Paper-

ECOSYS-87: A DYNAMIC MODEL FOR ASSESSING RADIOLOGICAL CONSEQUENCES OF NUCLEAR ACCIDENTS

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Abstract-The time-dependent radioecological simulation model ECOSYS-87 has been developed to assess the radiological consequences of short-term depositions of radionuclides. Internal exposure via inhalation and ingestion, as well as external exposure from the passing cloud and from radioactivity deposited on the ground, are included in the model. The site-specific parameter values of the model are representative of Southern German agricultural conditions; however, the model design facilitates adaption to other situations. The ingestion dose is calculated as a function of time considering 18 plant species, 11 animal food products, and 18 processed products. The ingestion and inhalation exposure is estimated for six age groups using age-dependent consumption and inhalation rates and age-dependent dose factors. Results demonstrate a pronounced influence regarding the time of year (season) of deposition on the ingestion dose and on the relative importance of the exposure pathways. Model results compare well with activities in foods measured after the Chernobyl accident.

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INTRODUCTION

AFTER accidental releases of radionuclides into the atmosphere leading to contamination of large areas, a fast and detailed prognosis of the resulting radiation exposure to the population is required in order to evaluate its radiological consequences and to support and optimize decisions concerning countermeasures. All exposure pathways that might be important have to be considered in such a prognostic dose assessment:

- Transfer of radionuclides through food chains and the subsequent internal exposure of humans due to ingestion of contaminated foodstuffs;
- 2) Internal exposure due to inhalation of radionuclides during passage of the cloud:

- External exposure from radionuclides in the passing cloud; and
- 4) External exposure from radionuclides deposited on the ground.

Models for the dose assessment, after accidental releases, have to consider the time dependency of the transfer processes since equilibrium in the model compartments will not be reached for a long time. Therefore, dynamic modeling of the processes and consideration of the seasonality in the growing cycles of crops, in the feeding practices of domestic animals, and in human dietary habits are essential. Furthermore, the models have to be flexible enough to enable the simulation of the actual region-specific radioecological situation in case of an emergency.

In the late 1970s, the development of dynamic radioecological models was started and led to a number of such models (e.g., Booth et al. 1971; Pleasant et al. 1980; Linsley et al. 1982; Matthies et al. 1982; Koch and Tadmor 1986; Whicker and Kirchner 1987). Some of these models were used to estimate the radiological consequences of the Chernobyl accident soon after its event (e.g., ISS 1986). After this accident, many measurements of activity in air, soil, and foodstuffs were performed in many countries. Several of these data sets were used to test the reliability of the existing models (i.e., Brown et al. 1988; Maubert et al. 1988; Müller and Pröhl 1988; Ng and Hoffman 1988). Two international model validation studies, BIOMOVS (Köhler et al. 1991) and VAMP (Linsley et al. 1990), have been launched.

The experiences after the Chernobyl accident concerning activity measurements and questions raised by decision makers and the public showed that many aspects were not addressed in most of the existing models, especially predictions of the concentrations of activity in a variety of foodstuffs that are of less importance for the dose to the average population but of great importance for critical population groups (e.g., milk produced on extensively cultivated pastures, fruit, and berries). In many models, the possibility to consider specific feeding regimes was very limited. Moreover, most of the existing models did not (or did only to a small degree) consider the actual state of development of the different plant species at time of deposition. In

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particular, the large variability of contamination among different grain species after the Chernobyl accident demonstrated the need for more differentiation in food chain modeling. These aspects gave rise to further development and improvement of the existing radioecological model ECOSYS (Matthies et al. 1982).

The new model version ECOSYS-87 has been available since the end of 1987 and has been applied to different studies [BIOMOVS (Köhler et al. 1991), VAMP (Linsley et al. 1990), and Pröhl et al. 1990a and b)]. Furthermore, ECOSYS-87 is the basis of emergency management systems in Germany ("PARK," Jacob et al. 1991), Austria ("OECOSYS," Gerzabek et al. 1989), and Switzerland (Schenker-Wicki 1990), and is also the basis of the European real-time dose assessment system, "EURALERT" (Catsaros et al. 1990; Müller et al. 1990).

