for a convex body when it is exposed to a uniform, isotropic field of straight infinite tracks *parallel to the X-Y plane*.

Preparation of histograms

Calculation of all chord distributions follows a similar methodology (using 3D array). A Monte-Carlo algorithm produces a line or segment described by probability distributions relevant to the selected kind of randomness. The line is divided into many discrete parts. Coordinates of points used to divide the line and the index of elementary cubes in a 3D array are calculated. Using cube coordinates, it is possible to find whether the point/line belongs to the body or not. For bodies with organs, it is possible to also find whether a particular organ contains a given point.

Let us consider a simple case without organs. Using the information described above, it is possible to find which part of a chord belongs to a given body. Instead of a 3D body, therefore, it is possible to prepare a probability distribution of chords/segments lengths for any given kind of randomness (see Fig. 3). This is an (1D) array with information defining the probability of a chord in a given distribution having a length between l_i and $l_i + \Delta l$. In this case, Δl is a minimum step in the histogram used for approximating a continuous distribution and each element of the array ("bin") with some index i corresponds to $l_i = i\ \Delta l$.

The whole process can be represented using the following diagram:

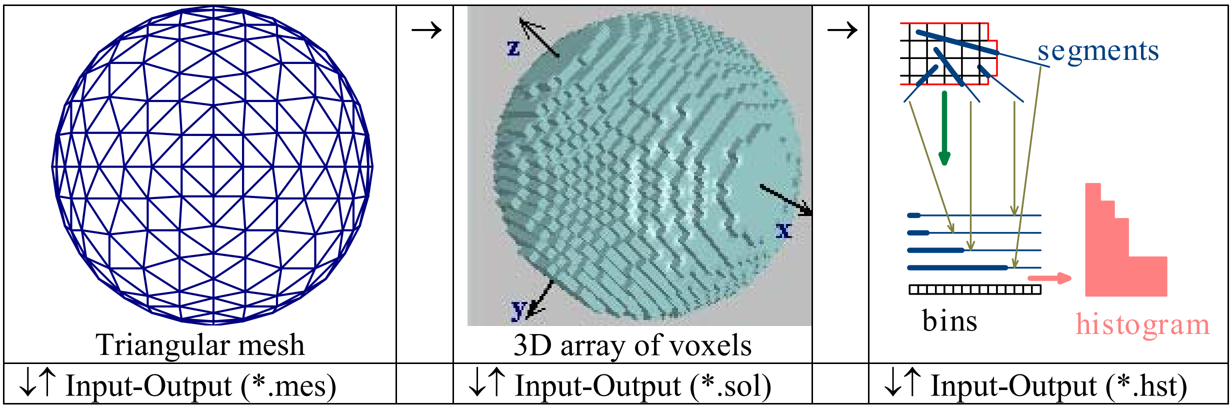


Figure 3. *Derivation of a probability distribution defining chord/seg,metn lengths within a specificed geometry.*

In this case, “input-output” arrows show the possibility to save and use data files for a particular step in the procedure. Files with meshes are usually used for working with an object because files with 3D arrays are often excessively large. The program accepts “packing” of data, but for data arrays with good resolution, this is a slow process. It should be mentioned that files with voxels (3D array) may also be useful. For example, such files were used during the testing of algorithms by comparison with Monte-Carlo results for mathematical phantoms. Mathematical phantoms are described using analytical expressions for shapes of organs and, in this case, 3D arrays should be calculated using such expressions and without any meshes. Furthermore, the array of chords is prepared directly from an array of voxels, despite the large size of such an array.

The following step is the calculation of absorbed doses using a model of the body defined by chord distributions.

3.2. Calculation of absorbed doses from internally incorporated radionuclides

For the assessment of internal dose it is necessary to first estimate the fraction of energy which is absorbed within the organism. The absorbed fraction is the ratio of the energy absorbed in a given target volume to the energy emitted by a radioactive source. The use of absorbed fraction to calculate the dose from radionuclides within the body has been described earlier [Brownell *et al.*, 1968; Ellet & Humes, 1971]. The average dose rate delivered to a target from a given radionuclide is given by:

$$\dot{D} = 5.04 \times 10^{-6} \cdot A \cdot \sum_i \Phi_T(E_i) \cdot E_i \cdot y_i \qquad (3)$$

where: $\dot{D}$ is the dose rate (Gy a^{-1});
A is the activity concentration (Bq kg^{-1} w.w.);
E_i is the energy of component <i> of emitted radiation (MeV);
y_i is the yield of emitted radiation of energy E_i (dis^{-1});
$\Phi_T(E_i)$ is the absorbed fraction in the target for energy E_i;
5.04×10^{-6} is the factor to account for conversions of MeV to Joules and seconds to years.

For each radionuclide data for the energy and yield of particle emissions have been extracted from the literature ICRP [1983].

A new approach for the calculation of absorbed fractions was used. In concordance with the approach taken by Kellerer (1971), two kinds of distributions have been defined to describe chords within a body. These are: *c(x)* - is probability density of chords with given randomness and *C(x)* probability that chord (segment) has a length more than x. If $\Phi_i(x)$ is the fraction of particles with an energy E_i,absorbed on a given length *x,* then the average absorbed fraction of particles in the target is:

$$\Phi_T(E_i) = \int_V c(x) \cdot \Phi_i(x) dx \qquad (4)$$

Let us find an explicit kind of function $\Phi_i(x)$ for photons, describing the loss of energy on the elementary segment *dx*. The exponential character of reduction of quantity of source photons is used for this purpose. Besides, we shall use only two groups of photons: N_1 initial (source) photons and N_2 first scattered photons. It is possible to write the following system of differential equations expressing the decrease in the amount photons on segment *dx*:

$$dN_1/dx = -\mu_1 N_1; \qquad dN_2/dx = \beta N_1 - \mu_2 N_2 \qquad (5)$$

where: $\mu_1 = \mu_{att,1}$ is the linear energy attenuation coefficient at energy first group of photons;
$\beta = \mu_{att,1} - \mu_{abs1}$ is scattering cross-section from first to second group, and
$\mu_2 = \mu_{abs2}$ is the linear energy absorption coefficient at energy second group of photons.

The solution of the system is:

$$N_1(x) = exp(-\mu_1 x) N_1(0),$$
$$N_2(x) = (\beta/(\mu_1 - \mu_2))\,(exp(-\mu_2 x) - exp(-\mu_1 x)) N_1(0) + exp(-\mu_2 x)\, N_2(0) \qquad (6)$$

where: $N_1(0)=1,\ N_2(0)=0$.

The function $\phi(x)$, determining the probability of absorption of photons of these two groups on an elementary segment *dx*: $\phi(x) = \mu_{abs1} N_1(x) + \mu_{abs2} N_2(x)$ can thus be found. Let us calculate now the function determining the probability of photon absorption on a segment with a length *x:*

$$\Phi_i(x) = \int_0^x \phi_i(x) dx = \Phi_1(x) + \Phi_2(x) \qquad (7)$$

Following integration, taking into account equation (6), we can derive the final expressions for the components of function $\Phi_i(x)$:

$$\Phi_1(x) = (1 - \beta/\mu_1)(1 - exp(-\mu_1 x)),$$
$$\Phi_2(x) = (\mu_2 \beta/(\mu_1 - \mu_2))\,(exp(-\mu_2 x)/\mu_2 - exp(-\mu_1 x)/\mu_1) \qquad (8)$$

Such a formula does not take into account the change of direction after scattering.

This has the effect that the photon, after scattering, travels a longer distance and results in an enlarged absorption fraction. For first scattering photons an expression for average angle θ at Compton scattering can be applied to account for this phenomenon [Hine & Brownell, 1956]:

$$cos\ \theta = 1 - 1/\alpha_1 + 1/\alpha_2 \qquad (9)$$

where: α_1 and α_2 are photon energies defined in terms of the rest energy of electron m_0c^2 (0.511 MeV). Then it is possible to formulate:

$$\Phi(x) = \Phi_1(x) + \Phi_2(kx) \qquad (10)$$

where: $k = (1+l)/(1+l^2+2l\ cos\ \theta)^{1/2}$,and $l = \mu_1/\mu_2$.

Then for calculating $\Phi_T(E_i)$ as a function *c(x)* in equation (4), the i-randomness was used. For calculation of the i-randomness, a random point inside the body and a random direction are produced using a (pseudo) random number generator. The segment from a given point (x,y,z), and direction (dx,dy,dz) is tracked using a fixed small step until escape from the interior of solid body has occurred. In order to check which points belong to the solid body, a three-dimensional data array is used.

For *β– and α*-particles functions, $\Phi_i(x)$ has other forms. The empirical formulae defining dose distribution functions of α- and β- radiations around point isotropic sources were taken from Loevinger *et al*. (1956), IAEA (1979) and Woodhead (2000).

External doses to organisms from radionuclides present in soil or in the water column are calculated using a variant of the simple formula for uniformly contaminated isotropic infinite absorbing medium:

$$\dot{D} = 5.04 \times 10^{-6} \cdot A \cdot \sum_i (1 - \Phi_T(E_i)) \cdot E_i \cdot y_i \qquad (11)$$

This equation:

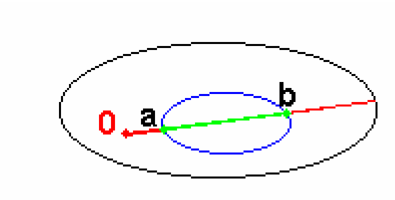
- approximates the dose rate to an organism immersed in an infinite contaminated medium;
- neglects density differences between the organism and the medium;
- allows for self shielding by the organism itself, and
- averages the dose rate throughout the volume of the organism.

Equation (11) has been used to calculate the external dose from β- γ-radiation for organisms buried in soil or free swimming in the water column; the relevant concentrations being those in the soil or water media as appropriate.

Note to the calculation of absorption fractions and doses for body with organs

In order to consider the absorbed fraction for an organ inside a body, it is necessary to consider absorption for part of the line inside of the organ:

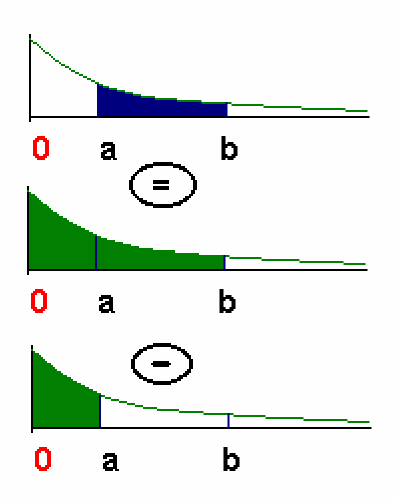
$$\Phi(a,b) = \int_a^b \phi(x)dx$$



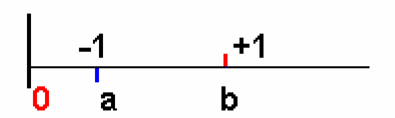
To work with such data using chords distributions, a special numerical manipulation is used. Let us rewrite the last formula:

$$\Phi(a,b) = \int_a^b \phi(x)dx = \int_0^b \phi(x)dx - \int_0^a \phi(x)dx = \Phi(b) - \Phi(a)$$

This expression may be represented with the following diagram:



This contribution to the absorbed fraction, is formally considered by taking into account two segments: first (0,b) as in the "usual" case, and second (0,a) with a negative sign (i.e. number of segments with such length is formally *reduced* by one):



So formally the same expression as before is used:

$$\Phi_T = \int_0^{\infty} c(x)\Phi(x)dx$$

The absorbed fraction in the target, *c(x)*, is now not a usual distribution function, but a difference

$$c(x) = c_+(x) - c_-(x),$$

where: $c_+(x)$ and $c_-(x)$ are distributions of length “source – escape from organ” (point ***b*** on pictures) and “source – entrance to organ’’ (point ***a*** on pictures) respectively.

To prepare such distributions $c_{st}(x)$, a computer trace records, for each simulation, the number of the organ where the particle was emitted and the number of organs intersected by a given track. So, for calculations of internal doses with n organs, instead of one histogram, a table with dimensions $n \times n$ is used, i.e. n^2 histograms for each pair source/target. For calculation of external doses, an array with n histograms is used, because the source is always the same, i.e. environment

3.3. Calculation of external doses from a plane surface source and uniformly contaminated slab

For the case of an organism exposed on the ground surface or at the sediment/water interface (contaminated slab) we used another approach, as described below. The most relevant radiation source following a release of radioactivity to the environment arises from the contamination of soil, which causes—dependent, of course, upon the effective half-life of the particular radionuclides present—a persistent radiation source for all terrestrial and some aquatic biota (for example, seal). The estimation of external exposures at the interface of environments with different densities is more complex than cases pertaining to infinite, uniformly-contaminated environments.

Due to the complexity of the processes involved and the enormous variability of organisms and their natural habitats, it was impossible to calculate, in this report, the values of dose conversion factors (DCF) for all possible exposure conditions. Therefore, typical exposure situations appropriate to and based around the geometries selected for reference organisms were selected for detailed consideration. Furthermore, DCFs were derived for only a limited number of radionuclides. Notwithstanding this, DCFs for radionuclides and exposure situations not considered here, can be determined by calculations using the computer program described below. The exposure conditions were defined taking into account the following criteria:

- DCF for external exposure was calculated for γ-emissions in all source-target exposure configurations. The exposure from β-emissions was taken into account only at an exposure in infinite media (soil, water). Due to the short range of α-radiation the external exposure from α-particles was assumed to be negligible although it is acknowledged that such an assumption may not be valid in the case of extremely small targets.
- For the calculations of DCF for species living *in the soil*, two source descriptions were assumed : (a) uniformly contaminated volume source was for natural radionuclides and (b) a planar isotropic source, located at the depth 0.5 $g \cdot cm^{-2}$ in the soil, for artificial radionuclides.
- For the derivation of DCF values for species living *on the ground*, two source descriptions were assumed : (a) a semi - infinite volume source for natural radionuclides and (b) a planar isotropic source located at a depth of 0.5 $g \cdot cm^{-2}$ in the soil for artificial radionuclides.,.
- For the derivation of DCF values for aquatic species at the sediment/water interface, two source description were assumed : (a) a volume source with a

depth of 5 cm for artificial radionuclides and (b) semi - infinite volume source for natural radionuclides.

A two-step method has been used. In the first step, the kerma in a specified location (above the soil/air interface, in soil at the given depth) is derived. In the second step, the ratio of the dose in an organism and the kerma is calculated for the different organisms and radionuclides.

Earlier a model of human external exposure in the forest from all elements of the ecosystem contaminated by radionuclides had been developed (Golikov *et al*., 1999). The results from this work have been used in the present study. A series of calculations were performed to derive the attenuation function of gamma-radiation dose rate from thin plane isotropic sources in soil and in forest equivalent media (FEM), which represent a mixture of forest biomass and air The computer code VICAR-2 was used for the numerical solution of the transport equation [Nikolayev *et al.*, 1984]. This code uses multi-group approximation of the method of integral equations [Bergelson *et al*., 1970; Barkovsky & Popkov, 1980]. The calculations were performed using the 23-group system of constants, which was created especially for this type of problem [Golikov *et al*., 1989].

The kerma rate values created by gamma radiation of plane isotropic sources located at different depths in soil and at different heights in the FEM were calculated. The calculations were performed for the following coordinates of the source:

- depths in soil: 0, 0.3, 1, 3, 10, 30, 50, 70 $g \cdot cm^{-2}$;
- heights in the FEM: 0.05, 0.5, 1, 3, 10, 30, 50 m.

In our calculations, we used the following atomic compositions (mass percents) of forest ecosystem model components and their physical densities:

- Air: N - 75.5, O - 23.2, Ar - 1.3; the composition is for condition of 40% relative humidity, a pressure of 760 mm Hg, a temperature of 20 ^{o}C, and density $\rho = 1.2\ kg \cdot m^{-3}$.
- The atomic composition of the forest biomass: C - 27, O - 63.9, H - 8.6, N - 0.19, Ca - 0.13 and 0.18 due to the trace amounts of other elements (K, P, Mg, Fe, Zn, S). The physical density of the forest biomass depends on its type. We have chosen for calculations a range from the set values of the forest biomass density from 0 to 5 kg/m^3 (the first value corresponds to the free air).
- The atomic composition for soil was taken from Saito & Jacob [1995]: Si - 26.2, Al - 8.5, Fe - 5.6, H - 2.2, O - 57.5. The soil density was taken to be 10^3 kg/m^3. All results were presented in mass coordinates and do not depend on the real soil density.

Calculations were made for 18 source energies from 20 keV to 3 MeV. On the basis of the results of "exact" calculations for plane isotropic sources, simple formulae for calculation of air kerma rates at 1 m above the ground surface, from the activity distribution in soil compartment, are obtained (Golikov *et al*., 1999). Here we present the formulae intended for kerma calculation in free air. It should be noted that they do not take into account any additional attenuation of radiation due to the presence of forest biomass.

For flat isotropic source located at a depth x (g·cm⁻²):

$$K_a(x) = a_1 \cdot \exp(-a_2 \cdot x) + a_3 \cdot \exp(-a_4 \cdot x) \qquad (12)$$

where: $K_a(x)$ is the air kerma rate $[10^{-12}\cdot(\mathrm{Gy\cdot s^{-1}})$ per $(\mathrm{Bq\cdot cm^{-2}})]$ at a height of 1 m above the ground from a plane isotropic source located in soil at depth x $(\mathrm{g\cdot cm^{-2}})$.

For an exponential distribution in the form $A^s_m(x_a) = A^s_a \cdot \beta \cdot \exp(-\beta \cdot x)$; where: $A^s_m(x)$ is the specific activity of soil $(\mathrm{Bq\cdot g^{-1}})$ at depth $\boldsymbol{x}$ $(\mathrm{g\cdot cm^{-2}})$; A^s_a is the activity per unit area $(\mathrm{Bq\cdot cm^{-2}})$ and β is the depth distribution parameter, which is the reciprocal of the relaxation length $(\mathrm{cm^2\cdot g^{-1}})$:

$$K^S_a(\beta) = 3.6 \cdot A^S_a \cdot \left\{ \frac{a_1}{1+\frac{a_2}{\beta}} + \frac{a_3}{1+\frac{a_4}{\beta}} \right\} \qquad (13)$$

where: $K^s_a(\beta)$ is the kerma rate $(\mathrm{nGy\cdot h^{-1}})$; A^s_a is the activity per unit area $(\mathrm{Bq\cdot cm^{-2}})$.

For homogeneous distributions of radionuclide activity in soil layer between $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ $(\mathrm{g\cdot cm^{-2}}$, $\boldsymbol{x}_1 < \boldsymbol{x}_2)$ with specific activity A^s_m $(\mathrm{Bq\cdot g^{-1}})$:

$$K^s_a(x_2, x_1) = 3.6 \cdot A^s_m \cdot \left\{ \begin{array}{l} \frac{a_1}{a_2} \cdot \exp(-a_2 \cdot x_1) \cdot [1 - \exp(-a_2 \cdot (x_2 - x_1))] \\ + \frac{a_3}{a_4} \cdot \exp(-a_4 \cdot x_1) \cdot [1 - \exp(-a_4 \cdot (x_2 - x_1))] \end{array} \right\} \qquad (14)$$

where: $K^s_a(x_2, x_1)$ is the kerma rate $(\mathrm{nGy\cdot h^{-1}})$. Formula (14) can be directly used for calculation of the kerma rate from experimentally obtained and analyzed soil samples.

The formula (14) for kerma calculation from a semi-infinite source in soil will be transformed to the simpler expression:

$$K^s_a(\frac{1}{2}\infty) = 3.6 \cdot A^s_m \cdot \left[\frac{a_1}{a_2} + \frac{a_3}{a_4} \right] \qquad (15)$$

The values of the parameters (a_1 - a_6) for artificial radionuclides used in this investigation are presented in the Table 3.1.

