Model Description of the Terrestrial Food Chain and Dose Module FDMT in RODOS PV6.0

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Model Description of the Terrestrial Food Chain and Dose Module FDMT in RODOS PV6.0

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Management Summary

This document contains a description of the model approaches used in the Terrestrial Food chain and Dose Module FDMT as it is integrated in RODOS PV4.0.

Programm documentation and User Guide for FDMT are available as extra reports (RODOS(WG3)-TN(99)09 and RODOS(WG3)-TN(99)13)

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1 Introduction

The software package FDMT (Food Chain and Dose Module for Terrestrial Pathways) is part of the "Real-time On-line Decision Support System" (RODOS).

Within the RODOS system, FDMT is the module for simulating the transfer of radioactive material in food chains, and for the assessment of doses via all relevant pathways (internal exposure via inhalation and ingestion, external exposure from the plume and from deposited radioactive material) to the population. Individual as well as collective doses can be estimated.

FDMT starts its calculations from the output of the atmospheric dispersion modules. The main input quantities are

- the time-integrated activity concentration in the near ground air
- the activity deposited by precipitation per unit ground area
- the amount of precipitation if wet deposition has occurred
- the date of the deposition (day, month)

Starting from these input data the transfer of radionuclides through the food chains is calculated in several steps as indicated schematically in Fig. 1.1

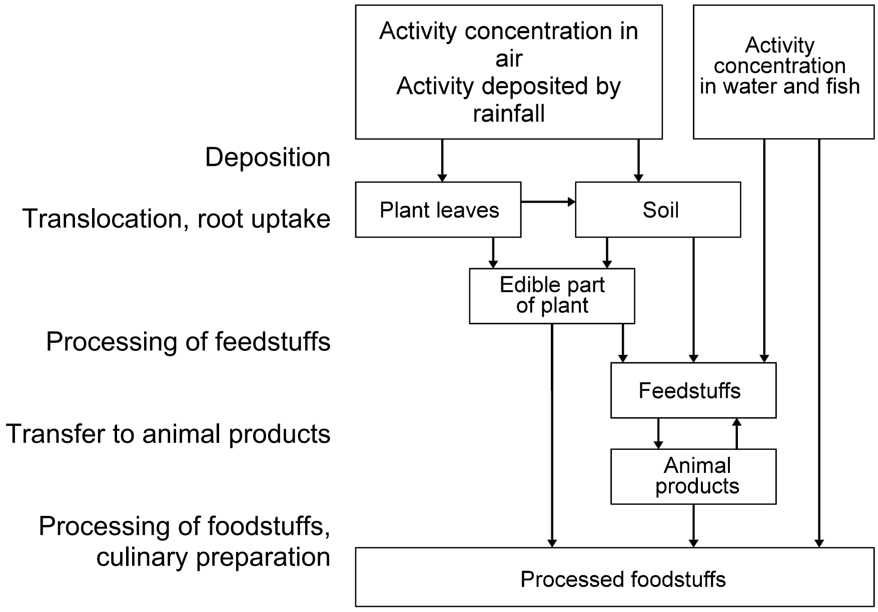

Fig 1.1: Steps of food chain transfer calculations

The methods applied to simulate the transfer of radionuclides in food chains are essentially those of the radioecological model ECOSYS (Müller and Pröhl, 1993). Several extensions to this model have been made for the food chain and dose module FDMT of RODOS which are explicitly referenced in the following.

The transfer of radionuclides in food chains and other processes controlling the radiation exposure depend on regional characteristics like climatological and agricultural properties, and therefore differ from region to region. This means, many parameters of the model have to be adjusted before it can be applied to a certain region. For this purpose, in RODOS so-called radioecological regions can be defined, i.e. regions with relatively uniform radioecological conditions for which the same set of model parameters can be used. The selection of such regions is predominantly determined by prevailing agricultural production regimes, growing periods of plants, harvesting times, feeding regimes for domestic animals, human consumption habits, etc.. Typically, a country is subdivided into 1 to 5 such radioecological regions; it wouldn't make sense to have finer subdivisions since the (unpredictable) year-to-year variations would be higher than the variations among such fine regions.

For each radioecological region the considered feed and foodstuffs as well as all corresponding model parameters can be defined individually.

Default model parameters which are representative for Central European conditions are given in Appendix B.

2 Deposition and Interception

The processes of the radionuclides' deposition to and interception by vegetation and soil are the starting point of their transfer in the food chains. The deposition to the human environment also controls the external exposure. A detailed description of all deposition calculations in RODOS can be found in the report RODOS(WG3)-TN(99)-22 „Deposition calculations in RODOS PV4.0“.

Dry and wet deposition are considered separately to take into account the actual circumstances as realistically as possible. The total deposition to plants is given by

$$A_i = A_{di} + f_{w,i}\ A_w \tag{2.1}$$

with A_i = total deposition ($Bq\ m^{-2}$) onto plant type i
$A_{d,i}$ = dry deposition onto plant type i ($Bq \cdot m^{-2}$)
$f_{w,i}$ = interception fraction for plant type i
A_w = total wet deposition ($Bq\ m^{-2}$).

The dry deposition to different plant species is calculated from the time-integrated air concentration using a deposition velocity which depends on the plant type:

$$A_{di} = v_{gi} \cdot \overline{C}_{air} \tag{2.2}$$

with $A_{d,i}$ = dry deposition onto plant type i ($Bq \cdot m^{-2}$)
$v_{g,i}$ = deposition velocity for plant type i ($m \cdot s^{-1}$)
$\overline{C}_{air}$ = time-integrated activity concentration in air ($Bq \cdot s \cdot m^{-3}$).

One way to consider the two parts of the dry deposition process such as the atmospheric and the surface part is the so-called resistance approach. There, the individual fractions can act either as a series of resistances or in parallel. As a first step, the atmospheric part and the surface can be treated as a series of resistances. If the deposition surface is a mixture of more than one fraction, e.g. plants and underlying soil, the deposition on all fractions has to be considered and the total resistance for each of the fractions act in parallel:

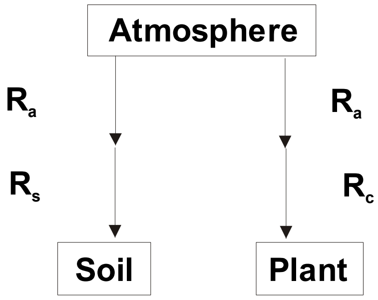

Fig 2.1: Deposition process in the resistance approach

$$R_{ts} = R_a + R_s \tag{2.3a}$$

$$R_{tc} = R_a + R_c \tag{2.3b}$$

where R_{ts} is the total resistance for soil, R_{tc} the total resistance for plant canopy, and R_a the atmospheric resistance.

The deposition velocity $v_{g,i}$ to plant canopy is defined as the inverse of R_{tc}, and the total deposition velocity to both surfaces (e.g., for depletion calculation) as the sum of the inverse of R_{tc} and R_{ts}:

$$v_{g,i} = 1 / R_{tc} \tag{2.4a}$$

$$v_{total} = 1 / R_{tc} + 1 / R_{ts} \tag{2.4b}$$

The atmospheric resistance R_a can be estimated as:

$$R_a = \frac{U}{u^{*2}} \tag{2.5a}$$

$$u^* = 0.4 \cdot \frac{U}{\log(z_U / z_0)} \tag{2.5b}$$

where u^* is the friction velocity, U is the mean wind speed at reference height z_U and z_0 is the roughness height (the atmospheric resistance is assumed to be nuclide independent; it certainly depends on the size of the aerosols, but this effect is not considered since no information on the size distributions of the aerosols is available).

The canopy resistance R_c is assumed to depend on the stage of development of the plant canopy. This causes a pronounced seasonality of the deposition to the plant. The plants' stage of development can be characterized by the actual leaf area index (LAI; unit: $m^2 \cdot m^{-2}$) which is defined as the area of leaves present on a unit area of ground. The canopy resistance is assumed to be inverse proportional to the LAI:

$$\frac{1}{R_c} = \frac{1}{R_{c,min}} \cdot \frac{LAI_i}{LAI_{i,max}} \tag{2.6}$$

with $R_{c,min}$ = minimum canopy resistance (s m^{-1}) for plant type i (i.e.for fully developed foliage - this corresponds to the maximum deposition velocity $v_{d,max}$ as described in the following)

LAI_i = leaf area index of plant type i at time of deposition

$LAI_{i,max}$ = leaf area index of plant type i at time of fully developed foliage.

The canopy resistance depends on the chemical form of the radionuclides. It is assumed that all radionuclides are bound to aerosol particles, except for iodine isotopes, where $f_{I,e}$, $f_{I,o}$ and $f_{I,a}$ denote the relative amount of elemental, organic bound and aerosol bound iodine ($f_{I,e} + f_{I,o} + f_{I,a} = 1.0$).

Data about deposition to plants is mainly available in form of measured maximum deposition velocities $v_{d,max}$, which include both the atmospheric part and the canopy surface part. Therefore, this data has to be subdivided into the two parts, which is done by assuming a reference atmospheric resistance $R_{a,ref}$ (since it is nearly impossible to determine the actual atmospheric conditions during all measurements). As reference values the atmospheric resistances are calculated (with eq. 2.5) for the wind speed U = 4m/s and the appropriate roughness height - see Table 1. The factor f is used to derive the reference values for various surfaces from the value for grass, which is defined as $R_{a,ref}$ =44 s/m. With this assumption the canopy resistance can be derived from the measured deposition velocity:

$$R_C = \frac{1}{v_{d,max}} - R_{a,ref} \qquad (2.7)$$

The default values of $v_{g,i,max}$ - the maximum deposition velocity for plants with fully developed foliage - used in FDMT are given in Table 2 of Appendix B. It is possible to modify these values for each radioecological region individually. If additional types of plants are considered in a region, the corresponding deposition velocities have to be defined.

The deposition velocity depends on the chemical form of the radionuclides. In FDMT it is assumed that all radionuclides are bound to aerosol particles, except for iodine isotopes, where $f_{I,e}$, $f_{I,o}$ and $f_{I,a}$ denote the relative amount of elemental, organic bound and aerosol bound iodine ($f_{I,e} + f_{I,o} + f_{I,a} = 1.0$).

The LAI is strongly dependent on the time of year. For every plant species considered, a specific tabulated function of the LAI is assumed. Default data for the season dependent LAI are given in Table 3 of Appendix B. However, it should be noted that these functions may vary from year-to-year and from region-to-region due to climatic factors and due to farm management factors, such as fertilization, choice of varieties, and time of seeding.

For urban environments and water no vegetation is assumed, i.e. there is no seasonal variation of the deposition velocity.

An exception is made for grass (pasture, grassland and lawn): here the yield instead of the leaf area index is input quantity for FDMT. The following function is used to estimate the LAI from the yield:

$$LAI_g = LAI_{g,max} \{1 - \exp(-k\ Y_g)\} \tag{2.8}$$

with LAI_g = leaf area index of grass at time of deposition

$LAI_{g,max}$ = maximum leaf area index of grass (7 $m^2\ m^{-2}$)

k = normalisation factor (1 $m^2\ kg^{-1}$)

Y_g = yield of grass ($kg\ m^{-2}$) at time of deposition.

The yield of grass (pasture and lawn) as a function of time is also given in Table 4 of Appendix B.

For the interception of wet deposited radionuclides, an approach is used which is based on the water storage capacity of the plants' leaves and the actual leaf area index. Account is taken for the builtup of the water film on the leaves during rainfall, the total amount of rainfall, and the radionuclide's ability to be fixed on the leaf. The interception fraction $f_{w,i}$ for plant type i is quantitatively expressed by

$$f_{w,i} = \frac{LAI_i \cdot S_i}{R} \cdot \left(1 - \exp\left(\frac{-\ln 2}{3 \cdot S_i} \cdot R\right)\right) \tag{2.9}$$

with S_i = retention coefficient (mm) of plant type i

R = amount of rainfall (mm) of a rainfall event.

If eqn (2.9) results in an interception fraction greater than 1.0, $f_{w,i}$= 1.0 is taken.

The values of the retention coefficient S_i applied in the model are given in Table 4 in Appendix B. Three groups of elements (representatives are e.g. iodine, cesium, and strontium) are differentiated. For all other elements considered here, no data about S_i are available; as a default, it is assumed that they behave similarly to cesium, except of barium for which the strontium data are used.