This paper describes the basic methods of modeling, the parameters used, the program structure, and some applications of the ECOSYS-87 model. More detailed descriptions of the modeling approaches and parameters used for the calculation of deposition, interception, and transfer in food chains are given elsewhere (Pröhl 1990).

In general, models are simplifications of reality and, therefore, the results are always associated with uncertainties. When estimating model uncertainties, ECOSYS-87 interfaces have been established for use in conjunction with the PRISM software package (Gardner et al. 1983) in order to determine the sensitivity of the model parameters and to estimate the uncertainty of model results. However, by using this method, the uncertainties due to parameter uncertainty, in particular, can be estimated. Another source of uncertainty (that can hardly be quantified) may be introduced by the incomplete knowledge of the scenario considered. The importance of the model parameters and the uncertainty of the results depend to a high degree on the specific situation (e.g., radionuclide considered or time of deposition). Therefore, in this paper, only selected examples of parameter sensitivity and uncertainty ranges of results are presented. A more systematic presentation of such results will be the subject of a specific paper in the future.

INPUT REQUIREMENTS AND MODEL STRUCTURE

The scheme of the ECOSYS-87 model is shown in Fig. 1. Inputs to ECOSYS-87 are the local time-integrated concentration of activity C_a (Bq s m⁻³) in air, the activity eventually deposited during precipitation A_w (Bq m⁻²), and the amount of rainfall R (mm) during the rainfall event. These are data that can be measured in an unambiguous way in environmental monitoring systems, or predicted with atmospheric dispersion and deposition models. The time of year during which the deposition occurs is important. The deposition and



Fig. 1. Scheme of the exposure pathways considered in ECOSYS-87.

other important transfer processes in the food chains are highly dependent on the season.

Besides these data describing a specific deposition event, there are a lot of input parameters that characterize the radioecological scenario considered. During model development, modeling approaches were selected that involved parameters that are relatively easy to determine. This approach facilitates the verification of the model and, during application in emergency situations, the iterative improvement of the reliability of the model results by interaction of predictions and measurements.

There are many model parameters that depend on the climatological, agricultural, or other characteristics of the region considered. The parameter values given in this paper are considered to be mainly representative of Southern German conditions. However, the design of ECOSYS-87 supports its adaptation to other agricultural, climatological, and radioecological situations enabling its application in different geographical regions.

The doses via inhalation and external exposure from the cloud are calculated from the concentration of activity in air. The model starts with estimating deposition to a variety of surfaces (vegetation and soil) for the ingestion pathway and external exposure from the ground. For the ingestion pathway, all relevant transfer processes among soil, plants, animals, and processed products, such as interception, translocation, root uptake, animal feeding, food processing, and culinary preparation are considered.

The results of ECOSYS-87 are the time-dependent and the time-integrated external and internal exposure, and the activity concentrations in 18 plants, 11 animal food products, and 18 processed products (Table 1) up to 70 y after deposition. Some of the foodstuffs considered are of limited importance in the diet of the average population but they have been included to identify possible pathways of high importance for critical groups. Doses are estimated for the age groups of 1, 5, 10, 15, or 20 y at the time of deposition. Age-dependent consumption rates and dose factors are applied to calculate the lifetime doses of these groups.

The methodologies applied for these calculations are described in the following sections.

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. Deposition to the human environment also controls the external exposure. In ECOSYS-87, dry and wet deposition are considered separately in order to re-enact the actual circumstances as realistically as possible. The total deposition to plants is given by

$$A_i = A_{di} + f_{w,i}A_w, \tag{1}$$

where

 A_i = total deposition onto plant type *i* (Bq m⁻²); A_{di} = dry deposition onto plant type *i* (Bq m⁻²); $f_{w,i}$ = interception fraction for plant type *i*; and 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 that depends on the plant type:

$$A_{di} = v_{gi} C_a, \tag{2}$$

where

 A_{di} = dry deposition onto plant type *i* (Bq m⁻²);

Table 1. Feed and foodstuffs considered in ECOSYS-87.