Table 3.1. *Numerical values of parameters in the formulas (12-14)*

Radionuclide	a_1	a_2	a_3	a_4
^{129}I	0.624	2.28	0.0819	0.695
^{131}I	2.29	0.540	1.72	0.0845
Cs-134	9.46	0.470	6.31	0.0699
Cs-137→Ba-137m	3.39	0.492	2.38	0.0723
^{241}Am	0.253	1.42	0.121	0.258

The value of the air kerma rate, 1 m above the ground surface is assumed to be characteristic of a radiation field that can be used in the estimation of external doses for organisms living on the ground surface. Such an assumption can be justified by considering the fact that if the source is located at any depth in the ground (not on the surface) the kerma value in air for photons with energies greater than 20 keV is practically the same from heights of 0 up to 1 m above ground. For an estimation of external doses for organisms buried in soil, results of "exact" calculations were also used. As an example, in Figure 4, the curves of kerma attenuation in soil for three energies of radiation are presented. In order to estimate exposure situations in soil, kerma values at depths of 50 cm and 100 cm from a planar isotropic source located at a depth of 0.5 $g \cdot cm^{-2}$ in the soil, for artificial radionuclides, were calculated. An infinite medium with uniform contamination was used as the source for estimation of exposure situations in soil from the β- γ-radiations of natural radionuclides.

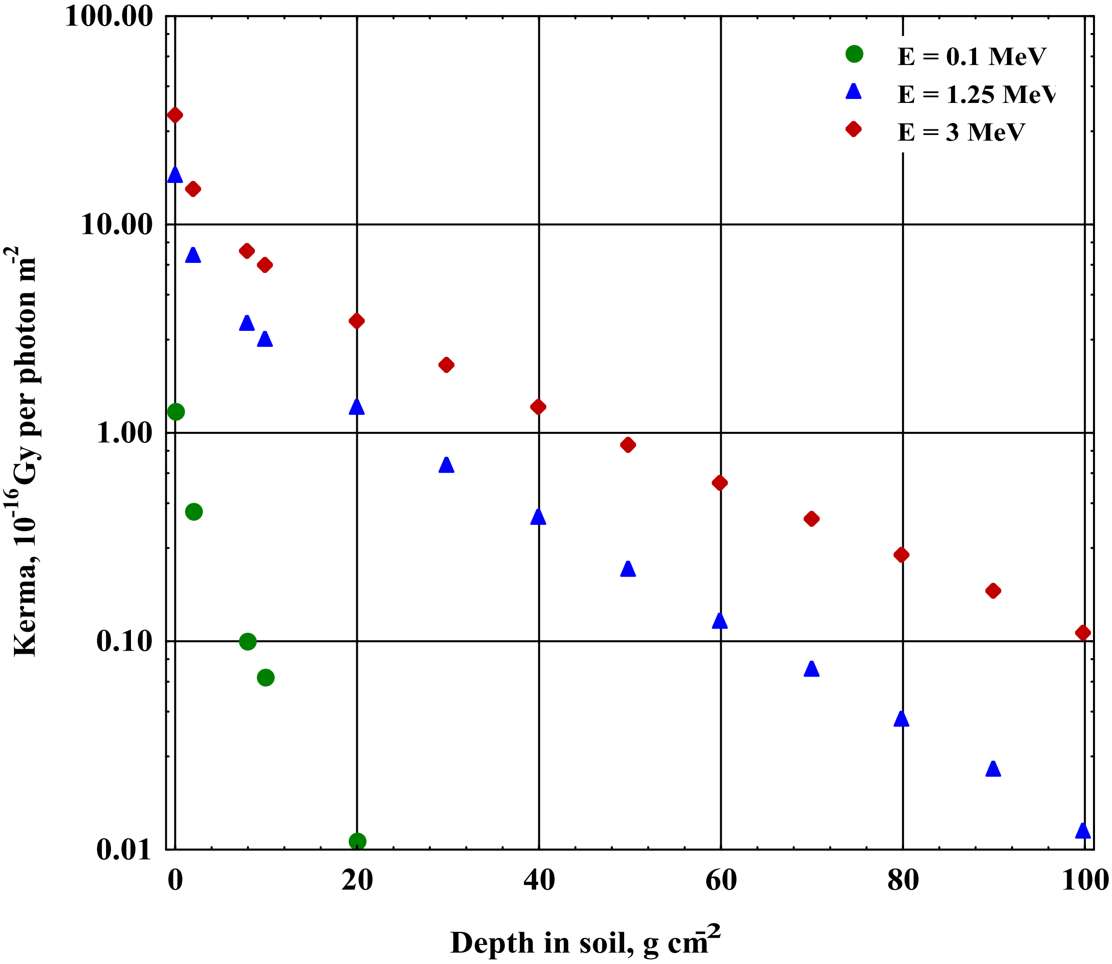


Figure 4. *The curves of kerma attenuation with the depth in soil for three energies of gamma radiation*

As considered above, the next stage of the method required the ratio of the dose in an organism and the kerma in medium to be calculated. For the majority of organisms and the irradiation conditions considered in the present investigation, this ratio will not differ significantly from unity, but will decrease for large organisms and small energies of radiation. For an estimation of this ratio at a specific value of kerma in the air, it is possible to use the following approach. Let us consider irradiation in an infinite air volume (equilibrium exposure). Under such circumstances in the environment, there is an equilibrium spectrum of gamma radiation with average energy E_{eq} and isotropic angular distribution of particles. It is possible to calculate the value of kerma K_a in free air using the expression:

$$K_a = \varphi_N \cdot E_{eq} \cdot \mu_{abs}^{air} \qquad (16)$$

where: φ_N is particle fluence in photons cm^{-2}; E_{eq} is the energy of photons in MeV; and μ_{abs}^{air} is the mass photon energy absorption coefficient at energy E_{eq} in cm^2 g^{-1}.

On the other hand, the following equation can be written for calculation of the average absorbed dose D_b in the organism positioned in an infinite, contaminated air volume:

$$D_b = \frac{N_\gamma \cdot E_{eq} \cdot \Phi^b_{abs}}{m_b} \tag{17}$$

where: N_γ is number of incident particles on the body; Φ^b_{abs} is the absorbed fraction for organism; and m_b is the mass of body.

It is known [Kerr, 1980] that for an isotropic field in an infinitive media, the following ratio can be written for the particles fluence φ_N in a free field and the number of incident particles on the body N_γ:

$$\varphi_N = \frac{4N_\gamma}{S_b} \tag{18}$$

where: S_b is the exterior surface area of the body.

By substituting the term for φ_N from Equation (18) into Equation (16), the following equation can be written for N_γ:

$$N\gamma = \frac{K_a \cdot S_b}{4E_{eq} \cdot \mu^{air}_{abs}} \tag{19}$$

And by substituting the term for N_γ from Equation (19) into Equation (17) and taking into account the fact that body mass m_b is a product of body density (ρ_b) and its volume (V_b) the following equation can be derived:

$$D_b = \frac{K_a \cdot S_b \cdot \Phi^b_{abs}}{4\mu^{air}_{abs} \cdot \rho_b \cdot V_b} = \frac{K_a \cdot \Phi^b_{abs}}{\mu^{air}_{abs} \cdot \rho_b \cdot \bar{x}_b} \tag{20}$$

where: $\bar{x}_b = \frac{4V_b}{S_b}$ is the mean chord in the convex body for the μ-randomness [sometimes called the Cauchy theorem; Cauchy, 1908].

Therefore, from the value of kerma in air, the value of absorbed dose rate in a body can be calculated. The expression for the absorbed fraction $\Phi_i(x)$ (Eq. 8) on a segment with length *x,* for the equilibrium exposure, also becomes simpler. In this case, we are dealing with only one group of photons with an average energy of equilibrium spectrum E_{eq} and for $\Phi_i(x)$ the following expression is given:

$$\Phi_i(x) = \left[1 - \exp(-\mu^b_{abs} \cdot x)\right] \tag{21}$$

where: μ^b_{abs} is the linear photon energy absorption coefficient in body at energy E_{eq} in cm^{-1}.

For the case when we use mean chord, instead of chord distribution, in the object, equation (21) can be used to derive (using Equation 20):

$$D_b = \frac{K_a \cdot \left[1 - \exp(-\mu_{abs}^{b} \cdot \bar{x}_b)\right]}{\mu_{abs}^{air} \cdot \rho_b \cdot \bar{x}_b} \tag{22}$$

For small objects, i.e. when $\bar{x}_b \to 0$, $D_b \to K_a \cdot \frac{\mu_{abs}^{b}}{\mu_{abs}^{air}}$, and for very large objects, i.e. when $\bar{x}_b \to \infty$, $D_b \to 0$.

Figure 5 shows the results of a comparison between the ratio of the average absorbed dose in tissue-equivalent sphere with a radius of 15 cm to kerma in free air (D_{sp}/K_a) calculated in accordance with formula (22) and those calculated by Monte-Carlo method [Hohlfeld & Groswendt, 1981]. As can be seen, even when we use an average chord value in the calculations, the results of the 'exact' method and those from formula (22) do not differ from each other by more than 10% in the energy range from 0.02 to 1.2 MeV.

The relationship between the initial energy of monoenergetic photons, E_0, emitted by the source in an infinite air volume and the average energy of equilibrium spectrum E_{eq} incident on the body are given in Table 3.1.

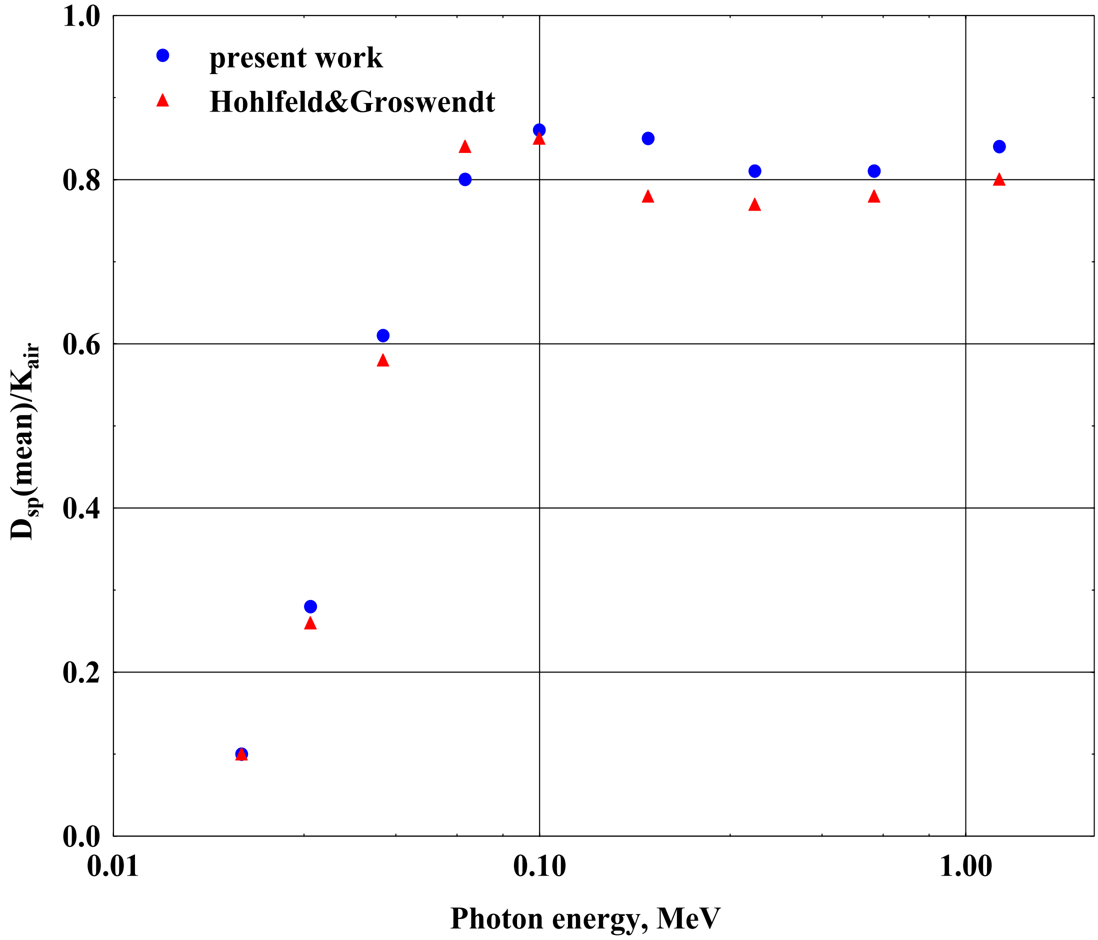


Figure 5. *Energy dependence of the conversion factor D_{sp}/K_z from the kerma in free air to the mean absorbed dose within the sphere (r = 15cm): circle – calculations by formula (22); triangles – Monte Carlo calculations of Hohlfeld & Groswendt [1981].*

Table 3.1. *Initial energy of monoenergetic photons E_0 emitted by the source in infinite air and average energy of equilibrium spectrum E_{eq} incident on the body*

E_0, MeV	*E_{eq}, MeV
0.010	0.010
0.015	0.015
0.020	0.020
0.030	0.029
0.050	0.043
0.10	0.067
0.20	0.10
0.50	0.18
1.0	0.32
1.5	0.46
2.0	0.61
4.0	1.20

*Calculated by T. Dillman [Dillman, 1974].

Is the approximation of an equilibrium spectrum valid for calculation of the ratio (D_{sp}/K_r) at the air/soil interface? To answer this question we calculated the energy distribution of air kerma from a plane isotropic source at the air/soil interface for the primary energies of photons of 0.1 and 3 MeV (Fig. 6 and Fig.7). Average energies of equilibrium spectrum with the primary energy of photons of 0.1 MeV were 0.09 MeV and 0.08 MeV at the air/soil interface and at a depth of 20 cm in soil, respectively. These do not change with an increase in soil depth. Average energies of equilibrium spectrum with the primary energy of photons of 3 MeV were 2.2 MeV and 1.1 MeV at the air/soil interface and at a depth of 20 cm in soil, respectively. At a depth of 50 cm in soil, this value falls to 0.9 MeV which corresponds to the energy of the equilibrium spectrum in soil. Therefore, for a source with a primary energy of photons of 0.1 MeV, the average energy of spectrum changes slightly (from 0.09 MeV to 0.08 MeV) for the conditions of exposure considered and the energy of equilibrium spectrum differs only slightly from the value in air (0.067 MeV). For a source with the primary energy of photons of 3 MeV, the average energy of spectrum decreases from the soil surface to a depth of 50 cm by more than a factor of 2. At a depth of 50 cm, the energy of equilibrium spectrum in the soil is practically identical to that in air. Nevertheless, in the energy range from 0.1 MeV to 3 MeV, the ratio of absorbed dose in organism to kerma in free air varies little in response to a change in energy. Moreover, the ratio exhibits a fairly insubstantial changes in reponse to changes in source geometry. Fig. 8 illustrates the ratio of effective dose for a human phantom to kerma in air depending on the energy of the source for two distinct configurations/geometries of exposure: for a plane source at the air/soil interface and semi-infinitive volume source with the homogeneously distributed activity in soil. As can be seen from the Figure, for such extreme cases (from the geometrical point of view) variations in the ratio considered do not exceed 10% for the energy range of interest, i.e. 0.1-2.0 MeV.

This allows us to use the conditions of exposure in an infinite air medium for calculations of the ratio of absorbed dose in organism to the kerma in free air without introducing additional considerable uncertainties.

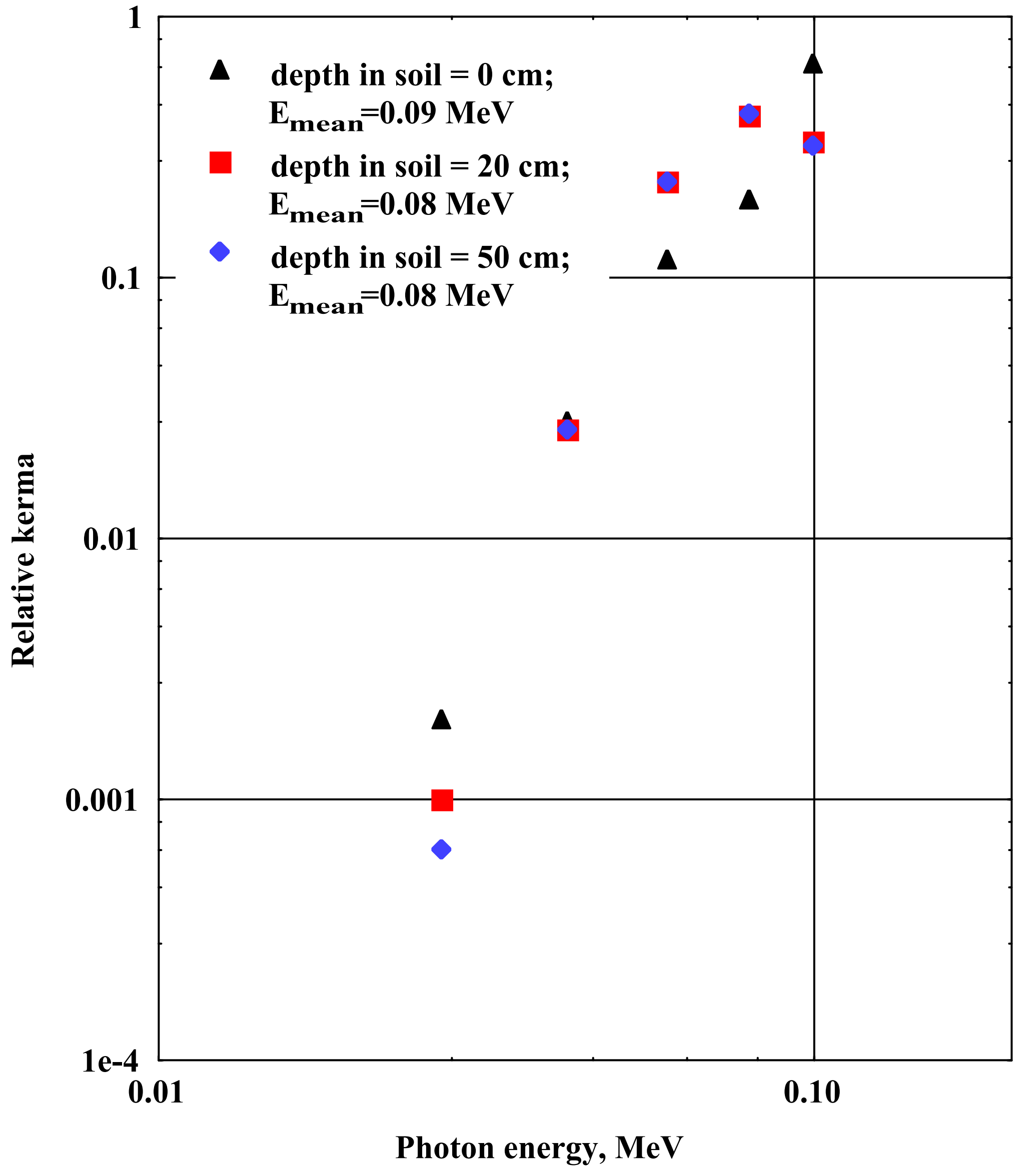


Figure 6. *Energy distribution of air kerma at the surface and at the depth 20 cm and 50 cm in soil for monoenergetic plane source with the energy of 0.1 MeV at the air/soil interface. The total kerma is normalized to unity.*