The calculation of the root uptake of plants as well as the external exposure from deposited radionuclides is based on the total (dry and wet) deposition onto soil and vegetation. Pasture is considered to be a representative vegetational type for root uptake, lawn is taken as reference surface for external exposure as it is done in the German dose assessment system PARK (Jacob et al., 1991). The activity removed by harvesting is considered to be recycled by organic fertilization. The total deposition to grassland is given by

$$A_s = A_{ds} + A_{dg} + A_w \tag{2.10}$$

with A_s = total deposition to grassland (Bq m^{-2})
A_{ds} = dry deposition to soil (Bq m^{-2})
A_{dg} = dry deposition to grass (Bq m^{-2})
A_w = total wet deposition (Bq m^{-2}).

The dry deposition to soil is estimated according to eqn (2.4b) using a deposition velocity (see Table 2 in Appendix B) independent of the time of year, i.e. not considering that the soil is protected to some degree from dry deposition by the plant canopy. This simplification is due to the lack of experiments separating clearly between deposition on the soil and that on the overhead canopy. A slight overprediction of the soil contamination for depositions during the vegetation period might be introduced by this assumption.

3 Food Chain Transfer

3.1 Contamination of plants

The contamination of plant products as a function of time results from the direct contamination of the leaves and the activity transfer from the soil by root uptake and resuspension:

$$C_i(t) = C_{i,l}(t) + C_{i,r}(t) \tag{3.1}$$

where $C_i(t)$ = total contamination of plant type i
$C_{i,l}(t)$ = contamination of plant type i due to foliar uptake
$C_{i,r}(t)$ =contamination of plant type i due to root uptake and resuspension.

3.1.1 Foliar uptake of radionuclides

Calculation of the contamination of plants must distinguish between plants which are used totally (leafy vegetables and grass) and plants of which only a special part is used (e.g., cereals and potatoes). In the first case, the activity concentration $C_{i,l}(t)$ at time t after the deposition is determined by the initial contamination of the plant and the activity loss due to weathering effects (rain, wind), radioactive decay and growth dilution. For plants which are totally consumed excluding pasture grass, growth is implicitely considered because the activity deposited onto the leaves is related to the yield at harvest. The concentration of activity is given by:

$$C_{i,l}(\Delta t) = \frac{A_i}{Y_i} \exp(-(\lambda_w+\lambda_r)\cdot\Delta t) \tag{3.2}$$

where $C_{i,l}(\Delta t)$ = concentration of activity in plant type i at time of harvest
A_i = total deposition (Bq m^{-2}) onto plant type i due to the plant's leaf area index at time of deposition
Y_i = yield (kg m^{-2}) of plant type i at time of harvest
λ_w = loss rate (d^{-1}) due to weathering
λ_r = radioactive decay rate (d^{-1})
Δt = time span between deposition and harvest (d).

The times of harvest and the yield Y_i for the different crops are given in Table 5 in Appendix B.

The approach for pasture grass is different because of its continuous harvest. Here, the decrease in activity due to growth dilution is explicitely considered. Furthermore, for elements which are mobile within the phloem (e.g., I or Cs), an additional slow component of decrease is taken into account which is due to translocation to the roots, and subsequent remobilization:

$$C_{g,l}(t) = \frac{A_g}{Y_g} \, [(1\text{-}a)\cdot \exp(-(\lambda_b+\lambda_w+\lambda_r)\cdot t + a\cdot \exp(-(\lambda_t+\lambda_r)\cdot t)] \qquad (3.3)$$

where $C_{g,l}(t)$ = activity concentration (Bq kg^{-1}) in grass at time t after deposition
A_g = total activity deposited onto grass (Bq m^{-2})
Y_g = yield of grass at time of deposition (kg m$^{-2)}$
a = fraction of activity translocated to the root zone
λ_b = dilution rate by increase of biomass (d^{-1})
λ_t = rate of slow activity decrease (d^{-1}) due to translocation to the root zone
t = time after deposition (d).

For the weathering rate constant λ_w, a value equivalent to a half-life of 25 d is assumed. The growth dilution rate λ_b is considered to be time-dependent. Monthly values as given in Table 6 in Appendix B are used; these values of λ_w and λ_b result in an effective half-life of 10 to 16 d. The long-term component of the activity decrease is taken as λ_t = 1.16x10^{-2} d^{-1} (half-life 60 d) with a contribution fraction a = 0.05.

The concentration of activity in hay and grass silage is taken as a weighted mean concentration in grass harvested between begin and end of hay harvesting period (see Table 5 in Appendix B). The first half of that period is weighted 70% and the second 30% to reflect the relative monthly growth of pasture grass.

For plants which are only partly used for animal feeding or human consumption, the translocation from the leaves to the edible part of the plant has to be considered. This process is strongly dependent on the physiological behaviour of the element considered: it is of importance for mobile elements such as I or Cs, but it does not occur with immobile elements like Sr. In the latter case, only the direct deposition onto the edible parts of the plants plays a role. Furthermore, the amount of translocated activity is highly dependent on the timespan Δt between deposition and harvest.

The translocation process is quantified by the translocation factor $T_i(\Delta t)$ which is defined as the fraction of the activity deposited on the foliage being transferred to the edible parts of the plants until harvest. It is dependent on the element, the plant type, and the time between deposition and harvest. The elements considered in FDMT have been grouped as follows:

Mobile:	Immobile:
Co, Cs, I, Mn, Mo, Na, Rb, Sb, Tc, Te	Ag, Am, Ba, Ce, Cm, La, Nb, Nd, Np, Pr, Pu, Rh, Ru, Sr, Y, Zr

The most reliable data for translocation are available for Cs and Sr. Therefore, as long as no other quantitative data are available, the translocation of mobile elements assumes that they behave like Cs, except for Mn, for which translocation factors are assumed to be lower by a factor 0.6 than for Cs. Strontium is considered to be representative for immobile elements. The translocation factors used in FDMT are summarized in Tables 7 and 8.

The concentration of activity for plant type i harvested at time Δt after deposition is given by

$$C_{i,l}(\Delta t) = \frac{A_i}{Y_i}\, T_i(\Delta t) \cdot \exp(-\lambda_r \cdot \Delta t) \tag{3.4}$$

where $T_i(\Delta t)$ = translocation factor for plant type i,
Y_i = yield of edible parts of plant type i,
and other symbols as defined earlier.

This approach is also used for fruits and berries. This is considered to be a very rough approximation, since due to lack of adequate data the translocation to and storage in stems and branches is not taken into account.

3.1.2 Root uptake of radionuclides

The estimation of the root uptake of radionuclides assumes that the radionuclides are well mixed within the entire rooting zone. The concentration of activity due to root uptake is calculated from the concentration of activity in the soil using the transfer factor TF_i which gives the ratio of concentration of activity in plants (fresh weight) and soil (dry weight):

$$C_{i,r}(t) = TF_i \cdot C_s(t) \tag{3.5}$$

where $C_{i,r}(t)$ = concentration of activity (Bq kg^{-1})in plant type i due to root uptake at time t after deposition
TF_i = soil to plant transfer factor for plant type i

$C_s(t)$ = concentration of activity (Bq kg^{-1}) in the root zone of soil at time t.

If the deposition occurs during the growing period less than 50 days before harvest, a reduced root uptake is assumed for the first harvest. The reduction factor is the ratio of the time span from deposition to harvest and 50 days (or the length of the whole growing period if it is less than 50 days).

Since the soil to plant transfer factors TF_i depend on the soil type, within each radioecological region four different soil types can be defined and according TF_i factors can be given for each of these soil types in the model parameter files. The RODOS data base assignes a soil type index to each of the grid points (locations) so that for each location a soil to plant transfer factor according to the local soil type can be used in the calculations.

The transfer factors TF_i used as a default in FDMT are summarized in Table 9 in Appendix B. Compared to intensively managed, well fertilized pasture, a higher availability of Cs and Sr can be observed on extensively used pastures. The soil conditions of such pastures are often characterized by a low pH-value together with a high organic matter, and low contents of clay, K, and Ca. Such soils are frequently found in upland areas, Scandinavia, and parts of Eastern Europe. The transfer factor 1.0 is used for both Cs and Sr in FDMT for extensively managed pastures.

The assessment of the concentration of plant available activity in the root zone of soil has been changed since the last version of FDMT according to a suggestion of Fesenko et al. (1998) in order to allow a better adaptation to the conditions of Russia and other East European regions. In addition to fixation (sorption) of radionuclides on soil particles - which was already in the model - now desorption from soil particles is considered. This is done by setting up two compartments representing the activity available and not available for plants. This model approach can be solved analytically (Fesenko et al., 1998).

Thus, the concentration of activity in the root zone of soil is given by

$$C_s(t) = \frac{A_s}{L\,\delta}\{a_s \cdot \exp(-b_1 \cdot t) + (1-a_s) \cdot \exp(-b_2 \cdot t)\} \cdot \exp(-\lambda_r \cdot t) \qquad (3.6)$$

where A_s = total deposition to soil (Bq m^{-2})
L = depth of root zone (m)
δ = density of soil (kg m^{-3})

and the coefficients

$$a_s = (\lambda_f - \lambda_d + \lambda_s + R)/(2 \cdot R)$$

$b_1 = (\lambda_f + \lambda_d + \lambda_s + R) / 2$

$b_2 = (\lambda_f + \lambda_d + \lambda_s - R) / 2$

where $R = \{(\lambda_f - \lambda_d + \lambda_s)^2 + 4 \cdot \lambda_f \cdot \lambda_d\}^{½}$

λ_f = rate of fixation (d^{-1}) of the radionuclides in the soil.

λ_d = rate of desorption (d^{-1}) of the radionuclides from the soil

λ_s = rate of activity decrease due to migration out of the root zone (d^{-1})

If the desorption rate λ_d is set to zero, then this approach is the same as that used in earlier versions.

In ECOSYS-87 the migration rate λ_s of radionuclides in soil is described by an approach based on the distribution coefficient K_d. Due to the strong sorption of a variety of elements to soil particles (e.g. Cs, Pu, Am, Ce), this approach leads to residence times in the order of several hundred years in the upper 25 cm soil layer, since the only downward transport process is due to sorption and desorption; this means only the transport of radionuclides dissolved in soil water is taken into account.

However, more recent investigations indicate (Bunzl et al., 1994; Bunzl and Kracke, 1994; etc.) that this approach causes pronounced overestimations of the residence time in soil. From measurements of depth profiles of Cs-137, Pu-239, Am-241 and Np-237 in undisturbed soils from both, Chernobyl and weapons' fallout, residence times can be derived that are considerably lower than those derived from the distribution coefficient K_d. It is interesting to note that the residence times of the radionuclides investigated are relatively similar although their chemical properties are different. Obviously, element-independent transport mechanisms as the transport of radionuclides attached to clay particles or bound to soil colloides play a more important role than previously assumed. Furthermore, the activity of soil animals as e.g. earthworms cause a turnover of soil.

The contributions of these processes for radionuclide transport in soil can hardly be separated. However, the overall migration can be estimated from the changes in the depth profiles with time. For radionuclides strongly sorbed to soil particles such as Cs-137, Pu-239/240 and Am-241, Bunzl et al. (1995) has determined migration velocities in the range of 0.3-1 cm/a. This is equivalent to a half-life of approximately 20-60 years in the ploughing layer. However, also forest soils were among the experimental sites. Although the observed migration in the mineral part of forest soils were not significantly different from the other soil types, the special conditions in forest soil could lead to an accelaration of migration due to the lower pH or higher concentrations of organic complexing agents. Therefore, in order to avoid overestimation of radionuclide migration, a default half-time of 100 y in the upper 25 cm soil layer seems to be appropriate for strongly bound radionuclides. In comparison to the approach applied up to now in ECOSYS, the revised residence half-times for cesium and plutonium are a factor of 6 lower.

Since the main transport mechanisms for strongly bound radionuclides are to a large extent element-independent, the value for the residence half-time for the upper 25 cm layer is applied for all other elements with high K_d as zirconium, niobium, ruthenium, cerium and plutonium. Iodine is under aerobic conditions strongly bound to organic matter, therefore also a half-life of 100 y is assumed.

The migration of strontium is somewhat faster since a larger fraction of strontium is present in a more mobile form. Observations indicate that strontium migrates approximately a factor of 2 faster than cesium. The distribution coefficient determined for barium, tellurium, manganese and zinc indicate that - similar to strontium - the migration as dissolved compound are more important than for cesium. Therefore, for these elements the same residence half-times in the upper soil layer are assumed as for strontium.