Plants	Animal products	Processed products
Grass ^a	Cow milk	Hay ^a
Winter wheat	Goat milk	Wheat flour
Spring wheat	Sheep milk	Rye flour
Winter barley	Beef (cow)	Wheat bran
Spring barley	Beef (bull)	Rye bran
Oats	Pork	Distillery residues
Rye	Veal	Brewing residues
Maize silage	Lamb	Butter
Corn cobs	Chicken	Cream
Beet	Eggs	Cheese ^b
Beet leaves	Roe deer	Skim milk
Potatoes		Whey ^c
Leafy vegetables		Milk substitute
Root vegetables		Animal meal
Fruit vegetables ^d		Beer
Fruit		
Berries		

^a Grass from intensively and extensively managed pastures is considered.

^b Cheese from rennet coagulation (includes hard and soft cheese) and from acid coagulation (includes cottage cheese) is considered.

" Whey from rennet and acid coagulation is considered.

^d Fruit vegetables are those vegetables from which only the fruits are consumed (e.g., tomatoes and cucumbers).

March 1993, Volume 64, Number 3

 v_{gi} = deposition velocity for plant type *i* (m s⁻¹); and C_a = time-integrated activity concentration in air (Bq s m⁻³).

The deposition velocity to vegetation is assumed to depend on the stage of development of the plant canopy. This causes a pronounced seasonality of the deposition velocity that is supported by the results of many experiments (e.g., Jonas 1984). The plants' stage of development can be characterized by the actual leaf area index (LAI; unit: $m^2 m^{-2}$) which is defined as the area of leaves present on a unit area of ground. In ECOSYS-87, the deposition velocity is assumed to be proportional to the LAI:

$$v_{gi} = v_{gi,\max} \frac{\text{LAI}_i}{\text{LAI}_{i,\max}},$$
(3)

where

- $v_{gi,max}$ = maximum deposition velocity (m s⁻¹) for plant type *i* (i.e., for fully developed foliage);
- LAI_i = leaf area index of plant type *i* at time of deposition; and
- $LAI_{i,max}$ = leaf area index of plant type *i* at time of fully developed foliage.

The default values of $v_{gi,max}$ used in ECOSYS-87 are given in Table 2. For the estimation of these values, a particle-size distribution with a maximum in the range $0.1-1 \ \mu m$ was assumed. This particle size is typical for an aged aerosol (Whitby 1978).

The LAI is strongly dependent on the time of year. For every plant species considered, a specific tabulated function of the LAI is assumed (Table 3) according to Nösberger (1970, 1971), Geisler (1980, 1983), Petr (1983), Friedrich (1986), and Krug (1986). These values can be regarded as typical for Southern Germany. However, it should be noted that these functions may vary from year-to-year and from region-to-region due to both climatic factors and farm management factors, such as fertilization, choice of varieties, and time of seeding.

For grass, the LAI is expressed by the yield because it is easier to determine. From the data of Nösberger (1970), Koblet (1979), and Hutchings (1991), the fol-

Table 2. Deposition velocities $v_{gi,max}$ used in ECOSYS-87 for soil and fully developed plant canopies.

9	Depositi	on velocity (n	nm s ⁻¹)
Surface type	Aerosol bound radionuclides	Elemental iodine	Organic bound iodine
Soil	0.5	3	0.05
Grass	1.5	15	0.15
Trees	5	50	0.5
Other plants	2	20	0.2

lowing function has been derived to estimate the LAI from the yield (see Fig. 2):

$$LAI_g = LAI_{g,max}[1 - exp(-kY_g)],$$

Table 3. Yield of pasture grass (kg m^{-2} fresh weight) and leaf area indices (all other plants: $m^2 m^{-2}$) for Southern German conditions as function of the time of the year for the plants considered in ECOSYS-87; between the given values linear interpolation is applied.