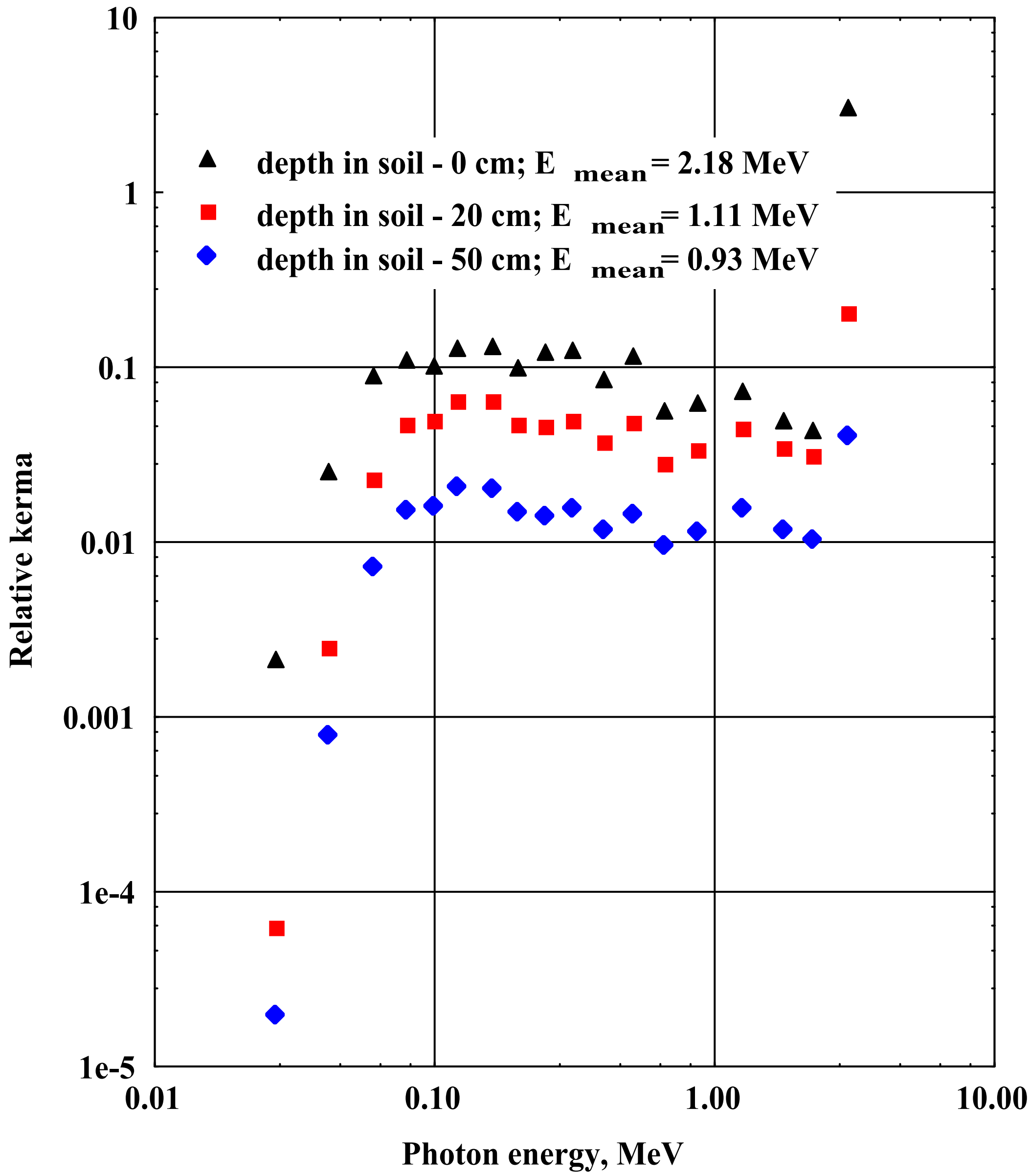


Figure 7. *Energy distribution of air kerma at the surface and at the depth 20 cm and 50 cm in soil for monoenergetic plane source with the energy of 3 MeV at the air/soil interface. The total kerma is normalized to unity.*

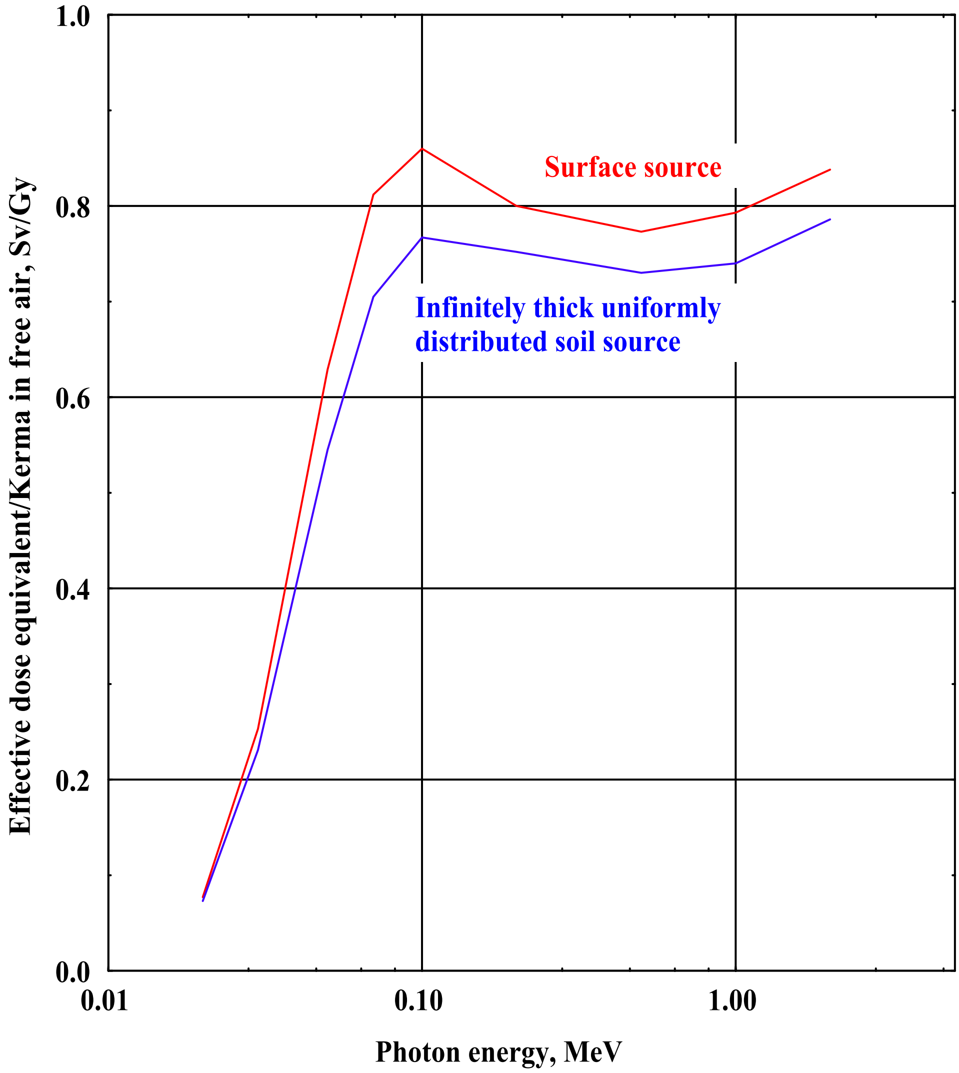


Figure 8. *The ratio of effective dose equivalent to the air kerma 1 m above the air/soil interface for an infinite plane source at the interface and infinitely thick uniformly distributed soil source [Eckerman & Rymon, 1983]*

3.4. Results and their validation

Estimation of absorbed fraction for monoenergetic photon sources uniformly distributed in organisms

Brownell *et al*. (1968) and Ellet & Humes (1971) used Monte Carlo methods to calculate absorbed fractions for internally distributed photon emitters in selected geometries. The methods adopted rigorously consider the contribution to the absorbed dose from both direct and scattered radiation. Tables are provided wherein absorbed fractions for various energy (ranging from 0.02 MeV to 2.75 MeV) and mass (ranging from 1 g to 200 kg) combinations are presented for the case of uniform distributions of activity in ellipsoids and small spheres. For the ellipsoid, principle axes are in the ratio: 1/1.8/9.27 (Brownell *et al.* (1968)) or 1/3/8 (Ellet & Humes (1971)). The density of the tissue-equivalent material used in all calculations is unity.

Using exactly the same energy-mass combinations as input data, a selection of the relevant activity distribution (i.e. "interior source") and the correct dimensions for the geometries, we calculated the absorbed fractions with the help of the above described algorithm. Four masses were selected for the uniform distribution of activity in ellipsoids, namely 0.001, 0.1, 2 and 70 kg, and four masses were selected for the uniform distribution of activity in spheres, namely 0.001, 0.1, 1 and 5 kg. In each case, the actual dimensions of the geometry had to be calculated from the mass, an assumed density of 1000 kg m^{-3} (or 1 kg/litre - water density).

The outputs from calculation using spheres of masses 0.001 and 0.1 kg, 1 and 5 kg are presented in Figures 9-10, respectively. Results of this comparison show that the greatest differences in values of absorbed fraction are observed for sphere of the smallest size (1 g). In this case calculations by the present model are on average 30 % higher than the results derived using the Monte Carlo method [Ellet and Humes (1971)]. For spheres with masses from 0.1 up to 5 kg, differences, on average, do not exceed 12 %. The maximum difference in values of absorbed fraction derived using the two methods was 37 % (mass of sphere 1 g and $E\ \gamma = 0.66$ MeV).

The outputs from calculation using ellipsoids of masses 0.001 and 0.1 kg, 2 and 70 kg are presented in Figures 11-12 correspondingly. Results of comparison show the same tendency as well as in the previous case. The greatest differences in values of absorption fraction are observed for the smallest size ellipsoids (1 g). In average they are 22 %. For ellipsoids in weight from 0.1 up to 70 kg the differences on the average do not exceed 6 %. In the worst case, the absorbed fraction, derived from the present model is no more than 47 % higher than similar value derived using the Brownell et al. methodology (this relatively poor fit was observed for a mass of 2 kg ellipsoid at an energy of 0.08 MeV).

In general, the absorbed fractions are non-linear functions of target size and energy of radiation and express a wide range covering several orders of magnitude. Their values decrease in the energy range from 20 to 100 keV by a factor of 3–7 for small organisms, whereas it is relatively constant between 100 keV and 1 MeV. Beyond energies of 1 MeV the decrease of the absorbed fraction values with energy is sharper.

Moreover, the mass and shape of a geometrical figure (at identical mass) appreciably influences the values of absorbed fraction. The value of the absorbed fraction for a sphere can be 1½ times that of an ellipsoid (with dimensions as defined above) of identical mass for photon energies less than 0.1 MeV.

Thus, for the case of uniformly distributed activity in spherical and arbitrarily selected ellipsoid geometries, the absorbed fraction derived from the present model in the energy range 0.02 – 3 MeV and the mass range 0.001 – 70 kg correspond very closely to those derived from an established methodology that employs Monte Carlo simulations.

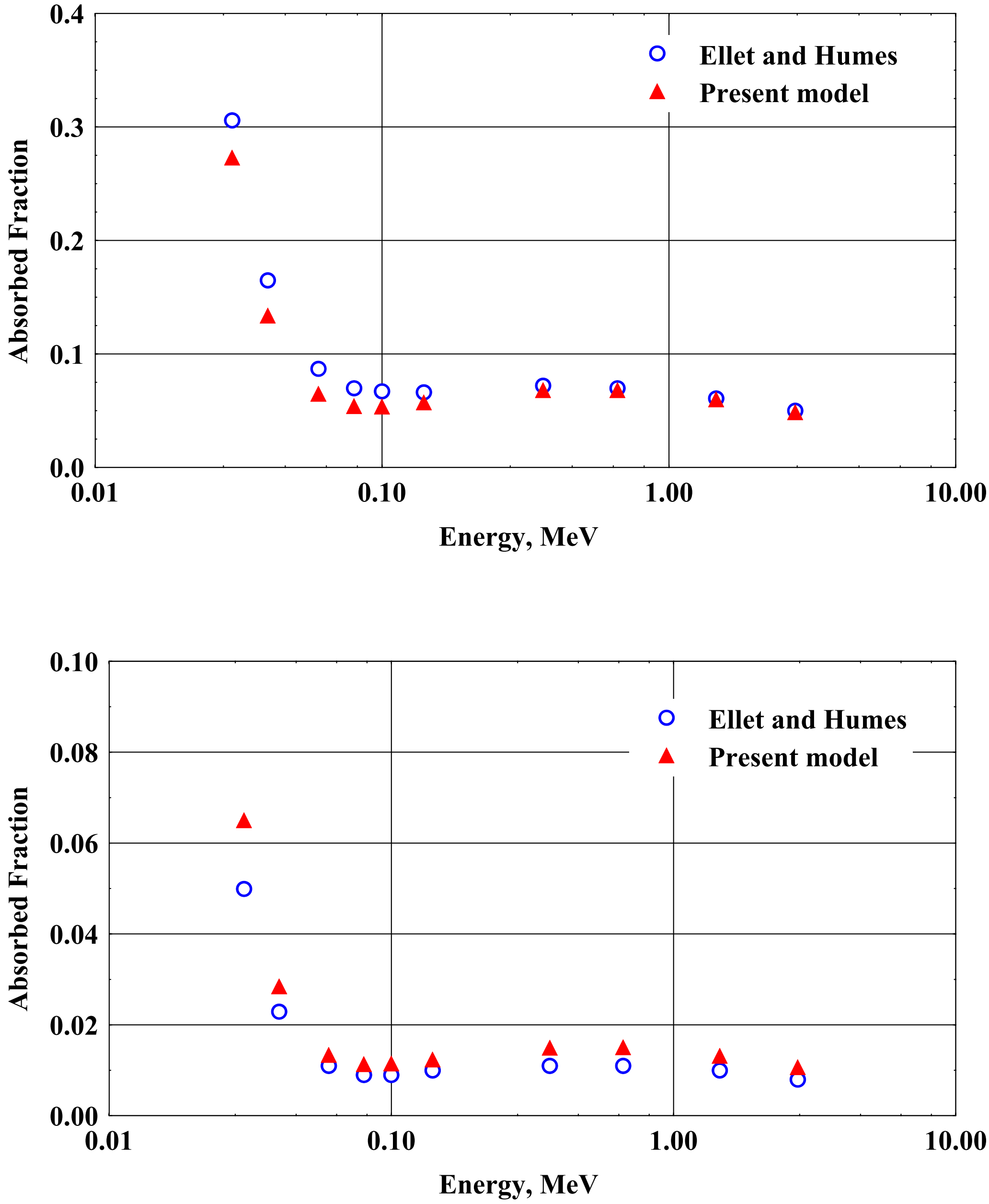


Figure 9. *Absorbed fraction versus energy derived from the 2 models for a 0.1 kg (upper figure) and 0.001 kg (lower figure) spheres*

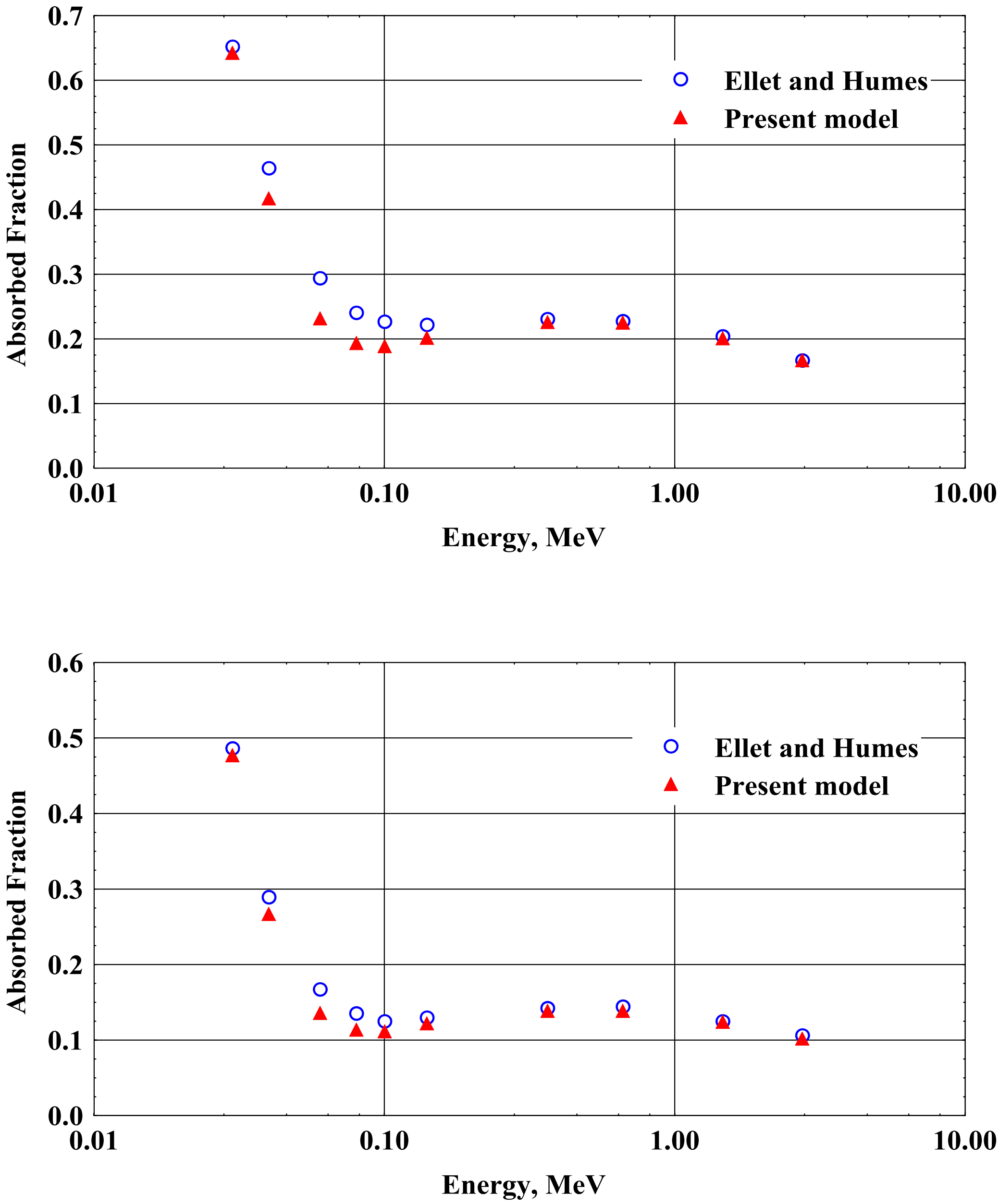
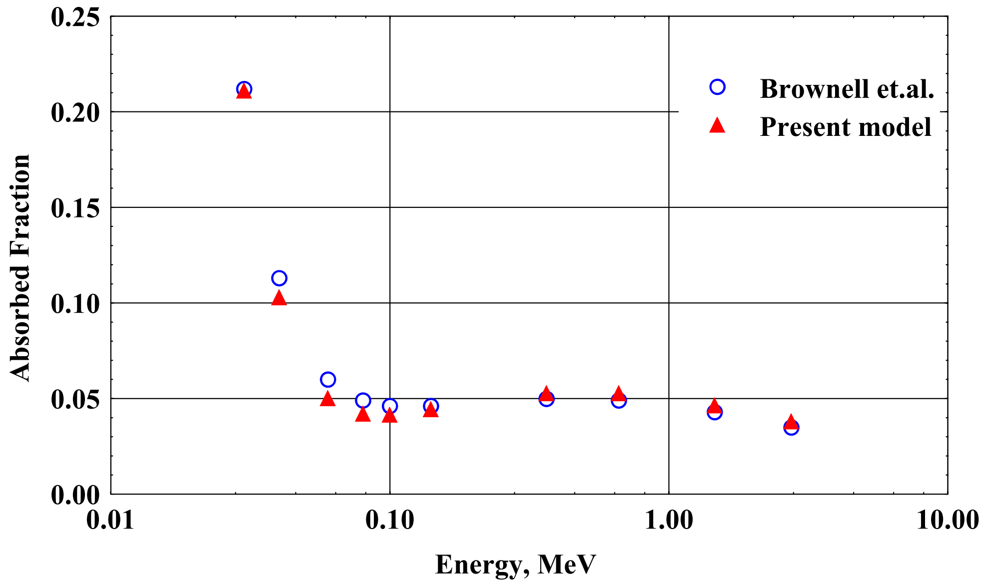


Figure 10. *Absorbed fraction versus energy derived from the 2 models for a 5 kg (upper figure) and 1 kg (lower figure) spheres*