It is obvious that the last assumption is associated with considerable uncertainties. However, one should have in mind that all isotopes of these elements considered in ECOSYS (with the exception of I-129) are short-lived, therefore this lack of knowledge does not impact the reliability of the results.

The migration rates λ_s used in the default data set are given in Table 10 in Appendix B.

Fixation is especially important for Cs and Sr. The fixation rate is estimated as $\lambda_f = 2.2 \times 10^{-4}$ d^{-1} for Cs and $\lambda_f = 9 \times 10^{-5}$ d^{-1} for Sr. For the other elements, fixation is of minor importance and is not considered in FDMT.

3.1.3 Resuspension

In FDMT, the plant contamination due to resuspended soil is estimated from the mean dust load of the near-ground air which is about 100 mg m^{-3} in rural areas. It is assumed that this dust originates from resuspended soil. This assumption leads to a resuspension factor of 10^{-8} m^{-1}.

Plant contamination due to resuspension is proportional to the activity in the soil. Therefore it can also be expressed in units of the transfer factor soil-plant. Assuming a deposition velocity of 1 mm s^{-1}, a grass yield of 1 kg m^{-2}, and a weathering half-life of approximately 14 d, the resuspension factor, as assumed in FDMT, is equivalent to a transfer factor soil-plant of about $1x10^{-3}$. Though the resuspension factor in FDMT is dependent on the plant type, this value is taken as a default for all plants since there is not sufficient information available to determine an individual value for each plant species.

The resuspended soil fractions are primarily silt and clay. The concentration of activity in these soil fractions might be increased considerably compared to the mean soil contamination due to the strong binding of many radionuclides to clay minerals. The lower the clay and silt content, the higher the enrichment of activity in the clay and silt fraction (Livens and Baxter, 1988). This is taken into account in the model by using an enrichment factor for resuspension f_r which is multiplied with the resuspension factor. This factor may be dependent on the radionuclide and on the soil type. But data on soil type dependency are too sparse to allow a reasonable differentiation; therefore, up to now a single generic value is used for all soil types. Two classes of radionuclides are considered in the estimation of the enrichment factor: those existing primarily as kathions and anions. The values applied for f_r as a default in FDMT for the two nuclide classes are given in Table 11 in Appendix B.

3.1.4 General assumptions concerning time dependency of contamination of plant products

The time array for which contamination of feed and foodstuffs, as well as ingestion doses are calculated in FDMT starts on the day of deposition. The time resolution is dependent on the time t since deposition. The step width ###t of the time array is as follows:

0 days < t ### 14 days => ###t = 1 day
2 weeks < t ### 8 weeks => ###t = 7 days
3 months < t ### 24 months => ###t = 30 days
end of year 3, 4, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100.

For allowing real-time assessments for a big number of locations (grid points) the time dependency of the crops' contamination is first calculated for unit deposition to the foliage and unit deposition to soil. These normalised functions are then multiplied with the actual deposition data at each location. Due to technical constraints (memory requirement) some simplifying assumptions have to be made in these calculations:

- The deposition occuring during one calendar day is considered to happen instantaneously at the beginning of the day.
- For longer lasting deposition events the whole deposition period is split up into daily deposition events. The deposition of each day is considered to happen instantaneously at the beginning of that day.
- During the first two weeks after beginning of deposition the contribution of each deposition day is added up. The relative time dependency of activity concentration in plants is considered to be the same for each deposition day as it is for the first deposition day.
- For all times later than three weeks after deposition the assumption is made that the whole deposition has occured at once on the first day of deposition.

Before the first day of deposition it is assumed that the feed and food products are uncontaminated; i.e. radioactivity already existing in the environment is not considered. Concerning the time dependency of the plant's contamination after the day of deposition several groups of plants are considered:

- Grass is considered to be harvested continuously. After some time external contamination is no longer considered and contamination is due to root uptake only.

  The grass model includes the production of hay: During hay harvest period the average contamination of fresh grass is calculated, and then multiplied by a factor of 5 (considering the loss of water during hay preparation). The harvest period is subdivided into two intervals by a parameter giving the end of the first interval. During the first interval a special weighting factor can be defined taking into account the varying harvesting intensity during the whole harvest period. Example: If the harvest interval for hay is from 1 June till September 30, the end of first intervall is 1 August, and the weighting factor of the first interval is 2, then it is assumed that 2/3 of the whole harvest is produced in the first half of the harvest period.

  Before the beginning of the first hay harvest period after deposition, hay is assumed to be uncontaminated. This may lead to an underestimation of animal products' contamination if there is some contamination of stored feed (e.g. if contaminated rain falls into a silo or hay storage).
- For points of time after the third calendar year no seasonal variations are considered in FDMT: here only an average annual contamination is calculated.

- For many plants it is assumed that they are stored for consumption inbetween two harvest periods. The contamination of the stored product can be calculated as

  * the average contamination of the preceeding harvest period, or

  * the contamination at the end of the preceeding harvest period.

  For this purpose, the harvest period is subdivided into two parts, and for the first sub-period a weighting factor for harvesting intensity is used. If this weighting factor is set to 1.0, then an average contamination over the whole harvest period is calculated; if the weighting factor is set to zero, then only the second sub-period (which can be defined as the last day only) is considered for the estimation of the stored products' contamination.

The approaches of FDMT for modelling the different types of plants can be grouped as given in the following table.

Type	Used e.g. for	External contamination	Contamination of stored products
1	Grass	Weathering Growth dilution explicitely Translocation into/from root zone	No storage; available all year round
2	Hay	Weathering Growth dilution explicitely Translocation into/from root zone	Average of harvest period (2 harvest intervals)
3	Maize [1] Beet leaves [1]	Weathering Growth dilution implicitely	Average of harvest period (2 harvest intervals)
4	Leafy vegetables	Weathering Growth dilution implicitely	No storage; available all year round (but no growth during winter time)
5	Cereals [1] Potatoes [1] Beet [1] Corn cobs [1] Root vegetables [2] Fruit vegetables [2] Fruit [1] Berries [2]	Translocation	Average of harvest period (2 harvest intervals)

[1] stored products have contamination of last day of harvest period

[2] stored products have average contamination of whole harvest period

3.2 Contamination of animal products

The contamination of animal products (milk, meat, eggs) results from the activity intake of the animals and the kinetics of the radionuclides within the animals. The amount of activity ingested by the animals is calculated from the concentration of activity in the different feedstuffs which have been contaminated by the pathways decribed above, and from the feeding rates.

Ingestion of soil by grazing cattle is included in the feedstuff contamination. The soil intake of animals is quantified in the model parameters by a factor f_{si} which is defined as the amount of soil (dry weight) per unit fresh weight of crop. This factor can be given for each of the plants separately. It varies widely depending on the grazing management and the condition of the pasture. Taking into account the feeding of mechanically prepared hay and silage during winter and an intensive grazing regime on well fertilized pasture, a mean annual soil intake of 2.5% ($f_{si} = 0.025$) of the grass dry matter intake seems to be appropriate. This nuclide-independent value is equivalent to a soil-plant transfer factor of 5×10^{-3}; it is added to the transfer and resuspension factor within FDMT when calculating the long-term crop's contamination. This means that, for all elements with a transfer factor lower than 5×10^{-3}, soil-eating is the dominating long-term pathway for the contamination of milk and meat from grazing cattle, presuming that resorption in the gut is the same for soil-bound and plant-incorporated radionuclides.

The intake of activity from feedstuffs by animal m is given by

$$A_{a,m}(t) = \sum_{k=1}^{K_m} C_k(t) \cdot I_{k,m}(t) \qquad (3.8)$$

where $A_{a,m}(t)$ = activity intake rate of the animal m (Bq d^{-1})
K_m = number of different feedstuffs fed to the animal m
$C_k(t)$ = activity concentration (Bq kg^{-1}) in feedstuff k
$I_{k,m}(t)$ = feeding rate (kg d^{-1}) for feedstuff k and animal m.

Inhalation of radionuclides by the animals is taken into account; this pathway may be relevant for early contamination of animal products in certain cases (deposition during wintertime), but it is relatively unimportant for the total resulting doses.

The activity intake from inhalation by animal m during the period of plume passage is

$$A_{inh,m} = \overline{C}_{air} \cdot I_{inh,m} \qquad (3.9)$$

where $\overline{C}_{air}$ = time-integrated activity concentration in air (Bq·s·m^{-3})

$I_{inh,m}$ = inhalation rate (m^3 s^{-1}) of animal m

The default inhalation rates of animals (according to Pröhl and Müller, 1999) are given in Table 12 in the appendix. For the inhaled activity the same transferfactor to animal products as for ingested activity is assumed. This assumption is justified by the fact that for most elements the same or very similar resorption factors f_1 for inhalation and ingestion is used in the metabolic models for deriving dose conversion factors.

Indoor deposition onto animals' feedstuffs (e.g. in the stable, in the silo) is another pathway which can be of relative relevance for milk contamination in the case that the animals are fed on feedstuffs harvested before the deposition (which are considered as uncontaminated in FDMT). However, it depends strongly on the actual situation so that no general model can be given.

Plants or products processed from plants or animal products (see eqn 3.10 below) can be considered to be feedstuffs for animals. The default feeding diets assumed in FDMT are summarized in Table 12 in Appendix B. These intake rates are used as long as no specific information is available. However, for a realistic dose assessment in emergency situations, the feeding regimes have to be adapted to the season-dependent feed compositions of the specific region under consideration. FDMT can consider complex time-depending feeding diets consisting of a mixture of up to 8 different feedstuffs.

The transfer of radionuclides from fodder into animal product l is described by the equilibrium transfer factor TF_m and one or two exponentials using biological excretion rates:

$$C_m(T) = TF_m \cdot \sum_{j=1}^{J} \left\{ a_{m,j} \cdot \int_0^T A_{a,m}(t) \cdot \lambda_{b,mj} \cdot \exp\left[-(\lambda_{b,mj} + \lambda_r)(T-t) \right] dt \right\} \tag{3.10}$$

where $C_m(T)$ = activity concentration (Bq kg^{-1}) in animal product m at time T

TF_m = transfer factor (d kg^{-1}) for animal product m

J = number of biological transfer rates

$a_{m,j}$ = fraction of biological transfer rate j

$\lambda_{b,mj}$ = biological transfer rate j (d^{-1}) for animal product m.

The feed-animal product transfer factors and the biological half-lives (according to the transfer rates) applied as a default in FDMT are given in Tables 13 and 14 in Appendix B, respectively. It is possible to modify these factors in the RODOS data base according to local conditions, if necessary.

It should be noted that the data base for the transfer of Zr, Nb, Te, Ru, Ba, Ce, Pu, Mn and Zn to animal food products is rather poor. Therefore, the uncertainty for these parameters is considerable. These parameters are often derived from short-time experiments; although, long-term components of the kinetics can contribute significantly to the transfer. Furthermore, the chemical forms of the tracers used in the experiments are often not representative of radionuclides released from nuclear facilities. However, the ingestion of contaminated animal food products does not contribute significantly to the total dose for these elements, and, in many cases, this pathway is negligible.

3.3 Contamination of feedstuffs and foodstuffs

The contamination of human foodstuffs and of the animals' fodder is calculated taking into account the activity enrichment or dilution during processing and culinary preparation as well as processing and storage times. The concentration of activity in product k (feed- or foodstuff) is calculated from the raw product by

$$C_k(t) = C_{k0}(t-t_{p,k})\cdot P_k \cdot\exp(-\lambda_r\cdot t_{p,k}) \qquad (3.11)$$

where $C_k(t)$ = activity concentration (Bq kg^{-1}) in product k ready for consumption at time t

$C_{k0}(t)$ = activity concentration (Bq kg^{-1}) in the raw product at time t

P_k = processing factor for product k

λ_r = radioactive decay constant (d^{-1})

$t_{p,k}$ = storage and processing time (d) for product k.

The default processing factors applied in FDMT are summarized in Table 15 in Appendix B. For strontium, iodine and cesium there is a relatively good data base available while for all other elements due to lack of data the default values as given in Table 15 in Appendix B are applied. The storage times given in Table 16 in Appendix B are considered to be the mean time period between the harvest and the beginning of product consumption. It should be noted that these storage and processing times may change considerably in the case of radioactive contamination if decontamination is a goal.