Plant		Yield or leaf area index (LA					
Grass	Date	1.1.	15.3.	15.5.	31.10.	1,11.	
4. A.	Yield	0.01	0.05	1.5	1.5	0.05	
Grass	Date	1.1.	15.3.	1.7.	31.10.	1.11.	
(extensive)	Yield	0.01	0.05	1.5	1.5	0.05	
Winter wheat	Date	1.1.	20.4.	10.6.	5.8.	6.8.	
	LAI	0	1	7	1	0	
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.	
đ.	LAI	0	1	6	1	0	
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		
Rve	Date	1.1.	20.3.	20.5.	1.8.	2.8.	
	LAI	0	1	6	1	0	
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.	114	
5 88535888	LAI	0	4	4	0	17	
Roots, fruit	Date	15.4.	1.7.	1.10.	1.11.		
vegetables, fruit, berries	LAI	0	5	5	0		



Fig. 2. Relationship between yield and leaf area index of grass. Symbols are measured data; the solid curve is a fit given by eqn. (4).

where

- $LAI_g = leaf$ area index of grass at time of deposition;
- $LAI_{g,max} = maximum leaf area index of grass (7 m²);$
 - k = normalization factor (1 m² kg⁻¹); and
 - $Y_g =$ yield of grass (kg m⁻²) at time of deposition.

The yield of grass as a function of time based on Voigtländer and Jacob (1987) is also given in Table 3.

For the interception of wet-deposited radionuclides, an approach is used that is based on the water storage capacity of the plants' leaves and the actual LAI. Buildup 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 (Hoffman et al. 1989; Pröhl 1990) are considered. The interception fraction $f_{w,i}$ for plant type *i* is quantitatively expressed by

$$f_{w,i} = \frac{\mathrm{LAI}_i S_i}{R} \left[1 - \exp\left(\frac{-\mathrm{ln}2}{3S_i} R\right) \right], \tag{5}$$

where

 S_i = retention coefficient (mm) of plant type *i*; and

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

If eqn (5) results in an interception fraction >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. The elements iodine, cesium, strontium, and barium are differentiated according to Angeletti and Levi (1977a,b), Angeletti (1980), Hoffman et al. (1989), and Pröhl (1990). 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.

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. Grassland is considered to be a representative vegetational type. The activity removed by harvesting is considered to be recycled by organic fertilization. The total deposition to grassland is given as

$$A_s = A_{ds} + A_{dg} + A_w, \tag{6}$$

Table 4. Retention coefficients S_i for different plants and elements.

	Retention coefficient (mm)							
Plant species	Iodine	Cesium, zirconium, niobium, ruthenium, tellurium, cerium, plutonium, manganese, zinc	Strontium, barium					
Grass, cereals,	0.1	0.2	0.4					
Other plants	0.15	0.3	0.6					

where

$$A_s$$
 = total deposition to grassland (Bq m⁻²);

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

$$A_{dg} = dry deposition to grass (Bq m-2); and$$

 $A_w = \text{total wet deposition (Bq m^{-2})}.$

The dry deposition to soil is estimated according to eqn (2) using a deposition velocity (see Table 2) 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 clearly distinguishing 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.

ESTIMATION OF THE INGESTION DOSE

Activity concentration of plant products

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:

$$C_i(t) = C_{i,1}(t) + C_{i,r}(t),$$
 (7)

where

 $C_i(t)$ = total contamination of plant type *i*;

- $C_{i,1}(t) =$ contamination of plant type *i* due to foliar uptake; and
- $C_{i,r}(t) =$ contamination of plant type *i* due to root uptake and resuspension.

Foliar uptake of radionuclides

Calculation of the contamination of plants must distinguish between plants that 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 $C_{i,1}(t)$ at time t after the deposition is determined by the initial contamination of the plant and the activity loss due to weathering effects (e.g., rain and wind), radioactive decay, and growth dilution. For plants that are totally consumed. excluding pasture grass, growth is implicitly considered because the activity deposited onto the leaves is related to the yield at harvest. The concentration of activity is given by

where

 $C_{i,1}(\Delta t) = \text{concentration of activity in plant type } i$ at time of harvest;

 $C_{i,1}(\Delta t) \approx \frac{A_i}{Y_i} \exp[-(\lambda_w + \lambda_r) \ \Delta t],$

- 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:
- $\lambda_w = \text{loss rate } (d^{-1})$ due to weathering;
- λ_r = radioactive decay rate (d⁻¹); and

 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.