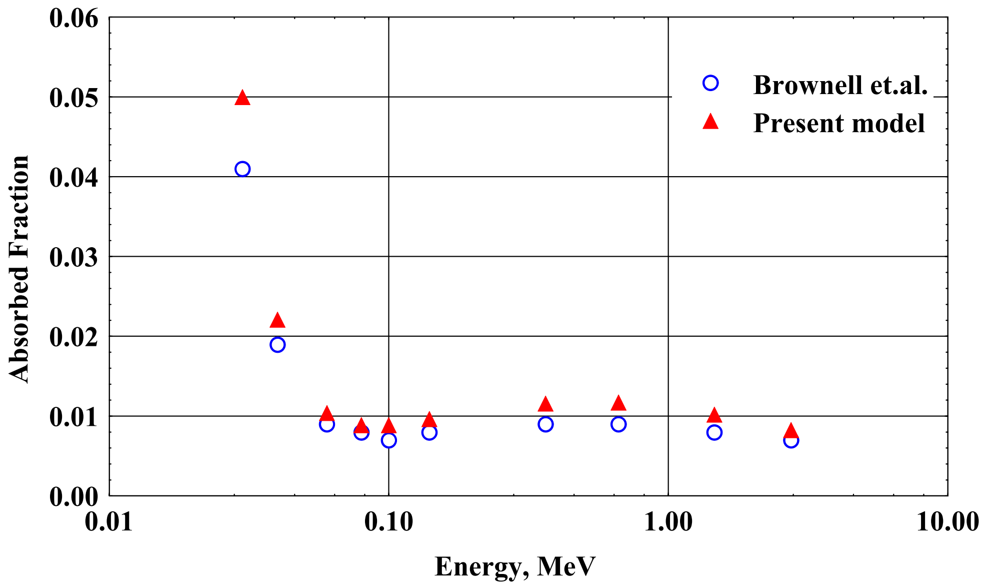
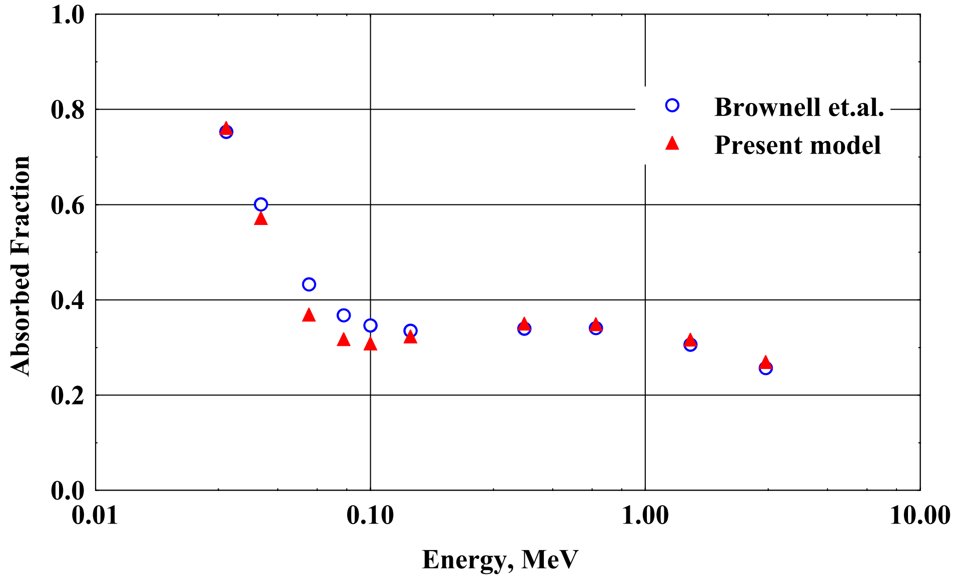


Figure 11. *Absorbed fraction versus energy derived from the 2 models for a 0.1 kg (upper figure) and 0.001 kg (lower figure) ellipsoids*



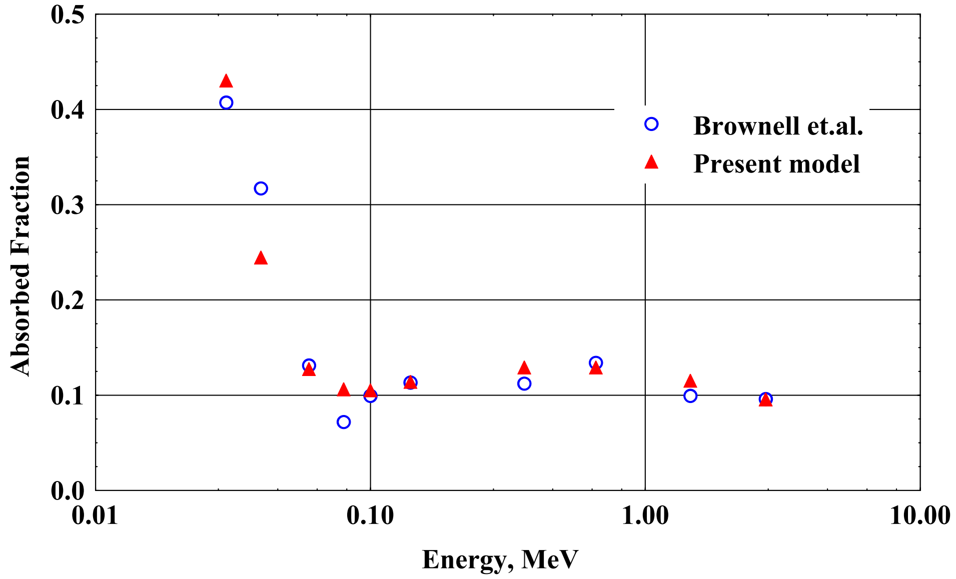


Figure 12. *Absorbed fraction versus energy derived from the 2 models for a 70 kg (upper figure) and 2 kg (lower figure) ellipsoids*

For β particles energies below 100 keV, the absorbed fraction is nearly 1 even for very small organisms. The range of β particles in soft tissue increases from 150 µm for 100 keV electrons to 15 mm for 3 MeV electrons. The absorbed fraction is close to unity if the diameter of the target is well above the range of β particles. The absorbed fraction of β particles becomes considerably smaller than 0.5 only in cases where targets are small and energies are high.

Example of comparison of absorbed fractions values for β particles calculated in the present report and in Copplestone *et al*. [2001] are given in Figure 13. It is notable that Copplestone *et al*. [2001] used the data of Berger (1971) on dose distribution around point sources of β particles in their calculations.

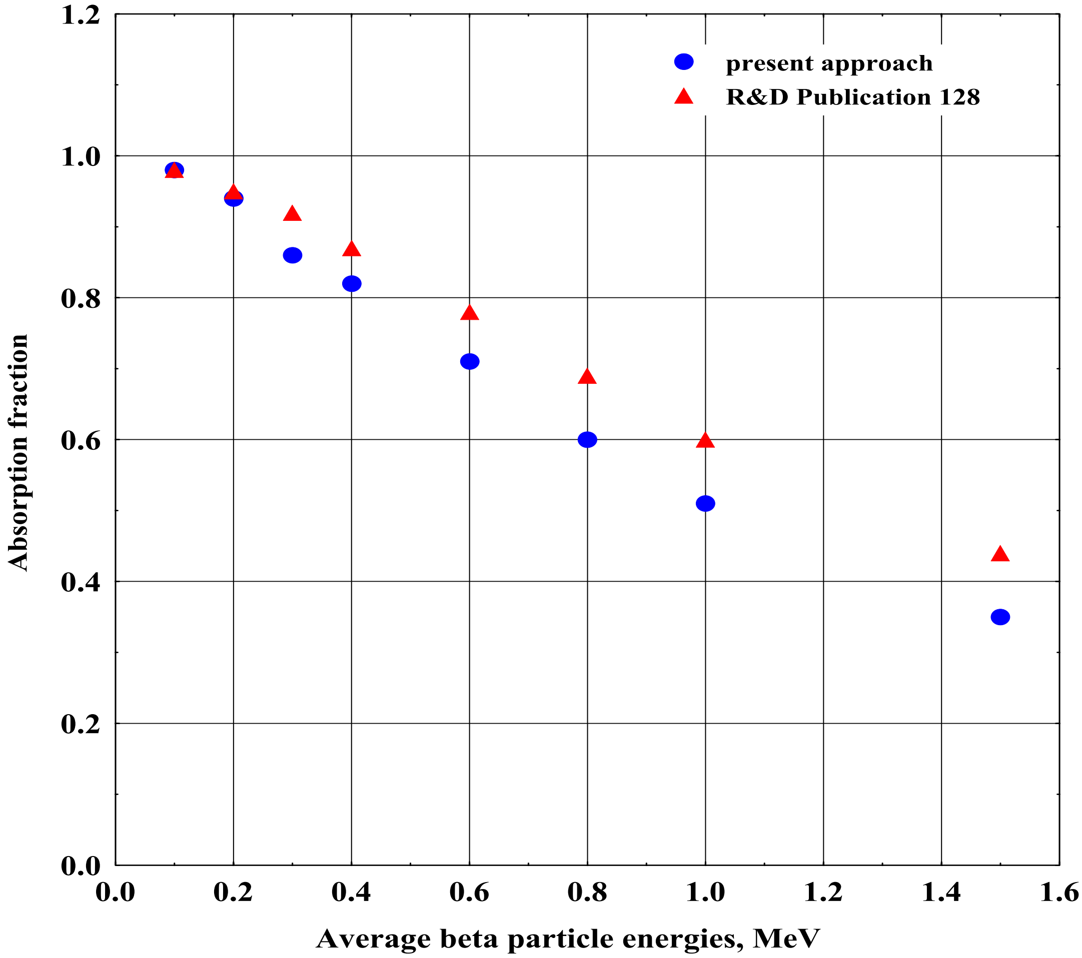


Figure 13. *Comparison of absorbed fractions for internally incorporated β emitters in a benthic mollusc (ellipsoid with axis 2.5 ×1.2 × 0.62 cm) calculated by two methods (present method and R&D Report 128 - Copplestone et al. [2001]).*

Estimation of absorption fraction for monoenergetic photon sources uniformly distributed in various organs of the organisms

The results of Monte Carlo calculations in the mathematical human phantom “MIRD–5” were used as data to verify calculations of relative absorbed fractions in bodies with internal organs [Snyder, *et al*., 1969]. The organs, or their sections in the MIRD-5 phantom, were modelled by “rotation” bodies (cylinders, ellipsoids, cones or parts of volume of these bodies). The diagram of voxels based on a mathematical description of the MIRD-5 phantom is presented in Figure 14.

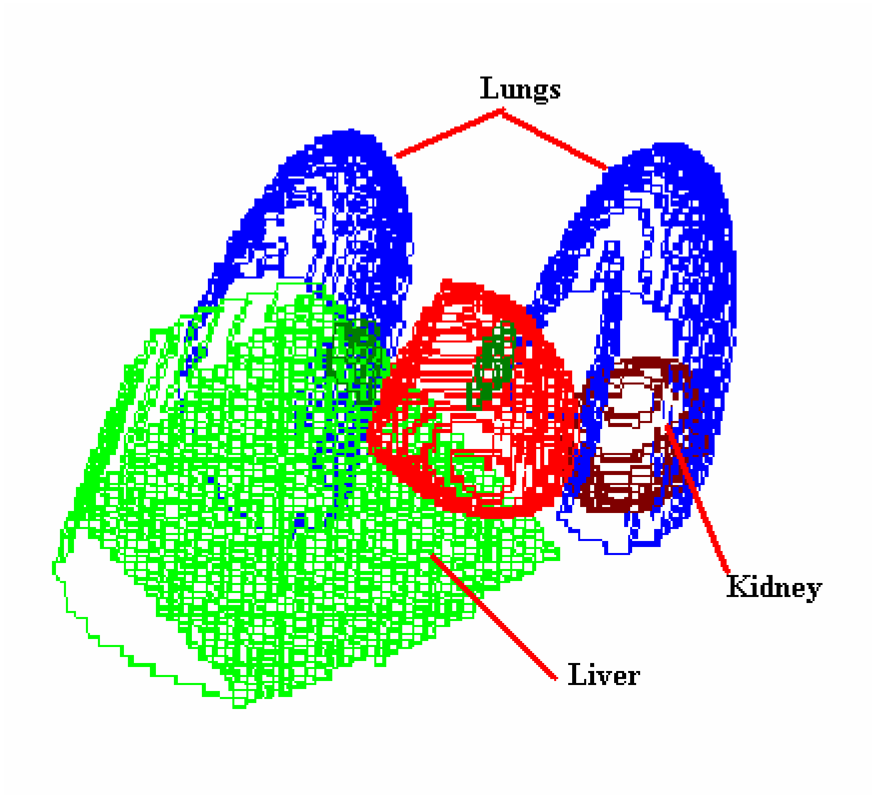


Figure 14. *The part of human phantom with internal organs*

Calculations were performed for four organs - liver, spleen, kidneys and pancreas and four energies of gamma radiation 0.05, 0.1, 1, and 4 MeV. In Tables 3.2 and 3.3, results of comparisons for two energies of gamma radiation 0.1 and 1 MeV are presented. Each table constitutes a square matrix 4 × 4. Along the diagonal, the values of absorbed fractions are given for the cases when an organ is both the source and the target. In the others squares forming the tables, values of relative absorbed fractions are specified. They are defined as the ratio of energy emitted by a source organ to the energy absorbed in a target organ.

Table 3.2. *Absorption fractions for monoenergetic photon source with energy 0.1 MeV uniformly distributed in four organs of MIRD-5 phantom calculated by resent approach and Monte Carlo (in brackets) method [Snyder et al., 1969]*

Source	Target			
	Liver	Spleen	Kidneys	Pancreas
Liver	0.14 (0.16)	0.00071 (0.00061)	0.0042 (0.0044)	0.0014 (0.0011)
Spleen	0.0063 (0.0072)	0.063 (0.071)	0.0069 (0.0095)	0.0048 (0.0047)
Kidneys	0.027 (0.028)	0.0053 (0.0061)	0.058 (0.066)	0.0018 (0.0017)
Pancreas	0.033 (0.033)	0.011 (0.013)	0.0061 (0.0073)	0.041 (0.038)

Table 3.3. *Absorption fractions for monoenergetic photon source with energy 1 MeV uniformly distributed in four organs of MIRD-5 phantom calculated by resent approach and Monte Carlo (in brackets) method [Snyder et al., 1969]*

Source	Target			
	Liver	Spleen	Kidneys	Pancreas
Liver	0.14 (0.14)	0.00053 (0.00063)	0.0032 (0.0034)	0.0011 (0.00086)
Spleen	0.0047 (0.0065)	0.073 (0.070)	0.0059 (0.0076)	0.0046 (0.0037)
Kidneys	0.0208 (0.0218)	0.0046 (0.0046)	0.067 (0.067)	0.0013 (0.001)
Pancreas	0.026 (0.022)	0.01 (0.01)	0.0046 (0.0055)	0.049 (0.040)

In total, for comparison of the two methods 64 values of absorbed fraction were calculated for monoenergetic photon sources with energies 0.05, 0.1, 1 and 4 MeV. The average value of the ratio, derived by dividing the results of one method by the results of the other method, was 1.02 with minimum and maximum values 0.71 and 1.54, respectively.

Kerma at the air/soil interface

The calculated results for air kerma rate 1 m above the air/soil interface according to the formulae 12 - 13 were compared to those derived using a Monte Carlo method for a plane isotropic source at a depth of 0.5 $g \cdot cm^{-2}$ [Jacob *et al.*, 1990] and for exponential (β = 0.33 and 3.33 $cm^2 \cdot g^{-1}$) activity distribution in soil [ICRU 53]. In Tables 3.4 and 3.5, the results of calculations by both methods are presented. The comparison did not show any differences greater than 20% for all geometries of sources.

Table 3.4. *Comparison of kerma rate calculated according to the formula (12) from a plane isotropic source located in soil on the depth of 0.5 $g \cdot cm^{-2}$ with the results of Monte Carlo calculations from [Jacob et al., 1990].*

Radionuclide	Kerma rate, $(nGy \cdot h^{-1})$ per $(kBq \cdot m^{-2})$	
	Present work	P. Jacob et.al. [ ]
^{129}I	0.093	0.076
^{131}I	1.22	1.18
^{134}Cs	4.89	4.68
^{137}Cs+^{137m}Ba	1.78	1.72
^{241}Am	0.083	0.069

Table 3.5. *Comparison of kerma rate calculated according to the formula (13) from an exponential distribution of source in soil with the results of Monte Carlo calculations from [ICRU 53].*

Radionuclide	Kerma rate for β = 0.33 cm^2 g^{-1}, ($nGy \cdot h^{-1}$) per ($kBq \cdot m^{-2}$)		Kerma rate for β = 3.33 cm^2 g^{-1}, ($nGy \cdot h^{-1}$) per ($kBq \cdot m^{-2}$)	
	Present work	ICRU 53 [ ]	Present work	ICRU 53 [ ]
^{129}I	0.038	0.033	0.16	0.15
^{131}I	0.81	0.82	1.31	1.39
^{134}Cs	3.28	3.27	5.21	5.50
^{137}Cs+^{137m}Ba	1.19	1.20	1.90	2.03
^{241}Am	0.042	0.042	0.11	0.14

4. Description of the computer program

On the basis of the algorithm described above, the computer program **DOSES3D** was developed. It allows doses of external (β particles, photons) and internal exposure (α, β particles, photons) in biological objects of the any size and form to be calculated. In theory, doses can be calculated for any radionuclide but, in the present version of the program, initial data for a limited number of 42 radionuclides have been used. The time of calculation for a selected variant is less than 30 seconds for Pentium 200 MHz computers (or better). A brief description of the program is presented below.

Program **DOSES3D** is the software which implements the mathematical methods discussed above. Visually it is presented as three separate modules, entitled **"MAIN", "GEOMETRY"** and **"NUCLIDES".**

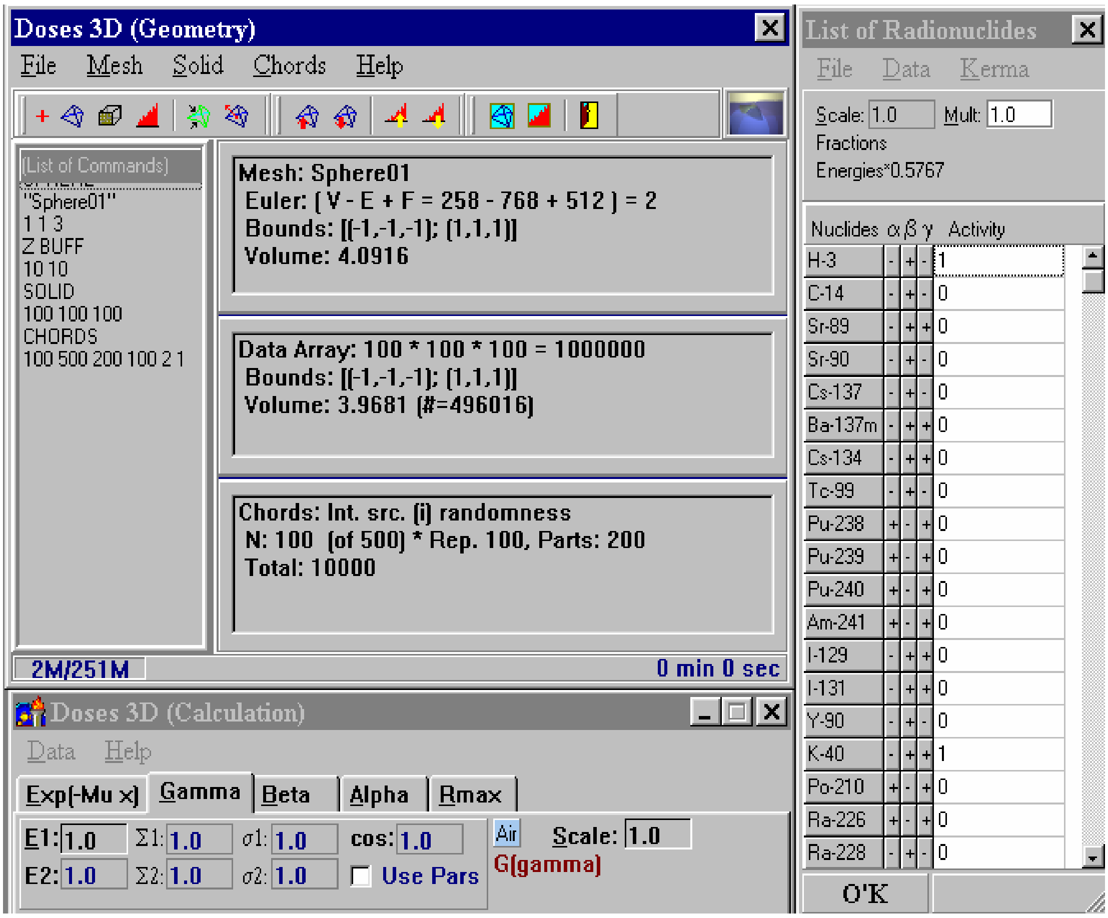
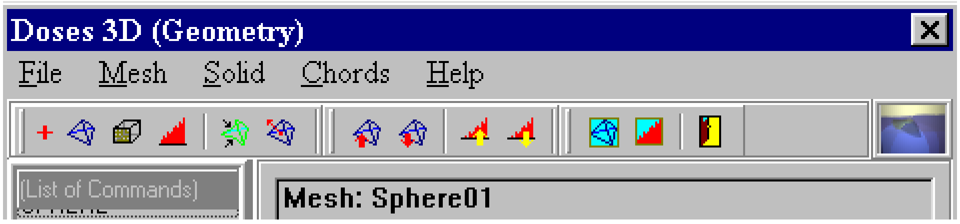


Figure 15. *Screen dump from Dose-3d : overview*

The “**GEOMETRY**” module (Figure 16) contains all functions necessary for creation of geometrical models (phantoms), and preparation of chords/segments arrays used for calculation of doses and absorption fractions. It is possible to create a mesh, save it as a file, read it from a file, create an array of voxels, calculate distributions of chords/segments with different kinds of randomness to use in subsequent dose calculation.