4 Dose calculation

4.1 Location factors

In RODOS location factors are defined as the ratio of the average effective dose rate received at a specific location to that received outdoors on an open lawn without any shielding or filtering structures for the same air concentration of radionuclides or deposited activity (in some references the terms "shielding factors" or "modifying factors" are used for location factors). By definition location factors include occupancy factors, which give the average fraction of time spent at the specific location. These occupancy factors are simply multiplied with the location factor as given for 100% occupancy of the specific location. The same location factors are also applied for all other organ doses besides effective dose, due to a lack of knowledge for organ specific location factors.

Since the dose rate on an open lawn is time dependent because of the increasing attenuation due to the migration of radionuclides in the soil and the physical decay, location factors only contain a relative time dependence, e.g. they can decrease or increase with time.

Location factors consider different processes which determine the radiation exposure depending on the regarded exposure pathway. Therefore, the assumptions for each exposure pathway are explained separately in this section.

In FDMT 6.0 a new possibility has been introduced: Location specific shielding factors can be given in the geographical data base (so-called “shielding grid”). The data given in the shielding grid are time averaged, i.e. considering both staying indoors and outdoors. Individual shielding factors for the pathways cloud shine, ground shine shortterm, ground shine long term, inhalation short term, inhalation long term (resuspension) and occupancy factors (fraction of time spent indoors) can be given. Occupancy factors are only used for the calculations if for one ore more exposure pathways no location factor is available (indicated by a negative number in the shielding grid).

Only if there is no location specific information available in the shielding grid (this is indicated by negative numbers), the model for calculating location factors as used in previous versions of FDMT is applied:

1. The prevailing house type (low, medium or high shielding) at one location is derived from the population density:

   if population density < lower limit $\Rightarrow$ low shielding houses
   if population density > lower limit and < upper limit

⇒ medium shielding houses

if population density > upper limit ⇒ high shielding houses

The limits are stored in the data base of RODOS and can be defined separately for each radioecological region. The population density is read in from the geographical data base of RODOS.

2. The location factors for an occupancy factor of 100% for each exposure pathway are read in from the RODOS data base for the according house type. The location factors are defined for each radioecological region separately to account for variations in house building standards in different countries.
3. The occupancy factors (fraction of time spent indoors on average) are taken – if available - from the data in the shielding grid. If there is no location specific occupancy factor available for a location (indicated by a negative number in the shielding grid), the region specific default occupancy factor is read in from the data base for the according radioecological region.
4. Location factors as retrieved from the data base are multiplied with the occupancy factors to determine the location factors for the given location. Both, location factors including the appropriate occupancy factor or an occupancy factor of 100% are provided as output of Subroutine LOCATION_FACTOR.

For the occupancy factor f_{in} (average fraction of time spent indoors) a default value of 0.8 is used. For each radioecological region more appropriate occupancy factors can be applied and stored in the RODOS data base.

4.2 Internal dose from ingestion

The intake of activity by man is calculated from the time-dependent concentrations of activity in foodstuffs and the human consumption rates:

$$A_h(t) = \sum_{k=1}^{K} C_k(t) \cdot V_k(t) \tag{4.1}$$

where $A_h(t)$ = human intake rate (Bq d^{-1}) of activity
K = number of foodstuffs considered
$C_k(t)$ = concentration of activity (Bq kg^{-1}) of foodstuff k
$V_k(t)$ = consumption rate (kg d^{-1}) of foodstuff k.

In FDMT the foodstuffs are assumed to be locally produced, i.e. the calculated ingestion doses represent potential doses for people producing all their food locally. Age-dependent consumption rates of the average population are applied. Besides that, consumption rates of some special groups (e.g. vegetarians) are used for estimating ingestion doses for these groups as input to the Dose Combination Module DCM. Though the data base of these consumption rates has considerable uncertainty, it can be used to get a feeling about the variability of the ingestion dose due to variability of the consumption rates.

All consumption rates can be adapted individually for each radioecological region. As a default, average German consumption rates for the age groups 1, 5, 10, 15 y and adults as given in Table 17 are applied.

In the Dose Combination Module DCM doses not only for the average population but also for some special groups are estimated. For this purpose, FDMT calculates also ingestion doses for vegetarians, hunters and fishermen (no or reduced ingestion of meat). Consumption rates for these groups have been estimated from (Arbeitsgemeinschaft 1995) and (CEC 1991).

The dietary habits can be assumed to be season-dependent. In the default data set, for leafy vegetables it is assumed that the consumption rate in summertime is higher than the mean annual rate, and in wintertime, only a small fraction of the consumed vegetables is harvested outdoors (the rest is produced in greenhouses or imported from abroad). From May through October, a factor of 1.5 and from November through April, a factor of 0.1 is applied to the consumption rates for leafy vegetables given in Table 17 in Appendix B.

The dose D_{Ing} (T) due to ingestion of contaminated foodstuffs within the time T after deposition is given by

$$D_{Ing}(T) = \int_0^T A_h(t)\, g_{Ing}(t)\, dt \qquad (4.2)$$

where D_{Ing} (T) = ingestion dose (Sv)
g_{Ing} (t) = age-dependent dose factor for ingestion (Sv Bq^{-1}).

The dose factors applied in FDMT were calculated using the NRPB internal dosimetry program PLEIADES, which is consistent with publications ICRP-68, ICRP-72, and IAEA BSS. They give the dose committment for an individual from its age at ingestion until the age of

70 y. For activity intake above the age of 20 y, the 50-year dose committment is calculated.

4.3 Internal dose from inhalation

4.3.1 Inhalation dose from plume

The dose D_{Inh} due to inhalation of radionuclides during the passage of the radioactive cloud is calculated from the time-integrated activity concentration in the near ground air, the inhalation rate, and the age-dependent dose factor for inhalation. In addition, a reduction factor can be applied taking into account the lower activity in air inside houses:

$$D_{Inh} = \overline{C}_{air} \cdot I_{Inh} \cdot g_{Inh} \cdot R_{Inh} \tag{4.3}$$

with D_{Inh} = inhalation dose (Sv)
$\overline{C}_{air}$ = time-integrated activity concentration in air ($Bq \cdot h \cdot m^{-3}$)
I_{Inh} = inhalation rate ($m^3 \cdot h^{-1}$)
g_{Inh} = dose factor for inhalation ($Sv \cdot Bq^{-1}$)
R_{Inh} = location factor for staying indoors.

The age-dependent inhalation rates applied for the five age-groups (average over day considering different states of corporeal activity) are given in Table 18 in Appendix B. They are based on ICRP publication 71 (1995).

In RODOS the following location factors R_{Inh} are default values; they can be adapted for each radioecological region separately. These location factors are given for an occupancy factor of 100% in Table 19 in Appendix B.

The same criteria as described in chapter 5.3.1 is used to derive the prevailing house type at each location.

In FDMT potential (R_{inh} is set to 1.0) and expected (using the above data) dose for inhalation can be calculated.

4.3.2 Inhalation dose from resuspended radionuclides

The amount of radioactive material which is resuspended from the soil by wind or other processes depends on many factors, as e.g. the conditions during deposition of the radionuclides (wet/dry deposition), the size and chemical conditions of the radioactive particles, the type of surface (vegetation, soil, urban surfaces), climatic conditions, and others (Sehmel, 1980). Therefore, there is large variability in the observed amount of resuspended material. A commonly used way to describe quantitatively the resuspension process is to apply the following approach:

$$C_{air,r}(t) = A_{soil} \cdot K_R(t) \cdot \exp(-\lambda_r \cdot t) \tag{4.4}$$

with $C_{air,r}(t)$ = concentration of activity in the near ground air ($Bq\ m^{-3}$) due to resuspension
A_{Soil} = total deposition to ground ($Bq\ m^{-2}$)
$K_R(t)$ = time dependent resuspension factor (m^{-1})

In many approaches in the literature (e.g. Linsley, 1978; Garland et al., 1992), the resuspension factor is expressed by an exponential together with a constant term:

$$K_R(t) = R_1 \cdot \exp(-R_2 \cdot t) + R_3 \tag{4.5}$$

with R_1 = resuspension factor (m^{-1}) immediately after deposition
R_2 = rate of exponential decrease of $K_R(t)$ after deposition (d^{-1})
R_3 = long term resuspension factor (m^{-1})

Before the time of the Chernobyl accident, typical values for R_1have been in the range of $1 \cdot 10^{-6}\ m^{-1}$ to $1 \cdot 10^{-4}\ m^{-1}$, where the lower values seem to be representative for vegetated surfaces in moderate humid climate while the higher values apply to urban areas with traffic. Measurements of Caesium in air after the Chernobyl accident at different locations could be fairly good fitted with an exponential using A_R values in the range $3.6 \cdot 10^{-9}\ m^{-1}$ to $4.9 \cdot 10^{-8}\ m^{-1}$, and values of the parameter R_2, which specified the exponential decline, were in the range of 0.026 to 0.124 per month (Garland et al., 1992). In this study, due to the limited observation period, a constant term R_3 could not be observed. The R_1 factor showed a significant negtive correllation with the total amount of deposited activity; possible explanations for this are different deposition patterns (wet resp. dry deposition) at locations with high and low deposition, or some long range transport of resuspended material.

In the dose module of RODOS the approach as given above is used for describing resuspension. The parameters R_1, R_2, and R_3 can be adjusted by the user. As default values, a short term resuspension factor of $5 \cdot 10^{-8}\ m^{-1}$ (representing the highest values observed after the Chernobyl accident), a decrease rate of $0.003\ d^{-1}$ (= $0.09\ month^{-1}$) and a long term resuspension factor of $1 \cdot 10^{-9}\ m^{-1}$ (though not observed after the Chernobyl accident, this value is taken to avoid underestimation for long times) seem appropriate for cesium (the above measurements are mostly based on cesium). As described in Chapter 3.1.3, the concentration of activity in the resuspended soil fractions might be increased considerably compared to the mean soil contamination; this is due to the strong binding of many radionuclides to clay minerals. Therefore, the activity concentration as described by equations (4.4) and (4.5) is multiplied by the resuspension enrichment factor f_r . The applied values for f_r for different elements and soil types are given in Table 11 (Appendix B). Since cesium has an enrichment factor of 3, the following values applied for R1 and R3 are taken in order to meet the above default resuspension factors for cesium: $R_1 = 1.5 \cdot 10^{-8}$ m^{-1}, $R_2 = 0.003$ d^{-1} and $R_3 = 3 \cdot 10^{-10}$ m^{-1}.

Calculation of inhalation dose from resuspended activity is done in the same way as for inhalation from the plume (see Section 4.3.1).

4.4 External dose from radionuclides in the cloud

RODOS is to be applied at very different distances from the source emitting radionuclides to the atmosphere: from a few hundred meters up to a European scale. While at large distances (at least several kilometers) a semi-infinite homogeneous cloud could be assumed for calculating γ-exposure due to radiation from the cloud, this is not justified for smaller distances; instead of it, the dose rate has to be calculated by 3-dimensional integration over the activity concentration in the plume. Therefore, in RODOS the average effective dose rate from airborn radionuclides for adults for each time interval of the atmospheric dispersion time grid, $\dot{D}_c(\Delta t_i)$, has been defined as interface between the atmospheric dispersion modules and the dose module FDMT. External γ-exposure from the cloud integrated over the time periods Δt_i for is calculated by:

$$D_c = \sum_i \dot{D}_c(\Delta t_i) \cdot \Delta t_i \cdot R_c \qquad (4.6)$$

where D_c = effective dose for adults due to external radiation from the cloud (Sv)

$\dot{D}_c$ = effective dose rate for adults due to external radiation from the cloud (Sv/s)

R_c = location factor

Doses and dose rates for other age groups or for specific organs are calculated from the effective doses or dose rates for adults by scaling with the respective ratio of dose conversion factors:

$$D_{c,ik} = D_c \cdot g_{c,ik} / g_c \tag{4.7}$$

$D_{c,ik}$ = Dose (Sv) for age group i and organ k

$g_{c,ik}$ = dose conversion factor for exposure from the cloud (Sv s^{-1} Bq^{-1} m^3) for age group i and organ k

g_c = dose conversion factor for exposure from the cloud (Sv s^{-1} Bq^{-1} m^3) for effective dose of adults

The age-dependent dose factors $g_{c,ik}$ for exposure from the cloud are taken from Jacob et al.(1990).