The approach for pasture grass is different because of its continuous harvest. Here, the decrease in activity due to growth dilution is explicitly considered. Furthermore, for elements that are mobile within the phloem (e.g., iodine or cesium), the translocation to the roots and the subsequent remobilization is taken into account:

$$C_{g,1}(t) = \frac{A_g}{Y_g} \{ (1-a) \exp[-(\lambda_b + \lambda_w + \lambda_r)t] + a \exp[-(\lambda_t + \lambda_r)t] \},$$
(9)

where

(8)

- $C_{g,1}(t) =$ 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_l = rate of activity decrease (d⁻¹) due to translocation to the root zone; and
 - t = time after deposition (d).

For the weathering rate constant λ_w , a value equivalent to a half-life of 25 d is assumed according to Aarkrog and Lippert (1969), Chadwick and Chamberlain (1970), Miller and Hoffman (1983), and ISS (1986). The growth dilution rate λ_b is considered to be timedependent. Monthly values were obtained from Ruhr-Stickstoff (1985) (Table 6). These values of λ_w and λ_b result in an effective half-life of 10-16 d.

Pröhl (1990) estimated the long-term component of the activity decrease as $\lambda_i = 1.16 \times 10^{-2} d^{-1}$ (half-

Table 5. Harvesting times and yields Y_i (fresh weight) of the crops considered in ECOSYS-87

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 vegetable	s 1.1. – 31.12,	2.0
Fruit vegetables	1.8 15.10.	1.5
Root vegetables	i 1.8. – 31.10.	2.0
Fruit	1.7 15.10,	2.0
Berries	1.7 15.10.	1.5

236

life 60 d) with a contribution fraction a = 0.05 using different measurements of grass contamination after the Chernobyl accident.

The concentration of activity in hay and grass silage is taken as a weighted mean concentration in grass harvested between 15 May and 15 September. The first one-half of that time period is weighted 70% and the second one-half is weighted 30% to reflect the relative monthly growth of pasture grass (Ruhr-Stickstoff 1985).

For plants that 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 behavior of the element considered: It is of importance for mobile elements such as iodine or cesium, but it does not occur with immobile elements like strontium. In the latter case, only 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.

In ECOSYS-87, 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. According to Aarkrog and Lippert (1969, 1971), Aarkrog (1972, 1975, 1983), Strasburger (1978), and Coughtrey et al. (1983), cesium, iodine, manganese, and tellurium are considered to be mobile elements, whereas strontium, barium, zirconium, niobium, ruthenium, cerium, and plutonium are assumed to be immobile. The most reliable data for translocation are available for cesium and strontium. Therefore, as long as no other quantitative data are available, the translocation of mobile elements assumes that they behave like cesium, except for manganese, for which, according to Aarkrog (1982), translocation factors are assumed to be lower by a factor 0.6 than for cesium. Strontium is considered to be representative for immobile elements. The translocation factors used in ECOSYS-87 are summarized in Tables 7 and 8.

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

$$C_{i,1}(\Delta t) = \frac{A_i}{Y_i} T_i(\Delta t) \exp(-\lambda_r \Delta t), \qquad (10)$$

where

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

 Y_i = yield of edible parts of plant type *i*; and other symbols are as defined earlier.

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

Table 6. Season-dependent growth dilution rates λ_b and according half-lifes for grass.

Month	Dilution rate (d ⁻¹)	Half-life (d)	
January-March	0.0		
April	1.65×10^{-2}	42	
May	3.85×10^{-2}	18	
June	3.47×10^{-2}	20	
July	3.65×10^{-2}	19	2
August	2.89×10^{-2}	24	
September	2.57×10^{-2}	27	
October	1.65×10^{-2}	42	
November-December	0.0		

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

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

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

Plant			Transloc	ation fact	or	
Wheat*	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 trai	nslocat	ion			
Root vegeta- bles	No trai	nslocat	ion			
Fruit vegeta-	Δt	150	30	0		
bles	$T(\Delta t)$	0	0.005	0.02		
Fruit, berries	Δt	150	30	0		
	$T(\Delta t)$	0	0.005	0.02		

* Winter and spring varieties.

March 1993, Volume 64, Number 3

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) as follows:

$$C_{i,r}(t) = TF_i C_s(t), \tag{11}$$

where

- $C_{i,t}(t) =$ 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*; and
- $C_s(t) =$ concentration of activity (Bq kg⁻¹) in the root zone of soil at time t.