“GEOMETRY” form

Figure 16. *The “**GEOMETRY**” module of Dose-3D*

4.1 Note about single/multi object modes

The program can operate with single or multiple objects. In reality, two different programs exist. The program dealing with the single-object model is saved for compatibility purposes. Work with a single object may also be performed in multi-object mode by defining the number of organs, “n”=1. Essentially, the multi-mode is considered as the main platform for work with the program both for bodies with and without organs. Activation of this newer version of the program can be performed using the “**Allow Multi”** option from the “**Mesh”** menu or by loading any file (mesh, solid, histogram, script) prepared in such a mode. After activation, the program works in such a mode until exit. Return to the older, single-object mode is not accepted after activation of newer multi-mode version.

Files with meshes have the same extension (MES) for both modes, but programs DOSES3D and SHOWMES distinguish between modes from information about the internal structure. Below, an example of two objects representing SHOWMES viewer included in package distributed with DOSES3D are presented (Figure 17).

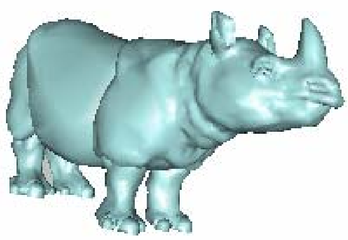
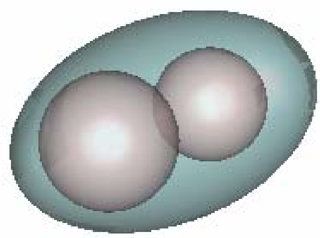
	
Single-object mesh (rhino.mes) Prepared using DXF2MES converter	Multi-objects mesh (sph3.mes) Prepared using DOSES3D

Figure 17*. To objects presented using th SHOWMES viewer within DOSES3D.*

The **"MAIN"** module is used for simpler calculations of absorbed fractions for specified radiation types, i.e. gamma or alpha ray with a particular energy, beta ray with a (continuous) spectra described by given parameters.

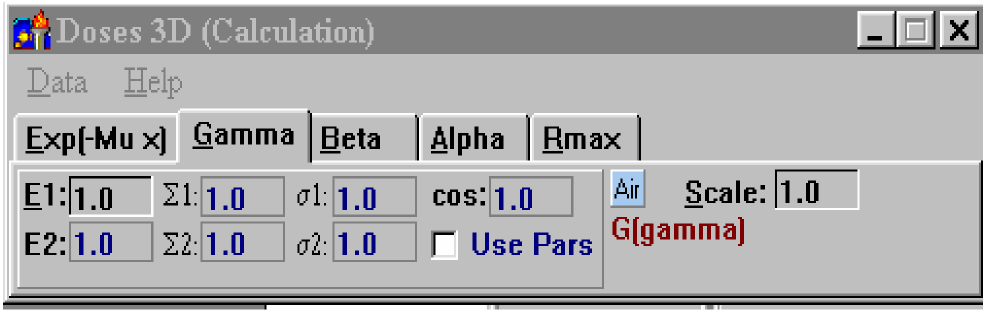
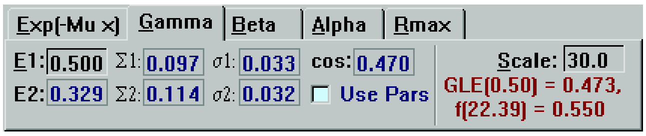


Figure 18. *"MAIN" module*

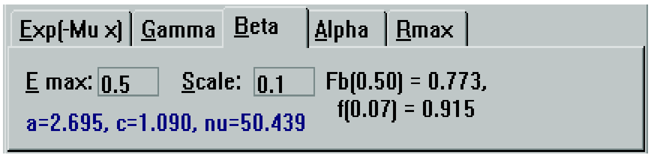
The module consists of a tab-delineated panel with five different tabs:

- "**Exp(- Mu x)**" - simplest analytical model for gamma rays with given absorption coefficient
- **Gamma** - model with two gamma rays groups described above
- **Beta** - model with Levinger formula for spectra
- **Alpha** – model of energy loss in continual slowing down approximation
- "**R** $_{\mathbf{max}}$" - simplest analytical model for alpha rays with linear absorption with given depth.



The Tab for gamma ray parameters normally requires the energy of primary gamma rays (E1), because the program automatically calculates all other parameter necessary for running the two groups of model described earlier. However, if necessary, it is possible to enter or correct any parameter: Σ1 – attenuation coefficient for the first group; σ1 – absorption coefficient for the first group; E2 – energy of first scatter photons (second group); Σ2 – attenuation coefficient for the second group; σ2 – absorption coefficient for the second group; cosine of scattering angle (if necessary). Access to these parameters is provided by the "**Use Pars**" check box.

The result of calculation is presented as *GLE*(*E*)=*AF*, f(*l*)=*Ab*, where *GLE* is a non-essential abbreviation for the function used in the calculation; *E* is energy in MeV; *AF* is absorbed fraction; *l* is the average chord in the object; and Ab is the absorbed fraction on the average chord, i.e. *Ab* is approximation of value *AF* using a crude method which utilises only an average chord instead of a full chord distribution. This value is presented simply in order to demonstrate the calculation error associated with a more rough approximation.



The Tab for beta rays requires only input of the maximal energy of the beta spectrum for calculation. Result is represented in similar form. Values of a, c, nu are coefficients in Loevinger formula.

The Tab for alpha rays uses the energy of alpha rays for calculation. The result again has the same form as described above. R_{max} is maximal range of α particles.

The "**NUCLIDES**" module is used for calculation of all doses for different radionuclides and mixtures of radionuclides. The program reads files with a list of nuclides and activity of each nuclide in Bq kg^{-1}. It is also possible to enter or change the activity in the list displayed by the form. Following this the program uses tables with parameters of decay for each transformation (*i*) alpha, beta, and gamma radiation [ICRP, 1983] and calculate dose rate in μGy h^{-1} for a specified radionuclide using the formula:

$$\dot{D} = 0.576 \cdot A \cdot \sum_i \Phi_T(E_i) \cdot E_i \cdot y_i$$

where: Φ_i is absorption fraction, E_i is energy of each kind of radiation in MeV, y_i is yield of photon or β or α particles of energy E_i per disintegrations, and A_i is concentration of radionuclide in Bq kg^{-1}. The Absorbed fraction is calculated by the program using chord distributions (histograms).

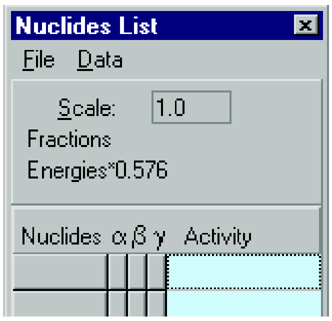


***Figure 19.** "**NUCLIDES**" form*

4.2 Calculation of external doses at the air/soil interface

The Method described above used an approximation of an infinite contaminated medium. Such a calculation can be sued to derive internal doses for an object, i.e. organism target,located within a medium with similar density (water, soil).

As already described above, for objects located at the air/soil interface, the values of kerma in free air, as oppose to radionuclide concentrations, are used as initial data. Let us consider the gamma tab with extended information.

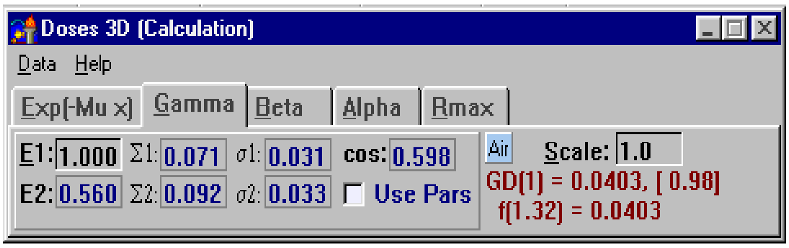


Figure 20. *DOSES3D modleu for calculating external doses*

The New data logo is $GD(E)=AF$, (F_{REL}), $f(l)=Ab$, where the new number F_{REL} is the ratio of absorbed dose in the object to the kerma in free air. The new parameter used for calculation of the absorbed dose is $D = F_{REL}\,K$, where K is kerma in free air. For kerma values, calculations used specific activity of radionuclides (surface, volume, mass) as initial data. The value of kerma in free air (without the presence of the object) for a unit specific activity is calculated by the program for a given geometry (configuration). The approach employs a "kerma calculator" fro this purpose. In the present version of the program the following source-target configurations are used:

- The source is a semi-infinite absorbing medium (appropriate for natural radionuclides in soil); the target is at the soil/air interface;
- The source is a thick layer (appropriate for artificial radionuclides in soil/sediment); the target is at the soil/air or sediment/water interface;
- The source is a thin layer at a given depth in soil (appropriate for freshly-deposited artificial radionuclides); the target is at the soil/air interface;
- The source is a thin layer at the soil/air interface; the target is at a given depth in soil (up to 100 cm) or at a given height in air (up to 30 m) (option "Above and Underground").

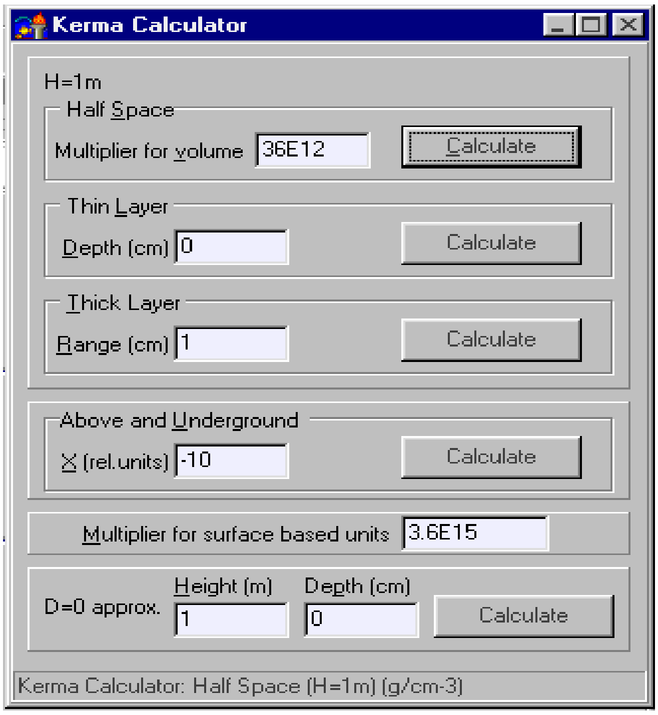
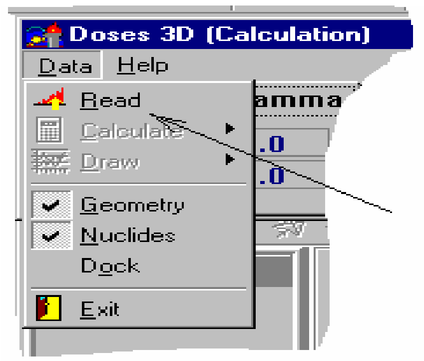


Figure 21. DOSES3D "Kerma calculator"

Examples

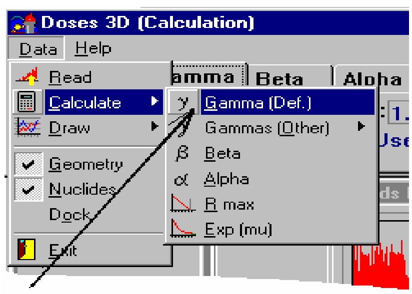
By way of example, let us consider a dose calculation for a case, where the histogram with chord distribution for given body has already been prepared.



In this case, "SphereInt.hst" or some other file with histogram already exist in your DOSES3D folder. See example of preparation of such histogram file below.

1) Open the Data Menu and choose Read.

2) Choose the File "SphereInt.HST" and,if everything is OK, the window with histogram will appear.



3) Open the Data Menu. Choose Calculate [it becomes enabled now] and Gamma (Def.) submenu.

Output of Calculation (Gamma)

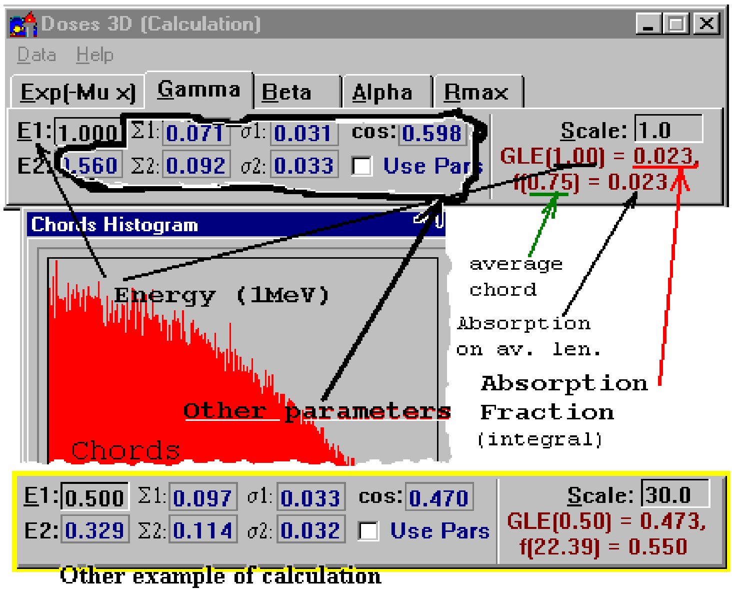
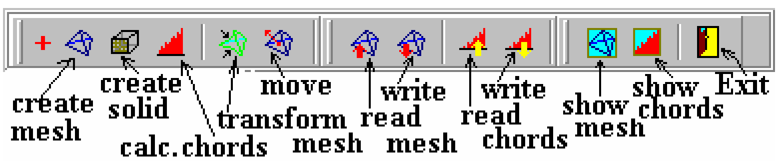


***Figure 22.** Example of results from DOSES3D*

An example of results from a calculation are presented in Figure 22. In order to calculate the gamma absorbed fraction, it is possible to select two main parameters: energy and scale. First energy of 1 MeV was used and a default scale (1). Because the chords were calculated for 1cm sphere, the absorbed fraction is small. It should be noted that it is also possible to re-scale the object without completly recalculating the chords. For example, looking at the (yellow) border at the bottom of Figure 22, a scale of 30 (30cm sphere) and energy of 0.5MeV were used. Similar calculations can be performed for other radiation types (alpha, beta)

How to prepare mesh, body and histograms

Below, an example of how a geometry is constructed and manipulated in order to prepare chord distributions, for subsequent dose calculation, is presented.



Toolbar

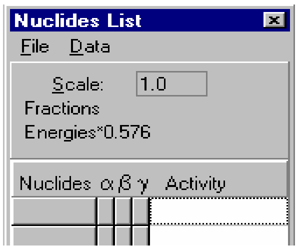
1) Press *Create Mesh* button on Toolbar (or *Create* in *Mesh* menu) Choose *Sphere* and press OK in Sphere Dialog to accept default parameters (512 faces polygon approximation and radius 1.0)

2) A mesh is created. Now *Create Solid* button on Toolbar (or in *Solid* menu) is enabled. Press it. In Solid Dialog again press OK to accept default parameters. (100x100x100 array is only 2MB memory, it is enough for demonstration. 200x200x200 is 16MB and 400x400x400 uses already 128MB RAM – in this case ZBuff should be 40x40 for best speed)

3) Press *Calculate* button on Toolbar (or in *Chords* menu) – it became enable if previous operations are successful. Press OK in Chords Dialog to accept default parameters. (**Repeat: 100** x 100 chords = 10 000. It is usually quite fast to choose 1000 for 100 000 chords. **N Parts: 200** is maximal amount of bins in the histogram. Interior source is default). Wait until the end of calculation of chord distribution or press **STOP** (this button appears during calculation). It is possible to save the distribution in a file for future use.

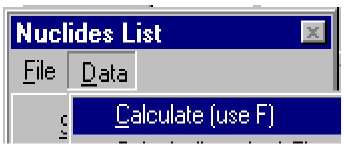
Everything is now ready for dose calculation.

Calculation for table with nuclides:

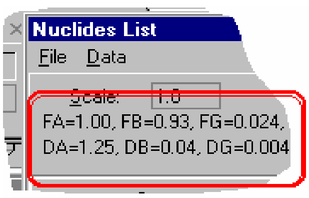


Before calculations some chord distributions should be loaded from a file via **Doses** or **Geometry** forms (see Simple Example of Calculation) or prepared via **Geometry** form (see **How to prepare mesh, body and histograms**).

It is necessary also to load some file with nuclides list via **File | Read** menu. The default file is **MixAll.mix**. There are also separate files with natural (mixnat) and artificial (mixart) nuclides.



Enter all necessary values of specific activity in Bq kg^{-1}. If necessary, change the scale. Click menu **Data | Calculate (use F)** to perform calculation of internal dose rate for given mixture (calculation of external dose uses next menu item **Data | Calc. Indirect (w 1-F)**).



Results of calculation of absorption fraction (FA,FB,FG in relative units) and doses (DA,DB,DG in μGy h^{-1}) for alpha, beta and gamma radiation respectively are presented on the top panel.

5. Conclusions

A methodology has been developed for the purpose of calculating instantaneous dose-rates in the bodies of reference organisms from both internal and external radiation sources. The approach employs the use of chord distributions. The results of these methods have been examined and verified using existing, established methodologies, .e.g. Monte Carlo approaches. Agreement between these differing approaches has been shown to be close leading to the conclusion that the methodology chosen is appropriate and robust.

A computer code has been developed using the described algorithms. The model has an inherent versatility that allows the user to select a wide range of geometry shapes and sizes and calculate absorbed fractions for a large energy range and various radiation types. It has therefore been an invaluable tool in deriving the absorbed fractions that were subsequently used to calculate radionuclide-specific dose conversion factors for uniformly distributed radionuclides within the bodies of reference organisms. For the specific case of seal, account has also been taken of internal organs for which appropriate DCFs have been derived. In addition the model has been employed to calculate external DCFs for a selected set of representative contamination scenarios and specified target-source configurations. **These internal and external DCFs are presented in Appendix 1.**

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APPENDIX: RADIONUCLIDE-DEPENDENT DOSE CONVERSION FACTORS

The approach to wildlife dosimetry used in this document summarized in the Chapter 2 and focus on estimating the instantaneous radiation dose rate to exposed organisms. There is a direct correlation between the concentration of particular radionuclide in the tissues of an organism, or in the medium surrounding it, and radiation dose rate to the organism. Thus, the dose conversion factors (DCFs) represent the instantaneous dose rate per unit activity concentration of the radionuclide in an organism or in the environment.

DCFs for internally incorporated radionuclides. The dose rates delivered to organisms are evaluated from the concentration of each internally incorporated radionuclide. For each radionuclide data for the energy and yield of β particle, photon and α particle emissions have been extracted from the literature (ICRP, 1983). Radioactive daughter nuclides are included in the calculation of the DCFs if their half-lives are shorter than 1 day. Each organism is characterised by particular shape and dimensions. For each radionuclide and each target DCF_T^{int} values in Gy a^{-1} Bq^{-1} kg for β particle, photon and α particle emissions are calculated as:

$$\frac{\dot{D}}{A_{org}} = DCF_T^{int} = 5.04\times10^{-6} \cdot \sum_i \Phi_T(E_i) \cdot E_i \cdot y_i \qquad \text{(A1)}$$

where: $\dot{D}$ is the dose rate (Gy a^{-1});
A_{org} is the activity concentration in organism (Bq kg^{-1} w.w.);
E_i is the energy of component <i> of emitted radiation (MeV);
y_i is the yield of emitted radiation of energy E_i (dis^{-1});
$F_T(E_i)$ is the absorbed fraction in the target for energy E_i;
5.04×10^{-6} is the factor to account for conversions of MeV to Joules and seconds to years.