The following location factors R_c are default values for; they can be adapted for each radioecological region separately. These location factors are given for an occupancy factor of 100% in Table 20 in Appendix B.

The criteria as described in chapter 4.1 is used to derive the prevailing house type at each location.

In FDMT potential (R_c is set to 1.0) and expected (as in the above formula) external dose from cloud can be calculated.

4.5 External dose from radionuclides deposited on ground

The dose by gamma radiation from deposited radionuclides is calculated by

$$D_g(T) = \dot{K}_g \cdot R_g \cdot \int_0^T y(t) \cdot g_g(t) \cdot \exp(-\lambda_r \cdot t) \cdot dt \tag{4.8}$$

where $D_g(t)$ = dose (Sv) from gamma radiation of deposited nuclides from time of deposition up to time t

$\dot{K}_g$ = kerma rate in air (Gy s^{-1}) at time of deposition from radionuclides deposited on ground (on lawn)

$g_g(t)$ = age-dependent dose factor for exposure from ground (Sv Gy^{-1})

R_g = location factor

$y(t)$ = corrective function for shielding due to migration of the radionuclides into deeper soil layers.

The age-dependent dose factors g_g for external exposure from deposited radionuclides are gained by dividing the dose-equivalent rates per unit activity per unit area by the kerma rate in air at 1 m above ground for infinite plane sources in ground at a depth of 5mm as given in Jacob et al.(1990).

The following location factors R_g for groundshine are default values; they can be adapted for each radioecological region separately. As a first approach location factors for short and long term are set to the same values. These location factors are given for an occupancy factor of 100% in Table 21 in Appendix B.

The criteria as described in chapter 4.1 is used to derive the prevailing house type at each location.

Future improvements may include:

- consideration of type of deposition (dominantly dry or wet) by comparing the wet and dry deposition onto a reference surface (e.g. lawn). This requires a larger data base which contains location factors for all three house categories and also for both types of deposition.
- consideration of time dependence of location factor. Some studies on the time dependence of the location factors show relatively small variations with time, but at least appropriate values for short term (first hours and days) and long term (months, years) should be introduced.
- consideration of age dependence of occupancy factors

The consideration of nuclide specific location factors due to the energy dependence of structure shielding seams not to be very reasonable due to the relatively small variations in location factors for most building types (low and medium shielding houses) compared with the uncertainties e.g. in the nuclide spectrum, the deposition, the urban environments or the occupancy times.

In FDMT potential (R_g is set to 1.0) and expected (as given above) external dose from ground can be calculated.

The following approach (Jacob 1991) is used for the corrective function for shielding y(t) :

$$y(t) = a_1 \exp(-\lambda_{m1} \cdot t) + a_2 \exp(-\lambda_{m2} \cdot t) \tag{4.9}$$

with

$\lambda_{m1}, \lambda_{m2}$ = migration rates ($\lambda_1 = 1.01 \times 10^{-3}$ d^{-1}, $\lambda_2 = 0.0$ d^{-1})
a_1, a_2 = contribution fractions of the migration rates ($a_1 = 0.6$, $a_2 = 0.4$).

These migration rates have been deduced from measurements of the external exposure from cesium deposited after the Chernobyl accident. They are regarded to be representative for a partly wet and partly dry deposition. For other elements no such data are available, but long term external exposure is of minor importance for most of them. Therefore up to now the above data for cesium are applied for all elements.

Attention! Due to technical reasons presently an older set of dose factors is used. It contains a time-dependent shielding function given by Gale!

4.6 External dose from radionuclides deposited on skin and clothes

Sparse data are available about calculation of external dose from contamination of skin and clothes. Especially calculation of deposition to these surfaces is associated with high uncertainty. Calculation of doses from this pathway in FDMT is based on the following assumptions:

- Dry deposition velocity $v_{g,sk}$ on skin is the same as that on clothes (Jones, 1991). This deposition velocity can be chosen by the user; a default value of $1 \cdot 10^{-3}$ m·s^{-1} is used. Reduction of dry deposition due to staying inside buildings is assumed to be equal to the reduction factor for inhalation, R_{Inh}.

- For wet deposition, the average contamination of cloth/skin is assumed to be $f_{sk,w}$ times that of the total wet deposition to ground. As a default, $f_{sk,w} = 0.1$ (Jones, 1991) is used. Wet deposition onto skin is only assumed during the fraction f_{out} (= 1 - f_{in}) of time when people are outdoors.

- A fraction of f_{cloth} of human skin surface is protected by clothes. This fraction can be chosen by the user; a default value of 0.8 is used.

- The time t_{sk} after which activity is removed is assumed to be the same for skin and clothes. As a default, 24 hours are taken for t_{sk}. During this time interval, reduction of radioactivity by radioactive decay only is considered.

- For skin contamination, skin dose is due to α-, β-, and γ-radiation of the nuclides, while for contamination of clothes the γ component only is efficient. The dose conversion factors, giving the dose rate in skin (averaged over depth of 50 - 100µm) and other organs for a unit skin contamination are taken from Jacobi et al. (1989):

  $g_{sk,sk}$ is the total dose rate in skin from unit skin contamination (Sv·s^{-1} per Bq·cm^{-2})

$g_{sk,sk,\gamma}$ is the γ-component of dose rate in skin from unit skin contamination (Sv·s-1 per Bq·cm^{-2})

$g_{sk,k}$ is the dose rate in organ k from unit skin contamination (Sv·s^{-1} per Bq)

With these assumptions, the mean skin dose H_{skm} is calculated by

$$H_{skm} = (C_{air} \cdot v_{g,sk} \cdot R_{Inh} + f_{sk,w} \cdot D_{wet} \cdot f_{out}) \cdot \{g_{sk,sk,\gamma} \cdot f_{cloth} + g_{sk,sk} \cdot (1 - f_{cloth})\} \cdot \frac{1}{\lambda_r} \cdot \{1 - \exp(-\lambda_r \cdot t_{sk})\} \qquad (4.10)$$

For organs other than skin the dose from skin/cloth contamination is

$$H_{sk} = (C_{air} \cdot v_{g,sk} \cdot R_{Inh} + f_{sk,w} \cdot D_{wet} \cdot f_{out}) \cdot g_{sk,k\gamma} \cdot A_{skin} \cdot \frac{1}{\lambda_r} \cdot \{1 - \exp(-\lambda_r \cdot t_{sk})\} \qquad (4.11)$$

with A_{skin} = total area of skin (m²)
and other symbols as defined above.

The location factor for the dry deposition component is the same as for the exposure from inhalation, since this factor gives the reduction of the indoor air concentration of radionuclides compared to the outdoor concentration and the dry deposition is linearly related to the air concentration. The location factor for the wet deposition component is simply zero, since wet deposition cannot occur indoors.

In FDMT potential (R_{Inh} and f_{out} is set to 1.0) and expected (as in the above formula) external dose from skin/cloth contamination can be calculated.

4.7 Calculation of collective doses

The assessments of collective doses in FDMT can only be regarded as rough estimations of the real collective doses since due to the limited input information several simplifying assumptions have to be made. Different approaches are used for collective doses for the ingestion pathway, and those for all other pathways. Therefore, no collective doses for the sum of all pathways is given.

Collective doses are first estimated individually for all locations of the calculation grid of RODOS by the methods described below. Then they are summed up over all locations to yield a total collective dose for the whole considered area, and a frequency distribution (giving the number of persons having a dose equal or below the respective dose) is built up. It has to be taken in mind that such a frequency distribution does not reflect the real distribution of individual doses since all people at one location are considered to have the same dose.

4.7.1 *Ingestion pathway:*

The collective dose at a location (i.e. grid point of calculation in RODOS) due to consumption of contaminated foodstuffs is based on the amount of foodstuffs produced at that location. Only that part of products which is consumed by humans is considered. Collective dose is estimated as that effective dose equivalent which arises if these products are eaten by adults, no matter where they are eaten (this might be by people living at the considered location, or somewhere else). Collective doses can be calculated only for those foodstuffs for which production data are available. Since it can be expected that production data will never be available for all produced foodstuffs, summing up the collective doses for all foodstuffs considered seems to be not very useful; the result would be a more or less arbitrary number.

For a given location, collective dose from ingestion of raw product k in the time period from deposition up to time T is calculated as

$$D_{\mathrm{Ing}}^{\mathrm{Col}}(T) = g_{\mathrm{Ing,a}} \cdot PR_k \cdot \exp(-\lambda_r \cdot t_{pk}) \cdot \int_0^T C_{k0}(t) \cdot dt \qquad (4.12)$$

with $D_{\mathrm{Ing}}^{\mathrm{Col}}(t)$ = collective dose from ingestion of foodstuff (raw product) k

$g_{\mathrm{Ing,a}}$ = ingestion dose factor (Sv Bq^{-1}) for adults

PR_k = production rate of foodstuff k (kg a^{-1})

t_{pk} = storage and processing time (d) for product k

$C_{k0}(t)$ = activity concentration (Bq kg^{-1}) in the raw product at time t

If a certain raw product is used to process more than one foodstuff, then the shortest storage and processing time t_{pk} is used in this calculation. Further, loss of activity from the food chain during food processing and culinary preparation is not considered in this estimation since production data are given for raw foodstuffs, and there is no information on processing of them. For these reasons, the resulting collective dose for a (raw) foodstuff has to be regarded as an upper limit.

4.7.2 Pathways different from ingestion:

For all exposure pathways except ingestion, collective dose is roughly estimated from the expected individual dose of an adult, multiplied by the number of inhabitants living at the location:

$$D_p^{COL} = D_p \cdot N \tag{4.13}$$

with D_p^{Col} = collective dose from pathway p for a certain location

D_p = individual dose of an adult at the considered location

N = number of inhabitants living at the considered location

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6 Appendix A: List of Symbols

δ = density of soil (kg m-3)

λ_b = dilution rate by increase of biomass (d-1)

$\lambda_{b,mj}$ = biological transfer rate j (d-1) for animal product m

λ_{m1},λ_{m2} = migration rates (d-1) for calculation of external exposure from deposited radionuclides

λ_f = rate of fixation (d-1) of the radionuclides in the soil

λ_r = radioactive decay rate (d-1)

λ_s = rate of activity decrease due to migration out of the root zone (d-1)

λ_t = rate of activity decrease (d-1) due to translocation to the root zone

λ_w = loss rate (d-1) due to weathering

a = fraction of activity translocated to the root zone

a_1,a_2 = contribution fractions of the migration rates

a_{mj} = fraction of biological transfer rate j

$A_{a,m}$ (t) = activity intake rate of the animal m (Bq d^{-1})

A_{ds} = dry deposition to soil (Bq m^{-2})

A_{dg} = dry deposition to grass (Bq m^{-2})

A_{di} = dry deposition onto plant type i (Bq m^{-2})

A_g = total activity deposited onto grass (Bq m^{-2})

A_h (t) = human intake rate (Bq d^{-1}) of activity

A_i = total deposition onto plant type i (Bq m^{-2})

A_s = total deposition to soil (grassland) (Bq m^{-2})

A_w = total wet deposition (Bq m^{-2})

C_{air} = concentration of activity in air (Bq m^{-3})

$\overline{C}_{air}$ = time integrated concentration of activity in air (Bq s m^{-3})

$C_{air,r}(t)$ = concentration of activity in the near ground air (Bq m^{-3}) due to resuspension

C_k (t) = activity concentration (Bq kg^{-1}) in feed or foodstuff k

$C_{i,r}(t)$ = concentration of activity (Bq kg^{-1})in plant type i due to root uptake at time t after deposition

$C_s(t)$ = concentration of activity (Bq kg^{-1}) in the root zone of soil at time t

D_c = dose due to external radiation from the cloud (Sv)

$\dot{D}_c$ = dose rate due to external radiation from the cloud (Sv s^{-1})

D_g = dose (Sv) from gamma radiation from ground from time of deposition up to time t

D_{Ing} = dose (Sv) from ingestion of contaminated foodstuffs

$D_{Ing}^{Col}(t)$ = collective dose from ingestion up to time t

D_{Inh} = inhalation dose (Sv)

D_{wet} = wet deposited activity (Bq·m^{-2})

f_{cloth} = fraction of human skin surface which is protected by clothes

f_{in} = fraction of time people spend indoors

f_{out} = fraction of time people spend outdoors

f_r = enrichment factor for resuspended soil

$f_{sk,w}$ = fraction of total wet deposition which is deposited onto skin or clothes