If the deposition occurs during the growing period, 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 the length of the whole growing period.

The transfer factors TF_i used in ECOSYS-87 are summarized in Table 9. They are based on the reviews in Ng et al. (1982a), Baes et al. (1984), Frissel and Koster (1987), and Pröhl (1990). Compared to intensively managed, well-fertilized pasture, a higher availability of cesium and strontium 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, potassium, and calcium. Such soils are frequently found in upland areas, Scandinavia, and parts of Eastern Europe. The transfer factors (1.0 for both cesium and strontium) used in ECOSYS-87 for extensively managed pastures are chosen according to Marei et al. (1972), Heine and Wiechen (1978), Kühn et al. (1984), and Kirton et al., (1990).

The concentration of activity in the root zone of soil is given by

$$C_s(t) = \frac{A_s}{L\delta} \exp[-(\lambda_s + \lambda_f + \lambda_r)t], \qquad (12)$$

where

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

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

2r

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

Table 9. Transfer	actors soil-p	plant TF_i and	d distributio	on coefficient	ts Ka used in	1 ECOSYS-8	7.					
				Transfer fact	tor soil-plant	(Bq kg ⁻¹ plant	fresh weight pu	er Bq kg ⁻¹ so	vil dry weight	()		
Plant	Cesium	Strontium	Iodine	Zirconium	Niobium	Tellurium	Ruthenium	Barium	Cenium	Plutonium	Manganese	Zinc
Grass	5×10^{-2}	5×10^{-1}	1×10^{-1}	4×10^{-4}	4×10^{-3}	5×10^{-3}	2×10^{-2}	3×10^{-2}	2×10^{-3}	2×10^{-4}	8×10^{-1}	2×10^{-1}
Maize silage	2×10^{-2}	3×10^{-1}	1×10^{-1}	6×10^{-4}	6×10^{-3}	1×10^{-2}	1×10^{-2}	5×10^{-2}	3×10^{-3}	2×10^{-3}	6×10^{-2}	2×10^{-1}
Corn cobs	1×10^{-2}	2×10^{-1}	1×10^{-1}	6×10^{-4}	6×10^{-3}	1×10^{-2}	1×10^{-2}	5×10^{-2}	3×10^{-3}	2×10^{-3}	6×10^{-2}	2×10^{-1}
Potatoes	1×10^{-2}	5×10^{-2}	1×10^{-1}	1×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-2}	4×10^{-3}	1×10^{-3}	1×10^{-4}	2×10^{-2}	1×10^{-1}
Beet	5×10^{-3}	4×10^{-1}	1×10^{-1}	1×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-2}	4×10^{-3}	1×10^{-3}	1×10^{-4}	2×10^{-2}	1×10^{-1}
Reet leaves	3×10^{-2}	8×10^{-1}	1×10^{-1}	1×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-2}	4×10^{-3}	1×10^{-3}	2×10^{-3}	2×10^{-2}	1×10^{-1}
Cereals	2×10^{-2}	2×10^{-1}	1×10^{-1}	4×10^{-4}	4×10^{-3}	3×10^{-3}	1×10^{-2}	1×10^{-2}	3×10^{-3}	1×10^{-4}	2×10^{-1}	9×10^{-1}
Leafy vegetables	2×10^{-2}	4×10^{-1}	1×10^{-1}	2×10^{-4}	2×10^{-3}	3×10^{-3}	1×10^{-2}	2×10^{-2}	1×10^{-3}	1×10^{-4}	8×10^{-2}	2×10^{-2}
Root veretables	1×10^{-2}	3×10^{-1}	1×10^{-1}	5×10^{-5}	5×10^{-4}	4×10^{-4}	1×10^{-2}	2×10^{-3}	4×10^{-4}	1×10^{-4}	2×10^{-2}	1×10^{-1}
Fruit vegetables	1×10^{-2}	2×10^{-1}	1×10^{-1}	5×10^{-5}	5×10^{-4}	4×10^{-4}	1×10^{-2}	2×10^{-3}	4×10^{-4}	1×10^{-4}	3×10^{-2}	6×10^{-2}
Fruit 6	2×10^{-2}	1×10^{-1}	1×10^{-1}	5×10^{-5}	5×10^{-4}	4×10^{-4}	1×10^{-2}	2×10^{-3}	4×10^{-4}	1×10^{-4}	3×10^{-2}	6×10^{-2}
Berries	2×10^{-2}	1×10^{-1}	1×10^{-1}	5×10^{-5}	5×10^{-4}	4×10^{-4}	1×10^{-2}	2×10^{-3}	4×10^{-4}	1×10^{-4}	3×10^{-2}	6×10^{-2}
Distribution coeffi- cient (e cm ⁻³)	1,000	100	100	1,000	400	100	1,000	60	900	1,000	70	40