DCFs for external exposure. External DCF_T^{ext} from radionuclides (only β and γ components) present in soil or in water column are calculated using a variant of the simple formula for uniformly contaminated isotropic infinite absorbing medium:

$$\frac{\dot{D}}{A_{env}} = DCF_T^{ext} = 5.04\times10^{-6}\cdot\sum_i(1-\Phi_T(E_i))\cdot E_i\cdot y_i \qquad \text{(A2)}$$

where: A_{env} is the activity concentration in the environment in Bq kg^{-1} or Bq m^{-3}.

For a case of an organism exposed on the ground surface or at the sediment/water interface two-step method has been used. In a first step the kerma in corresponding location (for example, above the soil/air interface) was defined. In a second step the ratio of the dose in an organism and the kerma is calculated for the different organisms and radionuclides. The following exposure situations were defined:

- *External exposure for species living on the ground.* A planar isotropic source located at the depth 0.5 gcm^{-2} in the soil and semi-infinite volume source for artificial and natural radionuclides, correspondingly, were assumed.
- *External exposure for species living in the soil.* A uniformly contaminated infinite source for natural radionuclides (used formula (A2)) and planar isotropic source located at the depth 0.5 $g{\cdot}cm^{-2}$ in the soil for artificial radionuclides were assumed.
- *External exposure for aquatic species at sediment/water interface.* A volume source with a depth of 5 cm and semi-infinite volume source for artificial and natural radionuclides, correspondingly, were assumed.

Use of this expressions for DCF results in the calculation of absorbed dose with no weighting factors for radiation type applied, i.e. unweighted absorbed dose.

MARINE REFERENCE ORGANISMS

Type of organisms: Small fish

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Pelagic	Capelin(*Mallotus villosus*), polar cod (Boreogadus saida)	Polar cod	$15 \times 3 \times 1.5$	ellipsoid	35

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External	
				From water column, Gy a^{-1} Bq^{-1} m^3	
	alpha	beta	gamma	beta	gamma
Sr-90	0.00E+00	9.77E-07	0.00E+00	1.29E-11	0.00E+00
Y-90	0.00E+00	3.98E-06	0.00E+00	7.39E-10	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	3.86E-13	0.00E+00
I-129	0.00E+00	3.22E-07	1.64E-08	1.75E-17	1.06E-10
I-131	0.00E+00	9.26E-07	6.91E-08	3.43E-11	1.85E-09
Cs-137	0.00E+00	1.19E-06	1.02E-07	5.72E-11	2.74E-09
Cs-134	0.00E+00	7.55E-07	2.79E-07	6.89E-11	7.58E-09
Pu-239	2.64E-05	0.00E+00	9.60E-12	0.00E+00	2.56E-13
Am-241	2.81E-05	0.00E+00	7.12E-09	0.00E+00	1.11E-10

Type of organisms: Small fish

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External	
				From water column, Gy a^{-1} Bq^{-1} m^3	
	alpha	beta	gamma	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	2.78E-17	0.00E+00
K-40	0.00E+00	2.45E-06	2.48E-08	1.90E-10	7.64E-10
U-238	2.15E-05	0.00E+00	4.30E-09	0.00E+00	2.58E-12
Th-234	0.00E+00	3.80E-06	8.73E-09	6.45E-10	1.13E-10
U-234	2.44E-05	0.00E+00	5.22E-09	0.00E+00	3.51E-12
Th-230	2.40E-05	0.00E+00	4.12E-09	0.00E+00	3.62E-12
Ra-226	2.46E-05	0.00E+00	9.92E-10	0.00E+00	2.99E-11
Rn-222	9.87E-05	3.87E-06	2.85E-07	8.78E-10	8.35E-09
Pb-210	0.00E+00	1.92E-07	1.23E-08	0.00E+00	1.20E-11
Bi-210	0.00E+00	1.85E-06	0.00E+00	1.17E-10	0.00E+00
Po-210	2.73E-05	0.00E+00	1.51E-12	0.00E+00	4.14E-14
Th-232	2.03E-05	0.00E+00	4.04E-09	0.00E+00	2.70E-12
Ra-228	0.00E+00	2.09E-06	1.76E-07	3.22E-10	4.52E-09
Th-228	2.78E-05	0.00E+00	4.83E-09	0.00E+00	1.18E-11
Ra-224	1.37E-04	3.82E-06	2.40E-07	4.99E-10	7.60E-09

Type of organisms: Large fish

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Pelagic	Cod *(Gadus morhua)*, hake *(Merluccius merluccius)*	Cod	$50 \times 10 \times 6$	ellipsoid	1570

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External	
				From water column, Gy a^{-1} Bq^{-1} m^3	
	alpha	beta	gamma	beta	gamma
Sr-90	0.00E+00	9.90E-07	0.00E+00	4.18E-13	0.00E+00
Y-90	0.00E+00	4.55E-06	0.00E+00	1.70E-10	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	1.08E-17	0.00E+00
I-129	0.00E+00	3.22E-07	4.91E-08	0.00E+00	7.36E-11
I-131	0.00E+00	9.56E-07	2.43E-07	4.22E-12	1.68E-09
Cs-137	0.00E+00	1.25E-06	3.55E-07	9.78E-12	2.49E-09
Cs-134	0.00E+00	8.10E-07	9.71E-07	1.34E-11	6.89E-09
Pu-239	2.64E-05	0.00E+00	2.97E-09	0.00E+00	6.92E-13
Am-241	2.81E-05	0.00E+00	2.14E-08	0.00E+00	9.70E-11

Type of organisms: Large fish

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External	
				From water column, Gy a^{-1} Bq^{-1} m^3	
	alpha	beta	gamma	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00	0.00E+00
K-40	0.00E+00	2.60E-06	8.67E-08	3.49E-11	7.03E-10
U-238	2.15E-05	0.00E+00	5.97E-09	0.00E+00	9.04E-13
Th-234	0.00E+00	4.30E-06	2.02E-08	1.48E-10	1.01E-10
U-234	2.44E-05	0.00E+00	7.29E-09	0.00E+00	1.44E-12
Th-230	2.40E-05	0.00E+00	5.59E-09	0.00E+00	2.15E-12
Ra-226	2.46E-05	0.00E+00	3.60E-09	0.00E+00	2.73E-11
Rn-222	9.87E-05	4.53E-06	9.85E-07	2.14E-10	7.64E-09
Pb-210	0.00E+00	1.92E-07	1.58E-08	0.00E+00	8.50E-12
Bi-210	0.00E+00	1.95E-06	0.00E+00	1.99E-11	0.00E+00
Po-210	2.73E-05	0.00E+00	5.26E-12	0.00E+00	3.77E-14
Th-232	2.03E-05	0.00E+00	5.42E-09	0.00E+00	1.33E-12
Ra-228	0.00E+00	2.34E-06	5.77E-07	7.20E-11	4.12E-09
Th-228	2.78E-05	0.00E+00	7.13E-09	0.00E+00	9.52E-12
Ra-224	1.37E-04	4.22E-06	8.20E-07	1.10E-10	7.02E-09

Type of organisms: Large crustacean

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Benthic	Crab	Crab	$10 \times 10 \times 5$ (total size), $5 \times 5 \times 3$ (body size without coat)	ellipsoid	40 (without coat)

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	From water column, Gy a^{-1} Bq^{-1} m^3		From bottom sediment, Gy a^{-1} Bq^{-1} kg	
				beta	gamma	beta (buried in sediment)	gamma
Sr-90	0.00E+00	9.78E-07	0.00E+00	4.36E-12	0.00E+00	6.54E-09	0.00E+00
Y-90	0.00E+00	4.19E-06	0.00E+00	2.56E-10	0.00E+00	3.84E-07	0.00E+00
Tc-99	0.00E+00	5.09E-07	0.00E+00	1.39E-13	0.00E+00	2.08E-10	0.00E+00
I-129	0.00E+00	3.22E-07	2.09E-08	8.06E-18	8.42E-11	1.21E-14	3.29E-08
I-131	0.00E+00	9.33E-07	8.79E-08	1.16E-11	1.75E-09	1.74E-08	4.97E-07
Cs-137	0.00E+00	1.21E-06	1.30E-07	1.94E-11	2.60E-09	2.92E-08	7.25E-07
Cs-134	0.00E+00	7.73E-07	3.54E-07	2.36E-11	7.16E-09	3.54E-08	1.98E-06
Pu-239	2.64E-05	0.00E+00	2.31E-09	0.00E+00	8.52E-13	0.00E+00	6.47E-11
Am-241	2.81E-05	0.00E+00	8.93E-09	0.00E+00	1.02E-10	0.00E+00	2.72E-08

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, $Gy\ a^{-1}\ Bq^{-1}\ kg$			External			
	alpha	beta	gamma	From water column, $Gy\ a^{-1}\ Bq^{-1}\ m^3$		From bottom sediment, $Gy\ a^{-1}\ Bq^{-1}\ kg$	
				beta	gamma	beta (buried in sediment)	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	1.26E-17	0.00E+00	1.89E-14	0.00E+00
K-40	0.00E+00	2.50E-06	3.16E-08	6.46E-11	7.28E-10	9.69E-08	3.77E-07
U-238	2.15E-05	0.00E+00	4.84E-09	0.00E+00	1.17E-12	0.00E+00	5.14E-10
Th-234	0.00E+00	3.98E-06	1.04E-08	2.24E-10	1.06E-10	3.36E-07	4.26E-08
U-234	2.44E-05	0.00E+00	5.88E-09	0.00E+00	1.78E-12	0.00E+00	7.16E-10
Th-230	2.40E-05	0.00E+00	4.57E-09	0.00E+00	2.42E-12	0.00E+00	8.16E-10
Ra-226	2.46E-05	0.00E+00	1.26E-09	0.00E+00	2.84E-11	0.00E+00	1.09E-08
Rn-222	9.87E-05	4.12E-06	3.61E-07	3.12E-10	7.92E-09	4.69E-07	3.98E-06
Pb-210	0.00E+00	1.92E-07	1.32E-08	0.00E+00	9.36E-12	0.00E+00	2.45E-09
Bi-210	0.00E+00	1.88E-06	0.00E+00	3.98E-11	0.00E+00	5.97E-08	0.00E+00
Po-210	2.73E-05	0.00E+00	1.92E-12	0.00E+00	3.92E-14	0.00E+00	1.99E-11
Th-232	2.03E-05	0.00E+00	4.48E-09	0.00E+00	1.56E-12	0.00E+00	5.98E-10
Ra-228	0.00E+00	2.18E-06	2.21E-07	1.11E-10	4.28E-09	1.67E-07	2.15E-06
Th-228	2.78E-05	0.00E+00	5.41E-09	0.00E+00	1.01E-11	0.00E+00	3.27E-09
Ra-224	1.37E-04	3.97E-06	3.04E-07	1.73E-10	7.26E-09	2.59E-07	3.60E-06

Type of organisms: Medium-size fish

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Benthic	Plaice, *(Pleuronectes platessa)*	Plaice	$25 \times 20 \times 3$	ellipsoid	800

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
				From water column, Gy a^{-1} Bq^{-1} m^3		From bottom sediment, Gy a^{-1} Bq^{-1} kg	
	alpha	beta	gamma	beta	gamma	beta (buried in sediment)	gamma
Sr-90	0.00E+00	9.88E-07	0.00E+00	4.66E-12	0.00E+00	6.99E-09	0.00E+00
Y-90	0.00E+00	4.43E-06	0.00E+00	5.94E-10	0.00E+00	8.91E-07	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	6.14E-15	0.00E+00	9.21E-12	0.00E+00
I-129	0.00E+00	3.22E-07	3.82E-08	0.00E+00	1.69E-10	0.00E+00	3.29E-08
I-131	0.00E+00	9.49E-07	1.84E-07	2.10E-11	3.48E-09	3.15E-08	4.97E-07
Cs-137	0.00E+00	1.24E-06	2.69E-07	4.02E-11	5.14E-09	6.03E-08	7.25E-07
Cs-134	0.00E+00	7.98E-07	7.37E-07	5.12E-11	1.42E-08	7.68E-08	1.98E-06
Pu-239	2.64E-05	0.00E+00	2.71E-09	0.00E+00	1.90E-12	0.00E+00	6.47E-11
Am-241	2.81E-05	0.00E+00	1.67E-08	0.00E+00	2.04E-10	0.00E+00	2.72E-08

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	From water column, Gy a^{-1} Bq^{-1} m^3		From bottom sediment, Gy a^{-1} Bq^{-1} kg	
				beta	gamma	beta (buried in sediment)	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	1.16E-23	0.00E+00	0.00E+00	0.00E+00
K-40	0.00E+00	2.57E-06	6.57E-08	1.37E-10	1.45E-09	0.00E+00	3.77E-07
U-238	2.15E-05	0.00E+00	5.53E-09	0.00E+00	2.70E-12	0.00E+00	5.14E-10
Th-234	0.00E+00	4.18E-06	1.65E-08	5.20E-10	2.10E-10	0.00E+00	4.26E-08
U-234	2.44E-05	0.00E+00	6.75E-09	0.00E+00	3.98E-12	0.00E+00	7.16E-10
Th-230	2.40E-05	0.00E+00	5.20E-09	0.00E+00	5.08E-12	0.00E+00	8.16E-10
Ra-226	2.46E-05	0.00E+00	2.72E-09	0.00E+00	5.64E-11	0.00E+00	1.09E-08
Rn-222	9.87E-05	4.38E-06	7.47E-07	7.32E-10	1.58E-08	0.00E+00	3.98E-06
Pb-210	0.00E+00	1.92E-07	1.48E-08	0.00E+00	1.89E-11	0.00E+00	2.45E-09
Bi-210	0.00E+00	1.92E-06	0.00E+00	8.18E-11	0.00E+00	0.00E+00	0.00E+00
Po-210	2.73E-05	0.00E+00	3.99E-12	0.00E+00	7.80E-14	0.00E+00	1.99E-11
Th-232	2.03E-05	0.00E+00	5.06E-09	0.00E+00	3.36E-12	0.00E+00	5.98E-10
Ra-228	0.00E+00	2.29E-06	4.42E-07	2.56E-10	8.52E-09	0.00E+00	2.15E-06
Th-228	2.78E-05	0.00E+00	6.47E-09	0.00E+00	2.04E-11	0.00E+00	3.27E-09
Ra-224	1.37E-04	4.13E-06	6.23E-07	3.92E-10	1.44E-08	0.00E+00	3.60E-06

Type of organisms: Bivalve mollusk

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Benthic	Mussels *(Mutilus edulis)*, Scallops (*Pecten maximus)*.	Common mussel	$5\times 3\times 2.5$ (total size); $3.2\times 2\times 1.5$ (body)	ellipsoid	5 (without shells)

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
				From water column, Gy a^{-1} Bq^{-1} m^3		From bottom sediment, Gy a^{-1} Bq^{-1} kg	
	alpha	beta	gamma	beta	gamma	beta (buried in sediment)	gamma
Sr-90	0.00E+00	9.75E-07	0.00E+00	1.48E-11	0.00E+00	2.23E-08	0.00E+00
Y-90	0.00E+00	4.07E-06	0.00E+00	6.50E-10	0.00E+00	9.76E-07	0.00E+00
Tc-99	0.00E+00	5.09E-07	0.00E+00	1.49E-12	0.00E+00	2.23E-09	0.00E+00
I-129	0.00E+00	3.22E-07	1.69E-08	2.52E-14	1.06E-10	3.77E-11	3.29E-08
I-131	0.00E+00	9.27E-07	7.04E-08	3.32E-11	1.85E-09	4.99E-08	4.97E-07
Cs-137	0.00E+00	1.20E-06	1.04E-07	5.28E-11	2.74E-09	7.91E-08	7.25E-07
Cs-134	0.00E+00	7.61E-07	2.84E-07	6.22E-11	7.58E-09	9.33E-08	1.98E-06
Pu-239	2.64E-05	0.00E+00	2.12E-09	0.00E+00	1.54E-12	0.00E+00	6.47E-11
Am-241	2.81E-05	0.00E+00	7.34E-09	0.00E+00	1.11E-10	0.00E+00	2.72E-08

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	From water column, Gy a^{-1} Bq^{-1} m^3		From bottom sediment, Gy a^{-1} Bq^{-1} kg	
				beta	gamma	beta (buried in sediment)	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	2.54E-14	0.00E+00	3.81E-11	0.00E+00
K-40	0.00E+00	2.47E-06	2.53E-08	1.73E-10	7.64E-10	2.59E-07	3.77E-07
U-238	2.15E-05	0.00E+00	4.49E-09	0.00E+00	2.38E-12	0.00E+00	5.14E-10
Th-234	0.00E+00	3.87E-06	9.02E-09	5.68E-10	1.13E-10	8.52E-07	4.26E-08
U-234	2.44E-05	0.00E+00	5.46E-09	0.00E+00	3.28E-12	0.00E+00	7.16E-10
Th-230	2.40E-05	0.00E+00	4.28E-09	0.00E+00	3.46E-12	0.00E+00	8.16E-10
Ra-226	2.46E-05	0.00E+00	1.01E-09	0.00E+00	3.00E-11	0.00E+00	1.09E-08
Rn-222	9.87E-05	3.97E-06	2.90E-07	7.76E-10	8.34E-09	1.16E-06	3.98E-06
Pb-210	0.00E+00	1.92E-07	1.26E-08	1.24E-23	1.17E-11	1.86E-20	2.45E-09
Bi-210	0.00E+00	1.86E-06	0.00E+00	1.08E-10	0.00E+00	1.62E-07	0.00E+00
Po-210	2.73E-05	0.00E+00	1.54E-12	0.00E+00	4.14E-14	0.00E+00	1.99E-11
Th-232	2.03E-05	0.00E+00	4.21E-09	0.00E+00	2.54E-12	0.00E+00	5.98E-10
Ra-228	0.00E+00	2.13E-06	1.80E-07	2.84E-10	4.52E-09	4.26E-07	2.15E-06
Th-228	2.78E-05	0.00E+00	5.02E-09	0.00E+00	1.16E-11	0.00E+00	3.27E-09
Ra-224	1.37E-04	3.89E-06	2.45E-07	4.42E-10	7.60E-09	6.64E-07	3.60E-06

Type of organisms: Sea bird

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Islands	Gulls *(Larus spp.)*	Larus spp.	15×11×8 (body); 21×16×11 (including feather)	ellipsoid	600

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
				On the water/air interface (from semi-infinite source in water), Gy a^{-1} Bq^{-1} m^3		From source on the depth 0.5 g cm^{-2} in soil, Gy a^{-1} kBq^{-1} m^2	
	alpha	beta	gamma	beta	gamma	beta	gamma
Sr-90	0.00E+00	9.88E-07	0.00E+00	5.82E-13	0.00E+00	0.00E+00	0.00E+00
Y-90	0.00E+00	4.54E-06	0.00E+00	5.98E-11	0.00E+00	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	1.56E-15	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	5.06E-08	9.04E-24	2.93E-11	0.00E+00	4.14E-07
I-131	0.00E+00	9.52E-07	2.39E-07	2.29E-12	7.93E-10	0.00E+00	9.53E-06
Cs-137	0.00E+00	1.24E-06	3.50E-07	4.18E-12	1.17E-09	0.00E+00	1.36E-05
Cs-134	0.00E+00	8.07E-07	9.58E-07	5.24E-12	3.26E-09	0.00E+00	3.72E-05
Pu-239	2.64E-05	0.00E+00	2.99E-09	0.00E+00	2.62E-13	0.00E+00	1.86E-09
Am-241	2.81E-05	0.00E+00	2.13E-08	0.00E+00	4.50E-11	0.00E+00	6.08E-07