$f_{w,i}$ = interception fraction for wet deposition onto plant type i

g_c = dose factor for exposure from the cloud (Sv Gy^{-1})

g_g = dose factor for exposure from ground (Sv Gy^{-1})

g_{Ing} = dose factor for ingestion (Sv Bq^{-1})

g_{Inh} = dose factor for inhalation (Sv·Bq^{-1})

$g_{sk,sk}$ = total dose rate in skin from unit skin contamination (Sv·s^{-1} per Bq·cm^{-2})

$g_{sk,sk,\gamma}$ = γ-component of dose rate in skin from unit skin contamination (Sv·s^{-1} per Bq·cm^{-2})

$g_{sk,k}$ = dose rate in organ k from unit skin contamination (Sv·s^{-1} per Bq·cm^{-2})

$I_{k,m}(t)$ = feeding rate (kg d^{-1}) for feedstuff k and animal m

I_{Inh} = inhalation rate (m^3·h^{-1})

k = normalization factor for calculation of LAI of grass from yield (m^2 kg^{-1})

K_d = distribution coefficient (cm^3 g^{-1})

$\dot{K}_g$ = kerma rate in air (Gy s^{-1}) from radionuclides deposited on ground (at time of deposition)

K_m = number of different feedstuffs fed to the animal m

L = depth of root zone (m)

LAI_g = leaf area index of grass at time of deposition

LAI_i = leaf area index of plant type i at time of deposition

P_k = processing factor for product k

R = amount of rainfall of a rainfall event (mm)

R_1,R_2,R_3 = parameters describing time dependency of resuspended activity concentration in air (m^{-1})

R_c = reduction factor for staying at different locations (external exposure from cloud)

R_g = reduction factor for staying at different locations (external exposure from ground)

R_{Inh} = reduction factor for staying indoors (inhalation dose)

S_i = retention coefficient of plant type i (mm)

t_{pk} = storage and processing time (d) for product k

t_{sk} = time after which activity is removed from skin/ clothes (h)

TF_i = soil to plant transfer factor for plant type i

TF_m = transfer factor (d kg^{-1}) for animal product m

$T_i(\Delta t)$ = translocation factor for plant type i

v_a = velocity of percolation water in soil (m a^{-1})

$v_{g,sk}$ = dry deposition velocity onto skin and clothes ($m \cdot s^{-1}$)

v_{gi} = dry deposition velocity for plant type i (m s^{-1})

V_k (t) = consumption rate (kg d^{-1}) of foodstuff k

y(t) = corrective function for shielding due to migration of the radionuclides into deeper soil layers.

Y_g = yield of grass at time of deposition (kg m^{-2})

Yi = yield of edible parts of plant type i

7 Appendix B: Default model parameters for Central European conditions

surface type	grassland	agricultural	forest	water	urban
z_0 (m)	0.05	0.1	1.0	0.0002	1.0
$R_{a,ref}$ (s/m)	44	33	8	183	8
f	1.0	0.75	0.18	4.16	0.18

Table 1: Roughness heights z_0, reference atmospheric resistances $R_{a,ref}$ and factors f (relative to the reference atmospheric resistance for grass) for different surface types

Surface type	Deposition velocity (mm s^{-1})		
	Aerosol bound radionuclides	Elemental iodine	Organic bound iodine
Soil	0.5	3.	0.05
Water	0.7	1.	0.5
Urban areas	0.5	5.	0.05
Pasture (grassland)	1.5	15.	0.15
Lawn	0.5	5.	0.05
Fruit trees	5.	50.	0.5
Other plants	2.	20.	0.2

Table 2: Deposition velocities $v_{gi,max}$ used in FDMT for soil, other surfaces and fully developed plant canopies

Plant species	Retention coefficient (mm)		
	I, Tc	Ce, Cs, Mn, Na, Nb, Pu, Rb, Ru, Sb, Te, Zr	Ag, Am, Ba, Cm, Co, La, Mo, Nd, Np, Pr, Rh, Sr, Y
Grass, cereals, maize	0.1	0.2	0.4
Other plants	0.15	0.3	0.6

Table 3: Retention coefficients S_i for different plants and elements used for calculation of wet interception

Plant species	Harvest	Yield (kg m^{-2})
Grass	1.5.-31.10.	1.5
Winter wheat	5.8.	0.5
Spring wheat	15.8.	0.5
Winter barley	15.7.	0.5
Spring barley	5.8.	0.4
Oats	10.8.	0.4
Rye	31.7.	0.4
Maize	15.8.-15.9.	5.0
Corn cobs	15.10.	1.5
Beet	20.9.-31.10.	5.0
Beet leaves	20.9.-31.10.	3.0
Potatoes	15.8.-24.9.	3.0
Leafy vegetables	1.1.-31.12.	2.0
Fruit vegetables	1.8.-15.10.	1.5
Root vegetables	1.8.-31.10.	2.0
Fruit	1.7.-15.10.	2.0
Berries	1.7.-15.10.	1.5

Table 4: Times of harvest and yields Y_i (fresh weight) of the crops considered in FDMT: default values for Central European conditions

Plant	Yield or leaf area index (LAI)							
Pasture	Date	1.1.	15.3.	15.5.	31.10.	1.11.		
	Yield	0.01	0.05	1.5	1.5	0.05		
Pasture (extensive)	Date	1.1.	15.3.	1.7.	31.10.	1.11.		
	Yield	0.01	0.05	1.5	1.5	0.05		
Lawn	Date	1.1.	15.3.	15.5.	31.10.	1.11.		
	Yield	0.01	0.05	0.5	0.5	0.05		
Winter wheat	Date	1.1.	20.4.	10.6.	5.8.	6.8.	25.10.	31.12.
	LAI	0.1	1	7	1	0	0	0.1
Spring wheat	Date	15.4.	20.6.	15.8.	16.8.			
	LAI	0	6	1	0			
Winter barley	Date	1.1.	1.4.	25.5.	15.7.	16.7.	5.10.	31.12.
	LAI	0.1	1	6	1	0	0	0.1
Spring barley	Date	15.4.	15.6.	5.8.	6.8.			
	LAI	0	5	1	0			
Oats	Date	15.4.	20.6.	10.8.	11.8.			
	LAI	0	5	1	0			
Rye	Date	1.1.	20.3.	20.5.	1.8.	2.8.	15.10.	31.12.
	LAI	0.1	1	6	1	0	0	0.1
Maize	Date	15.5.	20.6.	1.8.	15.10.	16.10.		
	LAI	0	1	5	4	0		
Beet	Date	10.5.	20.6.	1.8.	1.11	2.11.		
	LAI	0	1	4	3	0		
Potatoes	Date	20.5.	1.7.	1.8.	15.9.			
	LAI	0	4	4	0			
Root veg., fruit veg., fruit, berries	Date	15.4.	1.7.	1.10.	1.11.			
	LAI	0	5	5	0			

Table 5: Yield of pasture grass (kg m^{-2} f.w.) and leaf area indices (all other plants; m^2 m^{-2}) as function of the time of the year (between the given values linear interpolation is applied) for the plants considered in FDMT: default values for Central European conditions

Month	Dilution rate (d^{-1})	Half-life (d)
January - February	0.0	-
March	7.70×10^{-2}	9
April	2.89×10^{-2}	24
May	3.47×10^{-2}	20
June	3.47×10^{-2}	20
July	3.47×10^{-2}	20
August	3.47×10^{-2}	20
September	2.31×10^{-2}	30
October	1.73×10^{-2}	40
November - December	0.0	-

Table 6: Season dependent growth dilution rates λ_b and according half-lives for grass: default values for Central European conditions

Plant	Translocation factor					
Winter wheat	Δt	150	95	55	30	0
	T(Δt)	0	0.005	0.1	0.1	0.075
Spring wheat	Δt	120	80	50	30	0
	T(Δt)	0	0.005	0.1	0.1	0.075
Winter barley	Δt	150	75	50	25	0
	T(Δt)	0	0.01	0.1	0.1	0.075
Spring barley, oats	Δt	110	75	50	25	0
	T(Δt)	0	0.01	0.1	0.1	0.075
Rye	Δt	150	90	65	30	0
	T(Δt)	0	0.01	0.1	0.1	0.075
Corn cobs	Δt	155	115	85	45	0
	T(Δt)	0	0.01	0.1	0.1	0.02
Beet	Δt	174	122	91	0	
	T(Δt)	0	0.02	0.15	0.15	
Potatoes	Δt	128	72	55	0	
	T(Δt)	0	0.15	0.15	0	
Root veg.	Δt	183	122	14	0	
	T(Δt)	0	0.1	0.1	0.02	
Fruit veg.	Δt	167	106	14	0	
	T(Δt)	0	0.1	0.1	0.02	
Fruit	Δt	183	106	14	0	
	T(Δt)	0	0.1	0.1	0.02	
Berries	Δt	184	183	14	0	
	T(Δt)	0	0.1	0.1	0.02	

Table 7: Translocation factors $T_i(\Delta t)$ for mobile elements as function of the time Δt (d) before harvest.

Plant		Translocation factor				
Wheat [a]	Δt	80	55	40	20	0
	$T(\Delta t)$	0	0.002	0.005	0.02	0.075
Barley [a], oats	Δt	80	50	40	20	0
	$T(\Delta t)$	0	0.002	0.005	0.02	0.075
Rye	Δt	100	75	40	20	0
	$T(\Delta t)$	0	0.002	0.005	0.02	0.075
Corn cobs	Δt	85	0			
	$T(\Delta t)$	0	0.02			
Potatoes, beet		no translocation				
Root veg.		no translocation				
Fruit veg.	Δt	150	30	0		
	$T(\Delta t)$	0	0.005	0.02		
Fruit, berries	Δt	150	30	0		
	$T(\Delta t)$	0	0.005	0.02		

[a] Winter and spring varieties

Table 8: Translocation factors $T_i(\Delta t)$ for immobile elements as function of the time Δt (d) before harvest.

	Transfer factor soil-plant (Bq kg^{-1} plant f.w. per Bq kg^{-1} soil d.w.)								
Plant	Ag	Am	Ba	Ce	Cm	Co	Cs	I	La
Grass	$1\cdot10^{-1}$	$2\cdot10^{-4}$	$3\cdot10^{-2}$	$2\cdot10^{-3}$	$2\cdot10^{-4}$	$1\cdot10^{-2}$	$5\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Maize silage	$1\cdot10^{-1}$	$2\cdot10^{-5}$	$5\cdot10^{-2}$	$3\cdot10^{-3}$	$2\cdot10^{-5}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Corn cobs	$1\cdot10^{-1}$	$2\cdot10^{-5}$	$5\cdot10^{-2}$	$3\cdot10^{-3}$	$2\cdot10^{-5}$	$5\cdot10^{-3}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Potatoes	$2\cdot10^{-2}$	$1\cdot10^{-4}$	$4\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-4}$	$2\cdot10^{-2}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Beet	$2\cdot10^{-2}$	$1\cdot10^{-4}$	$4\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-4}$	$2\cdot10^{-2}$	$5\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Beet leaves	$2\cdot10^{-2}$	$1\cdot10^{-4}$	$4\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-4}$	$7\cdot10^{-2}$	$3\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Cereals	$1\cdot10^{-1}$	$2\cdot10^{-5}$	$1\cdot10^{-2}$	$3\cdot10^{-3}$	$2\cdot10^{-5}$	$5\cdot10^{-3}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Leafy vegetables	$5\cdot10^{-2}$	$1\cdot10^{-4}$	$2\cdot10^{-2}$	$1\cdot10^{-3}$	$1\cdot10^{-4}$	$3\cdot10^{-2}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Root vegetables	$1\cdot10^{-2}$	$1\cdot10^{-4}$	$2\cdot10^{-3}$	$4\cdot10^{-4}$	$1\cdot10^{-4}$	$2\cdot10^{-2}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Fruit vegetables	$1\cdot10^{-2}$	$1\cdot10^{-4}$	$2\cdot10^{-3}$	$4\cdot10^{-4}$	$1\cdot10^{-4}$	$5\cdot10^{-3}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Fruit	$1\cdot10^{-2}$	$1\cdot10^{-4}$	$2\cdot10^{-3}$	$4\cdot10^{-4}$	$1\cdot10^{-4}$	$5\cdot10^{-3}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$
Berries	$1\cdot10^{-2}$	$1\cdot10^{-4}$	$2\cdot10^{-3}$	$4\cdot10^{-4}$	$1\cdot10^{-4}$	$5\cdot10^{-3}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	$1\cdot10^{-1}$