The migration rate λ_s is estimated according to Bachhuber et al. (1984):

$$\lambda_s = \frac{\nu_a}{L(1 + K_d \delta/\Theta)},$$
 (13)

where

 v_a = velocity of percolation water in soil (m a⁻¹);

 K_d = distribution coefficient (cm³ g⁻¹); and Θ = water content of soil (g g⁻¹).

For the depth of the root zone, 0.25 m and 0.1 m are assumed for arable soil and pasture soil, respectively. According to Bachhuber et al. (1984), the mean annual percolation water velocity is assumed to be 2 m a⁻¹. The soil density is 1.4×10^3 kg m⁻³ and the mean water content is estimated to be 20%. The K_d -values (Table 9) are estimated according to Bachhuber et al. (1984), Baes et al. (1984), and Kocher and Killough (1986).

The fixation is especially important for cesium and strontium. According to Frissel and Koster (1987), the fixation rate is estimated as $\lambda_f = 2.2 \times 10^{-4} \text{ d}^{-1}$ for cesium and $\lambda_f = 9 \times 10^{-5} \text{ d}^{-1}$ for strontium. For the other elements, fixation is of minor importance and is not considered in ECOSYS-87.

Resuspension

In ECOSYS-87, the plant contamination due to resuspended soil is estimated from the mean dust load of the near-ground air which is about 100 μ g m⁻³ in rural areas (Nielsen 1981). It is assumed that this dust originates from resuspended soil. 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. According to Livens and Baxter (1988), the concentrations of activity for the resuspended soil fractions is assumed to be a factor of 5 higher than the average soil contamination. These assumptions lead to a resuspension factor as defined by Linsley (1978) of 5×10^{-8} m^{-1} . This value is consistent with the estimates given by Linsley (1978) and Nielsen (1981) using the timedependent functions for the resuspension for the humid conditions of Middle Europe. The integration of these functions over the mean residence time of the nuclides in the 0-1 cm soil layer results in an average resuspension factor of about 2.5×10^{-8} m⁻¹, which is in good agreement with the previous estimate.

Plant contamination due to resuspension is proportional to the activity in the soil. Therefore, it can also be expressed in units of the soil-plant transfer factor. 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 ECOSYS-87, is equivalent to a soil-plant

transfer of about 0.001. Due to the lack of plant-specific data, this value is applied to all plant species considered.

Contamination of animal products

The contamination of animal products (e.g., milk, meat, and eggs) results from the activity intake of the animals and the kinetics of the radionuclides within the animals. ECOSYS-87 considers the activity intake by applying feedstuffs that have been contaminated by the pathways previously described. Inhalation of radionuclides by the animals is not considered; this pathway may be relevant for milk contamination in certain cases but it is unimportant for the resulting doses (Zach 1985). Indoor deposition onto animals' feedstuffs (e.g., in the stable, in the silo) is another pathway that 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 ECOSYS-87). However, it depends strongly on the actual situation so that no general model can be given.

The amount of activity ingested by the animals is calculated from the concentration of activity in the different feedstuffs and the feeding rates:

$$A_{a,m}(t) = \sum_{k=1}^{K_m} C_k(t) I_{k,m}(t), \qquad (14)$$

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

Plants or products processed from plants or animal products [see eqn (16)] can be considered to be feedstuffs for animals. The default feeding diets assumed in ECOSYS-87 are summarized in Table 10. These intake rates are used as long as no specific information is available. However, for a realistic dose assessment in

Table 10. Default feeding diets I_k assumed in ECOSYS-87.