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	On the water/air interface (from semi-infinite source in water), Gy a^{-1} Bq^{-1} m^{3}		On the soil/air interface (from semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	
				beta	gamma	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	2.77E-23	0.00E+00	0.00E+00	0.00E+00
K-40	0.00E+00	2.59E-06	8.55E-08	1.42E-11	3.35E-10	0.00E+00	3.16E-07
U-238	2.15E-05	0.00E+00	6.01E-09	0.00E+00	3.19E-13	0.00E+00	5.88E-11
Th-234	0.00E+00	4.29E-06	2.01E-08	5.22E-11	4.80E-11	0.00E+00	3.55E-08
U-234	2.44E-05	0.00E+00	7.34E-09	0.00E+00	5.50E-13	0.00E+00	1.51E-10
Th-230	2.40E-05	0.00E+00	5.61E-09	0.00E+00	9.40E-13	0.00E+00	3.59E-10
Ra-226	2.46E-05	0.00E+00	3.52E-09	0.00E+00	1.30E-11	0.00E+00	9.51E-09
Rn-222	9.87E-05	4.52E-06	9.70E-07	7.37E-11	3.64E-09	0.00E+00	3.35E-06
Pb-210	0.00E+00	1.92E-07	1.58E-08	0.00E+00	3.77E-12	0.00E+00	1.11E-09
Bi-210	0.00E+00	1.94E-06	0.00E+00	8.55E-12	0.00E+00	0.00E+00	0.00E+00
Po-210	2.73E-05	0.00E+00	5.19E-12	0.00E+00	1.79E-14	0.00E+00	1.68E-11
Th-232	2.03E-05	0.00E+00	5.44E-09	0.00E+00	5.50E-13	0.00E+00	1.77E-10
Ra-228	0.00E+00	2.34E-06	5.69E-07	2.57E-11	1.96E-09	0.00E+00	1.81E-06
Th-228	2.78E-05	0.00E+00	7.13E-09	0.00E+00	4.43E-12	0.00E+00	2.45E-09
Ra-224	1.37E-04	4.21E-06	8.10E-07	3.96E-11	3.36E-09	0.00E+00	3.04E-06

Type of organisms: Pelagic crustacean

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Pelagic	Shrimps, (*Pandalus borealis)*	Northern pink shrimp	$7\times 1.5\times 1.5$	ellipsoid	5

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External	
				From water column, Gy a^{-1} Bq^{-1} m^3	
	alpha	beta	gamma	beta	gamma
Sr-90	0.00E+00	9.67E-07	0.00E+00	2.31E-11	0.00E+00
Y-90	0.00E+00	3.72E-06	0.00E+00	1.00E-09	0.00E+00
Tc-99	0.00E+00	5.08E-07	0.00E+00	2.13E-12	0.00E+00
I-129	0.00E+00	3.22E-07	1.18E-08	1.82E-14	1.11E-10
I-131	0.00E+00	9.08E-07	4.88E-08	5.21E-11	1.87E-09
Cs-137	0.00E+00	1.17E-06	7.18E-08	8.25E-11	2.77E-09
Cs-134	0.00E+00	7.26E-07	1.97E-07	9.70E-11	7.66E-09
Pu-239	2.64E-05	0.00E+00	1.74E-09	0.00E+00	1.92E-12
Am-241	2.81E-05	0.00E+00	5.22E-09	0.00E+00	1.13E-10

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External	
	alpha	beta	gamma	From water column, Gy a^{-1} Bq^{-1} m^3	
				beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	1.95E-14	0.00E+00
K-40	0.00E+00	2.37E-06	1.75E-08	2.70E-10	7.72E-10
U-238	2.15E-05	0.00E+00	3.76E-09	0.00E+00	3.12E-12
Th-234	0.00E+00	3.57E-06	6.98E-09	8.73E-10	1.15E-10
U-234	2.44E-05	0.00E+00	4.56E-09	0.00E+00	4.17E-12
Th-230	2.40E-05	0.00E+00	3.64E-09	0.00E+00	4.10E-12
Ra-226	2.46E-05	0.00E+00	6.97E-10	0.00E+00	3.02E-11
Rn-222	9.87E-05	3.58E-06	2.02E-07	1.17E-09	8.43E-09
Pb-210	0.00E+00	1.92E-07	1.13E-08	1.05E-25	1.30E-11
Bi-210	0.00E+00	1.80E-06	0.00E+00	1.69E-10	0.00E+00
Po-210	2.73E-05	0.00E+00	1.07E-12	0.00E+00	4.19E-14
Th-232	2.03E-05	0.00E+00	3.58E-09	0.00E+00	3.16E-12
Ra-228	0.00E+00	1.98E-06	1.27E-07	4.39E-10	4.57E-09
Th-228	2.78E-05	0.00E+00	4.23E-09	0.00E+00	1.24E-11
Ra-224	1.37E-04	3.65E-06	1.72E-07	6.83E-10	7.66E-09

Type of organisms: Seal

Habitat	Representative species of fish	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Islands	Seal *(Pagophilus groenlandicus)*	Greenland seal	$170 \times 45 \times 40$	ellipsoid	160 000

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	From water column, Gy a^{-1} Bq^{-1} m^3		On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	
				beta	gamma	beta	gamma
Sr-90	0.00E+00	9.90E-07	0.00E+00	6.84E-19	0.00E+00	0.00E+00	0.00E+00
Y-90	0.00E+00	4.71E-06	0.00E+00	1.29E-11	0.00E+00	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	1.03E-07	0.00E+00	1.92E-11	0.00E+00	1.51E-07
I-131	0.00E+00	9.60E-07	9.95E-07	5.58E-15	9.24E-10	0.00E+00	6.86E-06
Cs-137	0.00E+00	1.26E-06	1.44E-06	1.06E-13	1.40E-09	0.00E+00	9.84E-06
Cs-134	0.00E+00	8.23E-07	3.95E-06	3.56E-13	3.90E-09	0.00E+00	2.69E-05
Pu-239	2.64E-05	0.00E+00	3.47E-09	0.00E+00	2.06E-13	0.00E+00	1.10E-09
Am-241	2.81E-05	0.00E+00	7.14E-08	0.00E+00	4.70E-11	0.00E+00	4.18E-07

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	From water column, Gy a^{-1} Bq^{-1} m^3		On the soil/air interface (from semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	
				beta	gamma	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
K-40	0.00E+00	2.64E-06	3.60E-07	6.26E-13	4.28E-10	0.00E+00	2.09E-07
U-238	2.15E-05	0.00E+00	6.70E-09	0.00E+00	1.75E-13	0.00E+00	2.17E-11
Th-234	0.00E+00	4.42E-06	6.42E-08	1.12E-11	5.76E-11	0.00E+00	2.39E-08
U-234	2.44E-05	0.00E+00	8.33E-09	0.00E+00	4.02E-13	0.00E+00	8.20E-11
Th-230	2.40E-05	0.00E+00	6.80E-09	0.00E+00	9.38E-13	0.00E+00	2.32E-10
Ra-226	2.46E-05	0.00E+00	1.57E-08	0.00E+00	1.52E-11	0.00E+00	6.88E-09
Rn-222	9.87E-05	4.72E-06	4.07E-06	2.28E-11	4.56E-09	0.00E+00	2.26E-06
Pb-210	0.00E+00	1.92E-07	2.11E-08	0.00E+00	3.22E-12	0.00E+00	5.84E-10
Bi-210	0.00E+00	1.96E-06	0.00E+00	2.04E-13	0.00E+00	0.00E+00	0.00E+00
Po-210	2.73E-05	0.00E+00	2.14E-11	0.00E+00	2.16E-14	0.00E+00	1.13E-11
Th-232	2.03E-05	0.00E+00	6.26E-09	0.00E+00	4.84E-13	0.00E+00	1.08E-10
Ra-228	0.00E+00	2.41E-06	2.30E-06	4.72E-12	2.40E-09	0.00E+00	1.22E-06
Th-228	2.78E-05	0.00E+00	1.16E-08	0.00E+00	5.06E-12	0.00E+00	1.72E-09
Ra-224	1.37E-04	4.32E-06	3.45E-06	7.44E-12	4.40E-09	0.00E+00	2.05E-06

Seal. DCF for separate organs.
Internally incorporated radionuclides.

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg								
	Testis			Liver			Foetus		
	alpha	beta	gamma	alpha	beta	gamma	alpha	beta	gamma
Sr-90	0.00E+00	9.90E-07	0.00E+00	0.00E+00	9.90E-07	0.00E+00	0.00E+00	9.90E-07	0.00E+00
Y-90	0.00E+00	4.66E-06	0.00E+00	0.00E+00	4.69E-06	0.00E+00	0.00E+00	4.69E-06	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	0.00E+00	5.10E-07	0.00E+00	0.00E+00	5.10E-07	0.00E+00
I-129	0.00E+00	3.22E-07	3.65E-08	0.00E+00	3.22E-07	7.23E-08	0.00E+00	3.22E-07	8.04E-08
I-131	0.00E+00	9.60E-07	1.60E-07	0.00E+00	9.60E-07	4.02E-07	0.00E+00	9.60E-07	5.06E-07
Cs-137	0.00E+00	1.26E-06	2.35E-07	0.00E+00	1.26E-06	5.84E-07	0.00E+00	1.26E-06	7.31E-07
Cs-134	0.00E+00	8.22E-07	6.43E-07	0.00E+00	8.23E-07	1.60E-06	0.00E+00	8.23E-07	2.00E-06
Pu-239	2.64E-05	0.00E+00	2.93E-09	2.64E-05	0.00E+00	3.25E-09	2.64E-05	0.00E+00	3.28E-09
Am-241	2.81E-05	0.00E+00	1.52E-08	2.81E-05	0.00E+00	3.35E-08	2.81E-05	0.00E+00	4.07E-08

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg								
	Testis			Liver			Foetus		
	alpha	beta	gamma	alpha	beta	gamma	alpha	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	2.87E-08	0.00E+00	0.00E+00	2.87E-08	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00	2.50E-07	0.00E+00	0.00E+00	2.50E-07	0.00E+00
K-40	0.00E+00	2.64E-06	5.74E-08	0.00E+00	2.64E-06	1.42E-07	0.00E+00	2.64E-06	1.78E-07
U-238	2.15E-05	0.00E+00	5.98E-09	2.15E-05	0.00E+00	6.44E-09	2.15E-05	0.00E+00	6.47E-09
Th-234	0.00E+00	4.39E-06	1.56E-08	0.00E+00	4.41E-06	2.97E-08	0.00E+00	4.41E-06	3.55E-08
U-234	2.44E-05	0.00E+00	7.28E-09	2.44E-05	0.00E+00	7.89E-09	2.44E-05	0.00E+00	7.95E-09
Th-230	2.40E-05	0.00E+00	5.56E-09	2.40E-05	0.00E+00	6.08E-09	2.40E-05	0.00E+00	6.19E-09
Ra-226	2.46E-05	0.00E+00	2.31E-09	2.46E-05	0.00E+00	6.07E-09	2.46E-05	0.00E+00	7.75E-09
Rn-222	9.87E-05	4.63E-06	6.53E-07	9.87E-05	4.68E-06	1.61E-06	9.87E-05	4.68E-06	2.03E-06
Pb-210	0.00E+00	1.92E-07	1.54E-08	0.00E+00	1.92E-07	1.76E-08	0.00E+00	1.92E-07	1.83E-08
Bi-210	0.00E+00	1.96E-06	0.00E+00	0.00E+00	1.96E-06	0.00E+00	0.00E+00	1.96E-06	0.00E+00
Po-210	2.73E-05	0.00E+00	3.49E-12	2.73E-05	0.00E+00	8.64E-12	2.73E-05	0.00E+00	1.08E-11
Th-232	2.03E-05	0.00E+00	5.43E-09	2.03E-05	0.00E+00	5.83E-09	2.03E-05	0.00E+00	5.89E-09
Ra-228	0.00E+00	2.39E-06	3.90E-07	0.00E+00	2.40E-06	9.36E-07	0.00E+00	2.40E-06	1.17E-06
Th-228	2.78E-05	0.00E+00	6.78E-09	2.78E-05	0.00E+00	8.30E-09	2.78E-05	0.00E+00	8.85E-09
Ra-224	1.37E-04	4.29E-06	5.45E-07	1.37E-04	4.31E-06	1.35E-06	1.37E-04	4.31E-06	1.69E-06

Seal. DCF for separate organs.
External exposure from water column.

Dose Conversion Factors (Artificial radionuclides)

Nuclide	External, Gy a^{-1} Bq^{-1} m^3								
	Testis			Liver			Foetus		
	alpha	beta	gamma	alpha	beta	gamma	alpha	beta	gamma
Sr-90	0.00E+00	1.19E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y-90	0.00E+00	5.25E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.64E-17	0.00E+00
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	0.00E+00	4.40E-11	0.00E+00	0.00E+00	5.17E-12	0.00E+00	0.00E+00	7.03E-12
I-131	0.00E+00	1.61E-14	1.03E-09	0.00E+00	0.00E+00	8.31E-10	0.00E+00	0.00E+00	8.39E-10
Cs-137	0.00E+00	3.62E-13	1.58E-09	0.00E+00	0.00E+00	1.26E-09	0.00E+00	0.00E+00	1.27E-09
Cs-134	0.00E+00	1.32E-12	4.41E-09	0.00E+00	0.00E+00	3.52E-09	0.00E+00	0.00E+00	3.55E-09
Pu-239	0.00E+00	0.00E+00	7.78E-13	0.00E+00	0.00E+00	9.76E-15	0.00E+00	0.00E+00	1.26E-14
Am-241	0.00E+00	0.00E+00	6.23E-11	0.00E+00	0.00E+00	3.73E-11	0.00E+00	0.00E+00	3.82E-11

Dose Conversion Factors (Natural radionuclides)

Nuclide	External, Gy a^{-1} Bq^{-1} m^3								
	Testis			Liver			Foetus		
	alpha	beta	gamma	alpha	beta	gamma	alpha	beta	gamma
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
K-40	0.00E+00	2.25E-12	4.82E-10	0.00E+00	0.00E+00	3.92E-10	0.00E+00	0.00E+00	3.95E-10
U-238	0.00E+00	0.00E+00	7.27E-13	0.00E+00	0.00E+00	3.11E-15	0.00E+00	0.00E+00	4.81E-15
Th-234	0.00E+00	4.55E-11	7.66E-11	0.00E+00	0.00E+00	4.87E-11	0.00E+00	8.13E-17	4.91E-11
U-234	0.00E+00	0.00E+00	1.64E-12	0.00E+00	0.00E+00	1.95E-14	0.00E+00	0.00E+00	2.34E-14
Th-230	0.00E+00	0.00E+00	3.47E-12	0.00E+00	0.00E+00	1.64E-13	0.00E+00	0.00E+00	1.69E-13
Ra-226	0.00E+00	0.00E+00	1.61E-11	0.00E+00	0.00E+00	1.41E-11	0.00E+00	0.00E+00	1.42E-11
Rn-222	0.00E+00	9.53E-11	5.12E-09	0.00E+00	0.00E+00	4.15E-09	0.00E+00	5.12E-15	4.18E-09
Pb-210	0.00E+00	0.00E+00	1.04E-11	0.00E+00	0.00E+00	8.60E-13	0.00E+00	0.00E+00	9.05E-13
Bi-210	0.00E+00	6.96E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	0.00E+00	0.00E+00	2.44E-14	0.00E+00	0.00E+00	1.94E-14	0.00E+00	0.00E+00	1.96E-14
Th-232	0.00E+00	0.00E+00	1.92E-12	0.00E+00	0.00E+00	4.68E-14	0.00E+00	0.00E+00	4.97E-14
Ra-228	0.00E+00	1.89E-11	2.76E-09	0.00E+00	0.00E+00	2.16E-09	0.00E+00	1.18E-17	2.18E-09
Th-228	0.00E+00	0.00E+00	1.31E-11	0.00E+00	0.00E+00	2.50E-12	0.00E+00	0.00E+00	2.52E-12
Ra-224	0.00E+00	3.00E-11	4.90E-09	0.00E+00	0.00E+00	4.04E-09	0.00E+00	3.95E-17	4.07E-09

TERRESTRIAL REFERENCE ORGANISMS

Type of organisms: Soil invertebrate

Depth in soil/depth burrow, cm	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
Mainly in litter layer	Collembola spp.	0.5×0.1×0.1	ellipsoid	$2.6 \cdot 10^{-3}$

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External
	alpha	beta	gamma	On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
				gamma
Sr-90	0.00E+00	6.36E-07	0.00E+00	0.00E+00
Y-90	0.00E+00	6.08E-07	0.00E+00	0.00E+00
Tc-99	0.00E+00	4.47E-07	0.00E+00	0.00E+00
I-129	0.00E+00	3.11E-07	8.88E-10	6.40E-07
I-131	0.00E+00	4.11E-07	3.57E-09	1.04E-05
Cs-137	0.00E+00	5.90E-07	5.25E-09	1.51E-05
Cs-134	0.00E+00	1.92E-07	1.44E-08	4.14E-05
Pu-239	2.61E-05	0.00E+00	2.29E-10	5.06E-09
Am-241	2.78E-05	0.00E+00	4.19E-10	5.55E-07

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
				gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00
C-14	0.00E+00	2.41E-07	0.00E+00	0.00E+00
K-40	0.00E+00	6.99E-07	1.28E-09	3.76E-07
U-238	2.14E-05	0.00E+00	5.33E-10	4.76E-10
Th-234	0.00E+00	8.17E-07	7.98E-10	4.24E-08
U-234	2.42E-05	0.00E+00	6.46E-10	6.70E-10
Th-230	2.37E-05	0.00E+00	5.57E-10	7.76E-10
Ra-226	2.43E-05	0.00E+00	5.08E-11	1.09E-08
Rn-222	9.67E-05	7.78E-07	1.55E-08	3.97E-06
Pb-210	0.00E+00	1.91E-07	2.27E-09	2.30E-09
Bi-210	0.00E+00	6.02E-07	0.00E+00	0.00E+00
Po-210	2.70E-05	0.00E+00	7.80E-14	1.98E-11
Th-232	2.02E-05	0.00E+00	5.51E-10	5.59E-10
Ra-228	0.00E+00	4.25E-07	1.04E-08	2.15E-06
Th-228	2.74E-05	0.00E+00	6.30E-10	3.22E-09
Ra-224	1.34E-04	1.05E-06	1.40E-08	3.60E-06

Type of organisms: Soil invertebrate

Depth in soil/depth burrow	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
100 cm	Mites (The suborder Oribatida (oribatid or beetle, mites) of the order Acariformes	0.3×0.04	Flattened sphere	$1.4 \cdot 10^{-5}$

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
				On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	In soil at the depth 100 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2		
	alpha	beta	gamma	gamma	alpha	beta	gamma
Sr-90	0.00E+00	3.74E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y-90	0.00E+00	2.46E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	0.00E+00	3.54E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	2.92E-07	3.50E-10	6.42E-07	0.00E+00	0.00E+00	0.00E+00
I-131	0.00E+00	2.07E-07	1.40E-09	1.04E-05	0.00E+00	0.00E+00	9.22E-10
Cs-137	0.00E+00	4.20E-07	2.06E-09	1.51E-05	0.00E+00	0.00E+00	4.19E-09
Cs-134	0.00E+00	8.38E-08	5.65E-09	4.14E-05	0.00E+00	0.00E+00	1.60E-08
Pu-239	2.55E-05	0.00E+00	9.37E-11	5.17E-09	0.00E+00	0.00E+00	3.95E-14
Am-241	2.70E-05	0.00E+00	1.65E-10	5.56E-07	0.00E+00	0.00E+00	0.00E+00

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, $Gy\ a^{-1}\ Bq^{-1}\ kg$			External			
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), $Gy\ a^{-1}\ Bq^{-1}\ kg$	In soil at the depth 100 cm (from the infinite source in soil), $Gy\ a^{-1}\ Bq^{-1}\ kg$		
				gamma	alpha	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	2.50E-14	0.00E+00
C-14	0.00E+00	2.25E-07	0.00E+00	0.00E+00	0.00E+00	2.51E-08	0.00E+00
K-40	0.00E+00	3.12E-07	5.02E-10	3.77E-07	0.00E+00	2.33E-06	7.87E-07
U-238	2.10E-05	0.00E+00	2.20E-10	4.99E-10	5.06E-07	0.00E+00	6.66E-09
Th-234	0.00E+00	4.69E-07	3.25E-10	4.26E-08	0.00E+00	3.97E-06	1.21E-07
U-234	2.37E-05	0.00E+00	2.66E-10	6.98E-10	7.47E-07	0.00E+00	8.47E-09
Th-230	2.33E-05	0.00E+00	2.31E-10	8.00E-10	7.07E-07	0.00E+00	7.53E-09
Ra-226	2.38E-05	0.00E+00	2.00E-11	1.09E-08	7.60E-07	0.00E+00	3.09E-08
Rn-222	9.31E-05	3.48E-07	6.15E-09	3.97E-06	5.55E-06	4.40E-06	8.66E-06
Pb-210	0.00E+00	1.89E-07	9.72E-10	2.39E-09	0.00E+00	2.47E-09	2.33E-08
Bi-210	0.00E+00	2.77E-07	0.00E+00	0.00E+00	0.00E+00	1.69E-06	0.00E+00
Po-210	2.63E-05	0.00E+00	3.07E-14	1.99E-11	1.03E-06	0.00E+00	4.29E-11
Th-232	1.99E-05	0.00E+00	2.29E-10	5.82E-10	4.22E-07	0.00E+00	6.51E-09
Ra-228	0.00E+00	2.23E-07	4.14E-09	2.15E-06	0.00E+00	2.19E-06	4.69E-06
Th-228	2.67E-05	0.00E+00	2.61E-10	3.25E-09	1.09E-06	0.00E+00	1.64E-08
Ra-224	1.29E-04	5.19E-07	5.56E-09	3.60E-06	7.75E-06	3.81E-06	7.83E-06

Type of organisms: Small herbivorous mammal (burrowing)

Depth in soil/depth burrow	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
100 cm	Collared Lemming (*Lemus Dicrostonyx*)	[1]14×5.5×6.3 [2]8.8×3.4×3.9	Ellipsoid	60

[1]dimensions with hair; [2] dimensions of effective homogeneous ellipsoid.