Table 9: Transfer factors soil-plant TF_i and migration rate λ_s: default values for Central European conditions

	Transfer factor soil-plant (Bq kg^{-1} plant f.w. per Bq kg^{-1} soil d.w.)								
Plant	Mn	Mo	Na	Nb	Nd	Np	Pr	Pu	Rb
Grass	$8\cdot10^{-1}$	$5\cdot10^{-2}$	$5\cdot10^{-2}$	$4\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$2\cdot10^{-4}$	$1\cdot10^{-1}$
Maize silage	$6\cdot10^{-2}$	$5\cdot10^{-2}$	$5\cdot10^{-2}$	$6\cdot10^{-3}$	$1\cdot10^{-1}$	$3\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$
Corn cobs	$6\cdot10^{-2}$	$5\cdot10^{-2}$	$5\cdot10^{-2}$	$6\cdot10^{-3}$	$1\cdot10^{-1}$	$3\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$
Potatoes	$2\cdot10^{-2}$	$1\cdot10^{-2}$	$5\cdot10^{-2}$	$1\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$
Beet	$2\cdot10^{-2}$	$1\cdot10^{-2}$	$5\cdot10^{-2}$	$1\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$
Beet leaves	$2\cdot10^{-2}$	$2\cdot10^{-2}$	$5\cdot10^{-2}$	$1\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$
Cereals	$2\cdot10^{-1}$	$5\cdot10^{-2}$	$5\cdot10^{-2}$	$4\cdot10^{-3}$	$1\cdot10^{-1}$	$3\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$
Leafy vegetables	$8\cdot10^{-2}$	$2\cdot10^{-2}$	$5\cdot10^{-2}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$
Root vegetables	$2\cdot10^{-2}$	$1\cdot10^{-2}$	$5\cdot10^{-2}$	$5\cdot10^{-4}$	$1\cdot10^{-1}$	$2\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$
Fruit vegetables	$3\cdot10^{-2}$	$5\cdot10^{-3}$	$5\cdot10^{-2}$	$5\cdot10^{-4}$	$1\cdot10^{-1}$	$3\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$
Fruit	$3\cdot10^{-2}$	$5\cdot10^{-3}$	$5\cdot10^{-2}$	$5\cdot10^{-4}$	$1\cdot10^{-1}$	$3\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$
Berries	$3\cdot10^{-2}$	$5\cdot10^{-3}$	$5\cdot10^{-2}$	$5\cdot10^{-4}$	$1\cdot10^{-1}$	$3\cdot10^{-3}$	$1\cdot10^{-1}$	$1\cdot10^{-4}$	$1\cdot10^{-1}$

Table 9 (continued)

	Transfer factor soil-plant (Bq kg^{-1} plant f.w. per Bq kg^{-1} soil d.w.)								
Plant	Rh	Ru	Sb	Sr	Tc	Te	Y	Zr	
Grass	$1\cdot10^{-1}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	$5\cdot10^{-1}$	1	$5\cdot10^{-3}$	$1\cdot10^{-2}$	$4\cdot10^{-4}$	
Maize silage	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$3\cdot10^{-1}$	1	$1\cdot10^{-2}$	$1\cdot10^{-2}$	$6\cdot10^{-4}$	
Corn cobs	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$2\cdot10^{-1}$	1	$1\cdot10^{-2}$	$1\cdot10^{-2}$	$6\cdot10^{-4}$	
Potatoes	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$5\cdot10^{-2}$	1	$1\cdot10^{-3}$	$1\cdot10^{-2}$	$1\cdot10^{-4}$	
Beet	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$4\cdot10^{-1}$	1	$1\cdot10^{-3}$	$1\cdot10^{-2}$	$1\cdot10^{-4}$	
Beet leaves	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$8\cdot10^{-1}$	1	$1\cdot10^{-3}$	$1\cdot10^{-2}$	$1\cdot10^{-4}$	
Cereals	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$2\cdot10^{-1}$	1	$3\cdot10^{-3}$	$1\cdot10^{-2}$	$4\cdot10^{-4}$	
Leafy vegetables	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$4\cdot10^{-1}$	1	$3\cdot10^{-3}$	$1\cdot10^{-2}$	$2\cdot10^{-4}$	
Root vegetables	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$3\cdot10^{-1}$	1	$4\cdot10^{-4}$	$1\cdot10^{-2}$	$5\cdot10^{-5}$	
Fruit vegetables	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$2\cdot10^{-1}$	1	$4\cdot10^{-4}$	$1\cdot10^{-2}$	$5\cdot10^{-5}$	
Fruit	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	1	$4\cdot10^{-4}$	$1\cdot10^{-2}$	$5\cdot10^{-5}$	
Berries	$1\cdot10^{-1}$	$1\cdot10^{-2}$	$2\cdot10^{-2}$	$1\cdot10^{-1}$	1	$4\cdot10^{-4}$	$1\cdot10^{-2}$	$5\cdot10^{-5}$	

Table 9 (continued)

Soil category	migration rate λ_s (a^{-1})		
	Ag, Am, Ce, Cm, Co, Cs, I, La, Nb, Nd, Np, Pr, Pu, Rb, Rh, Ru, Y, Zr	Ba, Mn, Mo, Na, Sb, Sr, Te	Tc
Arable land	$6.9 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	$2.8 \cdot 10^{-1}$
Pasture	$1.7 \cdot 10^{-2}$	$3.5 \cdot 10^{-2}$	$6.9 \cdot 10^{-1}$

Table 10: Migration rate λ_s for different soil categories and elements

Soil type	Enrichment factor	
	I, Na, Sb, Tc, Te, Y	Ag, Am, Ba, Ce, Cm, Co, Cr, Cs, Fe, La, Mn, Mo, Nb, Nd, Np, Pr, Pu, Rb, Rh, Ru, Sr, Zn, Zr
Sand	1.	3.
Loam	1.	3.
Clay	1.	3.
Peat	1.	3.

Table 11: Enrichment factors for resuspended soil (soil dependency is not yet considered due to insufficient data)

Animal	Feedstuff	Intake rate ($kg\ d^{-1}$ fresh weight)	Inhalation rate ($m^3\ d^{-1}$)
Lactating cow	grass	70 [a]	120
Lactating sheep	grass	9 [a]	12
Lactating goat	grass	13 [a]	12
Beef cattle	maize silage	28	120
Calf	milk substitute	2.9	24
Pig	winter barley	3.0	16.8
Lamb	grass (extensive)	5 [a]	9.6
Hen, chicken	winter wheat	0.09	1.2

[a] Values given are for the vegetation period; during the winter an equivalent dry matter intake with hay or silage is assumed

Table 12: Standard feeding diets I_k and inhalation rates I_{inh} for animals: default values for Central European conditions.

Animal product	Transfer factor feed-animal product (d l^{-1}, d kg^{-1})								
	Ag	Am	Ba	Ce	Cm	Co	Cs	I	La
Cow milk	$2\cdot10^{-4}$	$1\cdot10^{-6}$	$5\cdot10^{-4}$	$2\cdot10^{-5}$	$1\cdot10^{-6}$	$2\cdot10^{-4}$	$3\cdot10^{-3}$	$3\cdot10^{-3}$	$2\cdot10^{-5}$
Sheep milk	$2.5\cdot10^{-3}$	$1\cdot10^{-5}$	$5\cdot10^{-3}$	$2\cdot10^{-4}$	$1\cdot10^{-5}$	$2\cdot10^{-3}$	$6\cdot10^{-2}$	$5\cdot10^{-1}$	$2\cdot10^{-4}$
Goat milk	$2.5\cdot10^{-3}$	$1\cdot10^{-5}$	$5\cdot10^{-3}$	$2\cdot10^{-4}$	$1\cdot10^{-5}$	$2\cdot10^{-3}$	$6\cdot10^{-2}$	$5\cdot10^{-1}$	$2\cdot10^{-4}$
Beef (cow)	$1\cdot10^{-3}$	$3\cdot10^{-4}$	$2\cdot10^{-4}$	$8\cdot10^{-4}$	$1\cdot10^{-4}$	$2\cdot10^{-4}$	$1\cdot10^{-2}$	$1\cdot10^{-3}$	$3\cdot10^{-4}$
Beef (bull)	$1\cdot10^{-3}$	$3\cdot10^{-4}$	$2\cdot10^{-4}$	$8\cdot10^{-4}$	$1\cdot10^{-4}$	$2\cdot10^{-4}$	$4\cdot10^{-2}$	$1\cdot10^{-3}$	$3\cdot10^{-4}$
Veal	$3\cdot10^{-3}$	$1\cdot10^{-3}$	$6\cdot10^{-4}$	$2\cdot10^{-3}$	$3\cdot10^{-4}$	$6\cdot10^{-4}$	$3.5\cdot10^{-1}$	$3\cdot10^{-3}$	$1\cdot10^{-4}$
Pork	$5\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$4\cdot10^{-3}$	$3\cdot10^{-4}$	$1\cdot10^{-3}$	$4\cdot10^{-1}$	$3\cdot10^{-3}$	$2\cdot10^{-3}$
Lamb	$1\cdot10^{-2}$	$3\cdot10^{-3}$	$2\cdot10^{-3}$	$8\cdot10^{-3}$	$1\cdot10^{-3}$	$2\cdot10^{-3}$	$5\cdot10^{-1}$	$1\cdot10^{-2}$	$3\cdot10^{-3}$
Chicken	$5\cdot10^{-1}$	$2\cdot10^{-4}$	$1\cdot10^{-2}$	$1\cdot10^{-2}$	$2\cdot10^{-4}$	2.0	4.5	$1\cdot10^{-1}$	$3\cdot10^{-3}$
Eggs	$5\cdot10^{-1}$	$5\cdot10^{-3}$	$9\cdot10^{-1}$	$5\cdot10^{-3}$	$5\cdot10^{-3}$	$3\cdot10^{-1}$	$3\cdot10^{-1}$	2.8	$3\cdot10^{-3}$

Table 13: Transfer factors feed-animal products TF_m used in FDMT

Animal product	Transfer factor feed-animal product (d l^{-1}, d kg^{-1})								
	Mn	Mo	Na	Nb	Nd	Np	Pr	Pu	Rb
Cow milk	$1\cdot10^{-4}$	$1\cdot10^{-3}$	$2\cdot10^{-2}$	$4\cdot10^{-7}$	$2\cdot10^{-5}$	$5\cdot10^{-6}$	$2\cdot10^{-5}$	$6\cdot10^{-5}$	$3\cdot10^{-3}$
Sheep milk	$1\cdot10^{-3}$	$1\cdot10^{-2}$	$2\cdot10^{-1}$	$6\cdot10^{-6}$	$2\cdot10^{-4}$	$5\cdot10^{-5}$	$2\cdot10^{-4}$	$4\cdot10^{-4}$	$6\cdot10^{-2}$
Goat milk	$1\cdot10^{-3}$	$1\cdot10^{-2}$	$2\cdot10^{-1}$	$6\cdot10^{-6}$	$2\cdot10^{-4}$	$5\cdot10^{-5}$	$2\cdot10^{-4}$	$4\cdot10^{-4}$	$6\cdot10^{-2}$
Beef (cow)	$5\cdot10^{-4}$	$1\cdot10^{-3}$	$1\cdot10^{-2}$	$3\cdot10^{-7}$	$3\cdot10^{-4}$	$1\cdot10^{-4}$	$3\cdot10^{-4}$	$6\cdot10^{-5}$	$1\cdot10^{-2}$
Beef (bull)	$5\cdot10^{-4}$	$1\cdot10^{-3}$	$1\cdot10^{-2}$	$3\cdot10^{-7}$	$3\cdot10^{-4}$	$1\cdot10^{-4}$	$3\cdot10^{-4}$	$6\cdot10^{-5}$	$4\cdot10^{-2}$
Veal	$2\cdot10^{-3}$	$3\cdot10^{-3}$	$3\cdot10^{-2}$	$1\cdot10^{-6}$	$1\cdot10^{-4}$	$3\cdot10^{-4}$	$1\cdot10^{-4}$	$2\cdot10^{-4}$	$3.5\cdot10^{-1}$
Pork	$4\cdot10^{-3}$	$3\cdot10^{-3}$	$5\cdot10^{-2}$	$2\cdot10^{-6}$	$2\cdot10^{-3}$	$3\cdot10^{-4}$	$2\cdot10^{-3}$	$3\cdot10^{-4}$	$4\cdot10^{-1}$
Lamb	$5\cdot10^{-3}$	$1\cdot10^{-2}$	$1\cdot10^{-1}$	$3\cdot10^{-6}$	$3\cdot10^{-3}$	$1\cdot10^{-3}$	$3\cdot10^{-3}$	$7\cdot10^{-4}$	$5\cdot10^{-1}$
Chicken	$5\cdot10^{-2}$	1	1	$3\cdot10^{-4}$	$3\cdot10^{-2}$	$2\cdot10^{-4}$	$3\cdot10^{-2}$	$2\cdot10^{-4}$	4.5
Eggs	$7\cdot10^{-2}$	1	6	$1\cdot10^{-3}$	$7\cdot10^{-3}$	$5\cdot10^{-3}$	$3\cdot10^{-3}$	$7\cdot10^{-3}$	$3\cdot10^{-1}$