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	In soil at the depth 100 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2		
				gamma	alpha	beta	gamma
Sr-90	0.00E+00	9.81E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y-90	0.00E+00	4.28E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	2.46E-08	5.35E-07	0.00E+00	0.00E+00	0.00E+00
I-131	0.00E+00	9.38E-07	1.05E-07	9.82E-06	0.00E+00	0.00E+00	9.38E-10
Cs-137	0.00E+00	1.22E-06	1.54E-07	1.42E-05	0.00E+00	0.00E+00	4.29E-09
Cs-134	0.00E+00	7.82E-07	4.23E-07	3.89E-05	0.00E+00	0.00E+00	1.64E-08
Pu-239	2.64E-05	0.00E+00	2.45E-09	2.34E-09	0.00E+00	0.00E+00	4.00E-14
Am-241	2.81E-05	0.00E+00	1.04E-08	5.82E-07	0.00E+00	0.00E+00	0.00E+00

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	In soil at the depth 100 cm (from the infinite source in soil), Gy a^{-1} Bq^{-1} kg		
				gamma	alpha	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00	0.00E+00	4.56E-15	0.00E+00
K-40	0.00E+00	2.52E-06	3.77E-08	3.45E-07	0.00E+00	6.61E-08	7.27E-07
U-238	2.15E-05	0.00E+00	5.09E-09	1.03E-10	0.00E+00	0.00E+00	1.20E-09
Th-234	0.00E+00	4.06E-06	1.16E-08	3.86E-08	0.00E+00	2.28E-07	1.06E-07
U-234	2.44E-05	0.00E+00	6.20E-09	2.10E-10	0.00E+00	0.00E+00	1.81E-09
Th-230	2.40E-05	0.00E+00	4.79E-09	4.18E-10	0.00E+00	0.00E+00	2.44E-09
Ra-226	2.46E-05	0.00E+00	1.51E-09	1.02E-08	0.00E+00	0.00E+00	2.85E-08
Rn-222	9.87E-05	4.22E-06	4.30E-07	3.66E-06	0.00E+00	3.19E-07	7.95E-06
Pb-210	0.00E+00	1.92E-07	1.37E-08	1.32E-09	0.00E+00	0.00E+00	9.47E-09
Bi-210	0.00E+00	1.89E-06	0.00E+00	0.00E+00	0.00E+00	4.08E-08	0.00E+00
Po-210	2.73E-05	0.00E+00	2.29E-12	1.83E-11	0.00E+00	0.00E+00	3.93E-11
Th-232	2.03E-05	0.00E+00	4.69E-09	2.21E-10	0.00E+00	0.00E+00	1.58E-09
Ra-228	0.00E+00	2.22E-06	2.61E-07	1.97E-06	0.00E+00	1.13E-07	4.29E-06
Th-228	2.78E-05	0.00E+00	5.72E-09	2.66E-09	0.00E+00	0.00E+00	1.01E-08
Ra-224	1.37E-04	4.02E-06	3.60E-07	3.31E-06	0.00E+00	1.76E-07	7.27E-06

Type of organisms: Small herbivorous mammal (burrowing)

Depth in soil/depth burrow	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
50 cm	Vole (*Microtus spp*)	[1]10.3×4×4.9 [2]6.6×2.6×3.3	Ellipsoid	30

[1]dimensions with hair; [2] dimensions of effective homogeneous ellipsoid.

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	In soil at the depth 50 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2		
				gamma	alpha	beta	gamma
Sr-90	0.00E+00	9.78E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y-90	0.00E+00	4.17E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.09E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	1.99E-08	5.62E-07	0.00E+00	0.00E+00	0.00E+00
I-131	0.00E+00	9.31E-07	8.36E-08	9.90E-06	0.00E+00	0.00E+00	6.63E-08
Cs-137	0.00E+00	1.21E-06	1.23E-07	1.44E-05	0.00E+00	0.00E+00	1.79E-07
Cs-134	0.00E+00	7.70E-07	3.37E-07	3.94E-05	0.00E+00	0.00E+00	5.42E-07
Pu-239	2.64E-05	0.00E+00	2.26E-09	2.59E-09	0.00E+00	0.00E+00	3.78E-12
Am-241	2.81E-05	0.00E+00	8.54E-09	5.71E-07	0.00E+00	0.00E+00	1.09E-13

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	In soil at the depth 100 cm (from the infinite source in soil), Gy a^{-1} Bq^{-1} kg		
				gamma	alpha	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00	0.00E+00	1.81E-13	0.00E+00
K-40	0.00E+00	2.49E-06	3.01E-08	3.52E-07	0.00E+00	9.07E-08	7.47E-07
U-238	2.15E-05	0.00E+00	4.75E-09	1.27E-10	0.00E+00	0.00E+00	1.52E-09
Th-234	0.00E+00	3.96E-06	1.00E-08	3.95E-08	0.00E+00	3.09E-07	1.08E-07
U-234	2.44E-05	0.00E+00	5.78E-09	2.41E-10	0.00E+00	0.00E+00	2.21E-09
Th-230	2.40E-05	0.00E+00	4.51E-09	4.43E-10	0.00E+00	0.00E+00	2.72E-09
Ra-226	2.46E-05	0.00E+00	1.20E-09	1.03E-08	0.00E+00	0.00E+00	2.91E-08
Rn-222	9.87E-05	4.08E-06	3.44E-07	3.74E-06	0.00E+00	4.29E-07	8.10E-06
Pb-210	0.00E+00	1.92E-07	1.31E-08	1.40E-09	0.00E+00	0.00E+00	1.01E-08
Bi-210	0.00E+00	1.87E-06	0.00E+00	0.00E+00	0.00E+00	5.61E-08	0.00E+00
Po-210	2.73E-05	0.00E+00	1.83E-12	1.86E-11	0.00E+00	0.00E+00	4.02E-11
Th-232	2.03E-05	0.00E+00	4.42E-09	2.42E-10	0.00E+00	0.00E+00	1.83E-09
Ra-228	0.00E+00	2.17E-06	2.11E-07	2.01E-06	0.00E+00	1.54E-07	4.39E-06
Th-228	2.78E-05	0.00E+00	5.32E-09	2.73E-09	0.00E+00	0.00E+00	1.06E-08
Ra-224	1.37E-04	3.94E-06	2.89E-07	3.38E-06	0.00E+00	2.39E-07	7.40E-06

Type of organisms: Large herbivorous mammal

Depth in soil/depth burrow, cm	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
-	Reindeer (*Rangifer tarandus)*	$200\times19\times32$	ellipsoid	64 000

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External
				On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^{2}
	alpha	beta	gamma	gamma
Sr-90	0.00E+00	9.90E-07	0.00E+00	0.00E+00
Y-90	0.00E+00	4.70E-06	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	9.07E-08	2.49E-07
I-131	0.00E+00	9.60E-07	6.88E-07	8.37E-06
Cs-137	0.00E+00	1.26E-06	9.93E-07	1.19E-05
Cs-134	0.00E+00	8.23E-07	2.72E-06	3.25E-05
Pu-239	2.64E-05	0.00E+00	3.37E-09	1.44E-09
Am-241	2.81E-05	0.00E+00	5.24E-08	5.33E-07

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
				gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00
K-40	0.00E+00	2.64E-06	2.45E-07	2.59E-07
U-238	2.15E-05	0.00E+00	6.60E-09	3.39E-11
Th-234	0.00E+00	4.42E-06	4.62E-08	2.94E-08
U-234	2.44E-05	0.00E+00	8.14E-09	1.08E-10
Th-230	2.40E-05	0.00E+00	6.45E-09	2.88E-10
Ra-226	2.46E-05	0.00E+00	1.07E-08	8.15E-09
Rn-222	9.87E-05	4.71E-06	2.78E-06	2.78E-06
Pb-210	0.00E+00	1.92E-07	1.94E-08	8.08E-10
Bi-210	0.00E+00	1.96E-06	0.00E+00	0.00E+00
Po-210	2.73E-05	0.00E+00	1.47E-11	1.39E-11
Th-232	2.03E-05	0.00E+00	6.06E-09	1.37E-10
Ra-228	0.00E+00	2.41E-06	1.59E-06	1.50E-06
Th-228	2.78E-05	0.00E+00	9.90E-09	2.07E-09
Ra-224	1.37E-04	4.32E-06	2.34E-06	2.52E-06

Type of organisms: Herbivorous bird

Depth in soil/depth burrow, cm	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
-	Willow ptarmigan or willow grouse (*Lagopus lagopus*)	[1]25×17×13 [2]14×9.4×7.2	ellipsoid	500

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External: On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
	alpha	beta	gamma	gamma
Sr-90	0.00E+00	9.87E-07	0.00E+00	0.00E+00
Y-90	0.00E+00	4.53E-06	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	4.66E-08	3.84E-07
I-131	0.00E+00	9.51E-07	2.15E-07	9.44E-06
Cs-137	0.00E+00	1.24E-06	3.16E-07	1.34E-05
Cs-134	0.00E+00	8.05E-07	8.64E-07	3.68E-05
Pu-239	2.64E-05	0.00E+00	2.94E-09	1.79E-09
Am-241	2.81E-05	0.00E+00	1.95E-08	6.07E-07

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
				gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00
K-40	0.00E+00	2.59E-06	7.72E-08	3.08E-07
U-238	2.15E-05	0.00E+00	5.93E-09	5.31E-11
Th-234	0.00E+00	4.27E-06	1.87E-08	3.47E-08
U-234	2.44E-05	0.00E+00	7.24E-09	1.42E-10
Th-230	2.40E-05	0.00E+00	5.53E-09	3.47E-10
Ra-226	2.46E-05	0.00E+00	3.16E-09	9.33E-09
Rn-222	9.87E-05	4.50E-06	8.76E-07	3.27E-06
Pb-210	0.00E+00	1.92E-07	1.55E-08	1.06E-09
Bi-210	0.00E+00	1.93E-06	0.00E+00	0.00E+00
Po-210	2.73E-05	0.00E+00	4.68E-12	1.64E-11
Th-232	2.03E-05	0.00E+00	5.37E-09	1.70E-10
Ra-228	0.00E+00	2.33E-06	5.16E-07	1.77E-06
Th-228	2.78E-05	0.00E+00	6.95E-09	2.40E-09
Ra-224	1.37E-04	4.19E-06	7.28E-07	2.97E-06

Type of organisms: Ground nesting bird egg

Depth in soil/depth burrow, cm	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
-	Red Grouse *(Lagopus lagopus scoticus)* egg	4.6×3.2×3.2	ellipsoid	25

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External
	alpha	beta	gamma	On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
				gamma
Sr-90	0.00E+00	9.78E-07	0.00E+00	0.00E+00
Y-90	0.00E+00	4.18E-06	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.09E-07	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	1.97E-08	5.89E-07
I-131	0.00E+00	9.32E-07	8.26E-08	1.00E-05
Cs-137	0.00E+00	1.21E-06	1.22E-07	1.47E-05
Cs-134	0.00E+00	7.72E-07	3.33E-07	4.00E-05
Pu-239	2.64E-05	0.00E+00	2.28E-09	3.01E-09
Am-241	2.81E-05	0.00E+00	8.48E-09	5.59E-07

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg
				gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00
K-40	0.00E+00	2.50E-06	2.97E-08	3.61E-07
U-238	2.15E-05	0.00E+00	4.78E-09	1.70E-10
Th-234	0.00E+00	3.97E-06	1.00E-08	4.05E-08
U-234	2.44E-05	0.00E+00	5.81E-09	2.95E-10
Th-230	2.40E-05	0.00E+00	4.53E-09	4.84E-10
Ra-226	2.46E-05	0.00E+00	1.18E-09	1.05E-08
Rn-222	9.87E-05	4.09E-06	3.40E-07	3.82E-06
Pb-210	0.00E+00	1.92E-07	1.31E-08	1.50E-09
Bi-210	0.00E+00	1.88E-06	0.00E+00	0.00E+00
Po-210	2.73E-05	0.00E+00	1.81E-12	1.91E-11
Th-232	2.03E-05	0.00E+00	4.44E-09	2.78E-10
Ra-228	0.00E+00	2.18E-06	2.09E-07	2.06E-06
Th-228	2.78E-05	0.00E+00	5.34E-09	2.82E-09
Ra-224	1.37E-04	3.96E-06	2.86E-07	3.46E-06

Type of organisms: Carnivorous mammal (burrowing)

Depth in soil/depth burrow	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
100 cm	Arctic fox *(Alopex lagopus)*	54×11×18	Ellipsoid	5500

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	On the soil/air interface (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2	In soil at the depth 100 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2		
				gamma	alpha	beta	gamma
Sr-90	0.00E+00	9.90E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y-90	0.00E+00	4.64E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc-99	0.00E+00	5.10E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	3.22E-07	7.33E-08	2.97E-07	0.00E+00	0.00E+00	0.00E+00
I-131	0.00E+00	9.58E-07	4.35E-07	8.92E-06	0.00E+00	0.00E+00	1.02E-09
Cs-137	0.00E+00	1.25E-06	6.30E-07	1.27E-05	0.00E+00	0.00E+00	4.64E-09
Cs-134	0.00E+00	8.17E-07	1.73E-06	3.46E-05	0.00E+00	0.00E+00	1.77E-08
Pu-239	2.64E-05	0.00E+00	3.22E-09	1.58E-09	0.00E+00	0.00E+00	4.37E-14
Am-241	2.81E-05	0.00E+00	3.55E-08	5.73E-07	0.00E+00	0.00E+00	0.00E+00

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External			
	alpha	beta	gamma	On the soil/air interface (from the semi-infinite source in soil), Gy a^{-1} Bq^{-1} kg	In soil at the depth 100 cm (from the infinite source in soil), Gy a^{-1} Bq^{-1} kg		
				gamma	alpha	beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.50E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
K-40	0.00E+00	2.62E-06	1.54E-07	2.80E-07	0.00E+00	9.93E-09	5.93E-07
U-238	2.15E-05	0.00E+00	6.37E-09	4.02E-11	0.00E+00	0.00E+00	3.91E-10
Th-234	0.00E+00	4.37E-06	3.14E-08	3.17E-08	0.00E+00	5.03E-08	8.33E-08
U-234	2.44E-05	0.00E+00	7.81E-09	1.20E-10	0.00E+00	0.00E+00	7.53E-10
Th-230	2.40E-05	0.00E+00	6.05E-09	3.13E-10	0.00E+00	0.00E+00	1.50E-09
Ra-226	2.46E-05	0.00E+00	6.61E-09	8.68E-09	0.00E+00	0.00E+00	2.24E-08
Rn-222	9.87E-05	4.64E-06	1.75E-06	2.99E-06	0.00E+00	7.53E-08	6.40E-06
Pb-210	0.00E+00	1.92E-07	1.76E-08	9.08E-10	0.00E+00	0.00E+00	5.77E-09
Bi-210	0.00E+00	1.96E-06	0.00E+00	0.00E+00	0.00E+00	5.25E-09	0.00E+00
Po-210	2.73E-05	0.00E+00	9.34E-12	1.50E-11	0.00E+00	0.00E+00	3.11E-11
Th-232	2.03E-05	0.00E+00	5.78E-09	1.50E-10	0.00E+00	0.00E+00	8.27E-10
Ra-228	0.00E+00	2.38E-06	1.01E-06	1.62E-06	0.00E+00	2.40E-08	3.42E-06
Th-228	2.78E-05	0.00E+00	8.40E-09	2.21E-09	0.00E+00	0.00E+00	7.53E-09
Ra-224	1.37E-04	4.27E-06	1.46E-06	2.72E-06	0.00E+00	3.66E-08	5.98E-06

Type of organisms: Plant roots

Depth in soil/depth burrow, cm	Proposed reference organism	Reference dimension (cm) of adult	Shape	Weight, g
0 - 30	Plant roots (Fine leaved grass) *[Vaccinium myrtillus]*	$29 \times 0.0035 \times 0.0035$	ellipsoid	$2.8 \cdot 10^{-5}$

Dose Conversion Factors (Artificial radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg (w.w.)			External
	alpha	beta	gamma	Mean value at the depth 0-30 cm (from source on the depth 0.5 g cm^{-2} in soil), Gy a^{-1} kBq^{-1} m^2
				gamma
Sr-90	0.00E+00	1.95E-07	0.00E+00	0.00E+00
Y-90	0.00E+00	8.83E-08	0.00E+00	0.00E+00
Tc-99	0.00E+00	2.36E-07	0.00E+00	0.00E+00
I-129	0.00E+00	2.80E-07	1.23E-10	1.86E-07
I-131	0.00E+00	9.26E-08	4.95E-10	2.56E-06
Cs-137	0.00E+00	3.44E-07	7.28E-10	3.97E-06
Cs-134	0.00E+00	3.22E-08	1.99E-09	1.10E-05
Pu-239	2.64E-05	0.00E+00	3.38E-11	1.09E-08
Am-241	2.81E-05	0.00E+00	5.85E-11	1.06E-07

Dose Conversion Factors (Natural radionuclides)

Nuclide	Internal, Gy a^{-1} Bq^{-1} kg			External	
	alpha	beta	gamma	From the infinite source in soil, Gy a^{-1} Bq^{-1} kg	
				beta	gamma
H-3	0.00E+00	2.87E-08	0.00E+00	0.00E+00	0.00E+00
C-14	0.00E+00	2.13E-07	0.00E+00	3.71E-08	0.00E+00
K-40	0.00E+00	1.23E-07	1.77E-10	2.51E-06	7.87E-07
U-238	2.15E-05	0.00E+00	7.96E-11	0.00E+00	6.80E-09
Th-234	0.00E+00	2.90E-07	1.17E-10	4.15E-06	1.21E-07
U-234	2.44E-05	0.00E+00	9.64E-11	0.00E+00	8.67E-09
Th-230	2.40E-05	0.00E+00	8.41E-11	0.00E+00	7.67E-09
Ra-226	2.46E-05	0.00E+00	7.05E-12	0.00E+00	3.09E-08
Rn-222	9.79E-05	1.39E-07	2.18E-09	4.61E-06	8.66E-06
Pb-210	0.00E+00	1.92E-07	3.61E-10	1.62E-12	2.39E-08
Bi-210	0.00E+00	1.12E-07	0.00E+00	1.85E-06	0.00E+00
Po-210	2.73E-05	0.00E+00	1.08E-14	0.00E+00	4.29E-11
Th-232	2.03E-05	0.00E+00	8.33E-11	0.00E+00	6.66E-09
Ra-228	0.00E+00	1.36E-07	1.47E-09	2.27E-06	4.70E-06
Th-228	2.78E-05	0.00E+00	9.49E-11	0.00E+00	1.65E-08
Ra-224	1.34E-04	2.36E-07	1.98E-09	6.63E-06	7.83E-06