Table 13 (continued)

Animal product	Transfer factor feed-animal product (d l^{-1}, d kg^{-1})								
	Rh	Ru	Sb	Sr	Tc	Te	Y	Zr	
Cow milk	$1\cdot10^{-2}$	$1\cdot10^{-4}$	$1\cdot10^{-4}$	$2\cdot10^{-3}$	$1\cdot10^{-4}$	$5\cdot10^{-4}$	$1\cdot10^{-5}$	$6\cdot10^{-7}$	
Sheep milk	$1\cdot10^{-2}$	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$1.4\cdot10^{-2}$	$1\cdot10^{-3}$	$4\cdot10^{-3}$	$1\cdot10^{-4}$	$6\cdot10^{-6}$	
Goat milk	$1\cdot10^{-2}$	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$1.4\cdot10^{-2}$	$1\cdot10^{-3}$	$4\cdot10^{-3}$	$1\cdot10^{-2}$	$6\cdot10^{-6}$	
Beef (cow)	$2\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$3\cdot10^{-4}$	$5\cdot10^{-4}$	$7\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-6}$	
Beef (bull)	$2\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$3\cdot10^{-4}$	$5\cdot10^{-4}$	$7\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-6}$	
Veal	$5\cdot10^{-3}$	$2\cdot10^{-3}$	$3\cdot10^{-3}$	$2\cdot10^{-3}$	$1\cdot10^{-3}$	$2\cdot10^{-2}$	$3\cdot10^{-3}$	$3\cdot10^{-6}$	
Pork	$1\cdot10^{-2}$	$5\cdot10^{-3}$	$5\cdot10^{-3}$	$2\cdot10^{-3}$	$1\cdot10^{-3}$	$3\cdot10^{-2}$	$5\cdot10^{-3}$	$5\cdot10^{-6}$	
Lamb	$2\cdot10^{-2}$	$1\cdot10^{-2}$	$1\cdot10^{-2}$	$3\cdot10^{-3}$	$5\cdot10^{-3}$	$7\cdot10^{-2}$	$1\cdot10^{-2}$	$1\cdot10^{-5}$	
Chicken	$2\cdot10^{-2}$	$7\cdot10^{-3}$	$1\cdot10^{-1}$	$4\cdot10^{-2}$	$1\cdot10^{-1}$	$6\cdot10^{-1}$	$1\cdot10^{-2}$	$6\cdot10^{-5}$	
Eggs	$2\cdot10^{-2}$	$6\cdot10^{-3}$	$1\cdot10^{-1}$	$2\cdot10^{-1}$	1	5	$2\cdot10^{-3}$	$2\cdot10^{-4}$	

Table 13 (continued)

Element	Product [a]	a_1	$T_{b,1}$ (d)	a_2	$T_{b,2}$ (d)
Ag	milk	0.1	3	0.9	60
	meat	1.0	60		
	chicken	0.7	3	0.3	100
	eggs	1.0	3		
Am	milk, meat	1.0	700		
	chicken, eggs	1.0	1		
Ba	milk	0.9	3	0.1	100
	meat	0.2	10	0.8	100
	chicken	0.5	3	0.5	100
	eggs	0.5	2	0.5	20
Ce	milk	0.5	1	0.5	20
	meat, chicken	1.0	4000		
	eggs	1.0	3		

[a] meat stands for pork, beef, veal, lamb

Table 14: Biological halflifes $T_{b,i}$ according to the biological transfer rates $\lambda_{b,mj}$ and their contribution fractions a_{mj} as applied in FDMT

Element	Product [a]	a_1	$T_{b,1}$ (d)	a_2	$T_{b,2}$ (d)
Cm	milk, meat	1.0	7000		
	chicken, eggs	1.0	1		
Co	milk	0.8	2	0.2	400
	meat	0.1	40	0.9	800
	chicken	0.5	10	0.5	200
	eggs	1.0	3		
Cs	milk	0.8	1.5	0.2	15
	beef (cow), veal	1.0	30		
	beef(bull)	1.0	50		
	pork	1.0	35		
	lamb, chicken	1.0	20		
	eggs	1.0	3		
I	milk, eggs	1.0	0.7		
	meat, chicken	1.0	100		
La	milk, eggs	1.0	1		
	meat	1.0	30		
	chicken	1.0	10		
Mn	milk, meat, chicken	0.4	40	0.6	700
	eggs	1.0	3		
Mo	milk	1.0	1		
	meat, chicken	1.0	50		
	eggs	1.0	3		
Na	milk	1.0	1		
	meat	1.0	10		
	chicken, eggs	1.0	1		
Nb	milk	1.0	1		
	meat, chicken	0.02	4	0.98	200
	eggs	1.0	3		
Nd	milk, eggs	1.0	1		
	meat	1.0	30		
	chicken	1.0	10		
Np	milk, meat	0.1	3	0.9	100
	chicken, eggs	1.0	1		
Pr	milk, eggs	1.0	1		
	meat	1.0	30		
	chicken	1.0	10		

[a] meat stands for pork, beef, veal, lamb

Table 14 (continued)

Element	Product [a]	a_1	$T_{b,1}$ (d)	a_2	$T_{b,2}$ (d)
Pu	milk, meat	1.0	7000		
	chicken, eggs	1.0	25		
Rb	milk	0.8	1.5	0.2	15
	beef (cow), veal	1.0	30		
	beef(bull)	1.0	50		
	pork	1.0	35		
	lamb, chicken	1.0	20		
	eggs	1.0	3		
Rh	milk,eggs	1.0	1		
	meat	1.0	30		
	chicken	1.0	10		
Ru	milk, meat, chicken	0.1	30	0.9	1000
	eggs	1.0	3		
Sb	milk	1.0	1		
	meat	1.0	30		
	chicken	1.0	10		
	eggs	1.0	3		
Sr	milk	0.9	3	0.1	100
	meat	0.2	10	0.8	100
	chicken	0.5	3	0.5	100
	eggs	0.5	2	0.5	20
Tc	milk,eggs	1.0	1		
	meat, chicken	1.0	3		
Te	milk	1.0	1		
	meat, chicken	0.1	20	0.9	5000
	eggs	1.0	3		
Y	milk, eggs	1.0	1		
	meat, chicken	1.0	30		
Zr	milk	1.0	1		
	meat, chicken	1.0	8000		
	eggs	1.0	3		

[a] meat stands for pork, beef, veal, lamb

Table 14 (continued)

Raw Product	Processed Product	Element						
		Ag, Co, Mo,Na, Sb, Tc, Te	Ba	Cs, Rb	I	Pu	Ru,Am, Cm, Ce, La, Mn, Nb, Nd, Pr, Np, Rh, Y, Zr	Sr
Wheat	Wheat flour	0.5	0.5	0.5	0.5	0.2	0.5	0.5
	Wheat bran	3.0	3.0	3.0	3.0	4.0	3.0	3.0
Rye	Rye flour	0.5	0.5	0.6	0.5	0.2	0.5	0.5
	Rye bran	3.0	3.0	2.7	3.0	4.0	3.0	3.5
Spring barley	Beer	0.1	0.04	0.1	0.1	0.04	0.04	0.04
	Brewing residues	0.1	0.25	0.1	0.1	0.25	0.25	0.25
Winter wheat	Distillery residues	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Potatoes	Potatoes, peeled	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Vegetables [a]	Vegetables [a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Fruit, berries	Fruit and berries	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Milk (cow)	Butter	1.0	1.0	0.2	0.5	1.0	1.0	0.2
	Cream (30% fat)	1.0	1.0	0.7	0.7	1.0	1.0	0.4
	Skim milk	1.0	1.0	1.04	1.0	1.0	1.0	1.1
	Cheese (rennet)	1.0	1.0	0.6	0.6	1.0	1.0	6.0
	Cheese (acid)	1.0	1.0	0.6	1.4	1.0	1.0	0.8
	Whey (rennet)	1.0	1.0	1.05	1.05	1.0	1.0	0.4
	Whey (acid)	1.0	1.0	1.05	0.95	1.0	1.0	1.04
	Condensed milk	2.7	2.7	2.7	2.7	2.7	2.7	2.7
	Milk substitute	8.0	9.3	8.7	9.4	8.0	8.0	9.3

[a] Root, fruit, and leafy vegetables

Table 15: Processing factors for feedstuffs and foodstuffs as applied in FDMT

Product(s)	Storage time (d)
Cereals and cereal products	45
Brewing residues	60
Distillery residues	45
Maize and beet leaves	0
Corn cobs	45
Potatoes and beet	7
Leafy vegetables	1
Root vegetables	7
Fruit vegetables	2
Fruit and berries	2
Milk	1
Butter	3
Cream	2
Condensed milk	7
Skim milk	1
Cheese (rennet coagulation)	30
Cheese (acid coagulation)	7
Whey	2
Milk substitute	15
Beef	14
Pork, veal	2
Chicken, lamb	7
Eggs	2

Table 16: Storage and processing times t_{pk} as applied inFDMT

Foodstuff	Consumption rates (g d^{-1}) for age group				
	1 a	5 a	10 a	15 a	adults
Spring wheat, whole grain	0.7	1.4	1.8	2.0	2.6
Spring wheat, flour	3.9	8.1	10	12	15
Winter wheat, whole grain	6.0	13	16	18	23
Winter wheat, flour	35	73	91	100	130
Rye, whole grain	2.2	4.8	6.0	6.9	8.7
Rye, flour	9.3	19	24	28	35
Oats	2.9	3.1	3.9	4.4	5.6
Potatoes	45	35	60	83	160
Leafy vegetables	58	74	79	86	94
Root vegetables	21	24	29	33	33
Fruit vegetables	12	36	41	46	47
Fruit	150	72	91	100	120
Berries	0	10	12	14	14
Milk	560	140	180	210	230
Condensed milk	0	11	14	16	18
Cream	0	9.6	13	14	16
Butter	0	6.1	9.5	12	18
Cheese (rennet)	0	10	14	19	26
Cheese (acid)	0	6.6	8.9	12	17
Beef (cow)	1.5	18	19	23	27
Beef (cattle)	3.0	35	38	46	55
Veal	0.2	1.4	1.5	1.8	2.2
Pork	3.9	72	78	90	108
Chicken	1.5	11	12	14	17
Eggs	5.0	18	25	36	43
Beer	0	0	12	130	610

Table 17: Age-dependent German consumption rates V_k as applied as default in FDMT

Age group (years)	Inhalation rate (m^3 h^{-1})
1	0.21
5	0.36
10	0.64
15	0.84
Adults	0.93

Table 18: Average inhalation rates (ICRP 1995) used for estimation of inhalation doses in FDMT.

house type	R_{Inh}		
	noble gases	elem. iodine	aerosols
low shielding	1	0.5	0.5
medium shielding	1	0.5	0.5
high shielding	1	0.5	0.5
street	1	1	1

Table 19: Default values for location factors for internal exposure from inhalation in RODOS

house type	R_c
low shielding	0.8
medium shielding	0.5
high shielding	0.2
street	1.0

Table 20: Default values for location factors for external exposure from cloudshine in RODOS

house type	R_g
low shielding	0.5
medium shielding	0.1
high shielding	0.01
street	1.0

Table 21: Default values for location factors for external exposure from groundshine in FDMT

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