Animal	Feedstuff	Intake rate (kg d ⁻¹ fresh weight)
Lactating cow	grass	70°
Lactating sheep	grass	9ª
Lactating goat	grass	13ª
Beef cattle	maize silage	28
Calf	milk substitute	2.9
Pig	winter barley	3.0
Lamb	grass	5ª
Hen, chicken	winter wheat	0.09
Roe deer	grass (extensive)	4ª

* Values given are for the vegetation period, during the winter an equivalent dry matter intake with hay or silage is assumed.

emergency situations, the feeding regimes have to be adapted to the season-dependent feed compositions of the specific region under consideration. ECOSYS-87 can consider complex time-depending feeding diets consisting of a mixture of different feedstuffs. A variety of typical German feeding regimes, as applied in ECOSYS-87, are described in Pröhl (1990).

In addition to the intake of activity with contaminated feedstuffs. ECOSYS-87 also considers radionuclide intake due to soil ingestion. The soil intake of animals varies widely depending on the grazing management and the condition of the pasture. If the feeding of mechanically prepared hay and silage during winter and an intensive grazing regime on well-fertilized pasture are assumed, according to Healy (1968), Fries (1982), and Green and Dodd (1988), a mean annual soil intake of 2.5% 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 in ECOSYS-87. 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 transfer of radionuclides from fodder into animal product m is described by the equilibrium transfer factor TF_m and one or two exponentials using biological excretion rates:

$$C_m(T) = TF_m \sum_{j=1}^{J} \left\{ a_{mj} \int_0^T A_{a,m}(t) \lambda_{b,mj} \right.$$

$$\left. \cdot \exp[-(\lambda_{b,mj} + \lambda_r)(T-t)] dt \right\},$$
(15)

where

- $C_m(T)$ = activity concentration (Bq kg⁻¹) in animal product *m* at time *T*;
 - $TF_m = \text{transfer factor } (d \text{ kg}^{-1}) \text{ for animal product}$ m;
 - J = number of biological transfer rates;
 - a_{mj} = fraction of biological transfer rate *j*; and
 - $\lambda_{b,mj}$ = 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 in ECOSYS-87 are given in Tables 11 and 12, respectively. These values are based on Ng et al. (1977, 1982b), Baes et al. (1984), Voigt et al. (1987), Assima-kopoulos et al. (1987), Johnson et al. (1988), Ennis et al. (1988), Voigt et al. (1989a, c), and Pröhl (1990). For some of the elements, there is a lack of data for sheep and goat's milk. In these cases, transfer factors 10 times higher than for cow's milk are assumed as suggested by Johnson et al. (1988). If no specific data were available on the transfer to veal, pork, lamb, and roe deer, the transfer was estimated from the feed-beef transfer factor

		Zinc	3×10^{-3}	3×10^{-2}	3×10^{-2}	2×10^{-2}	2×10^{-2}	6×10^{-2}	1×10^{-1}	2×10^{-1}	2×10^{-1}	6.5	2.6
		Manganese	1×10^{-4}	1×10^{-3}	1×10^{-3}	5×10^{-4}	5×10^{-4}	2×10^{-3}	4×10^{-3}	5×10^{-3}	5×10^{-3}	5×10^{-2}	7×10^{-2}
		Plutonium	6×10^{-5}	4×10^{-4}	4×10^{-4}	6×10^{-5}	6×10^{-5}	2×10^{-4}	3×10^{-4}	7×10^{-4}	9×10^{-4}	2×10^{-4}	7×10^{-3}
		Cerium	2×10^{-5}	2×10^{-4}	2×10^{-4}	8×10^{-4}	8×10^{-4}	2×10^{-3}	4×10^{-3}	8×10^{-3}	8×10^{-3}	1×10^{-2}	5×10^{-3}
	-1, d kg ⁻¹)	Barium	5×10^{-4}	5×10^{-3}	5×10^{-3}	2×10^{-4}	2×10^{-4}	6×10^{-4}	1×10^{-3}	2×10^{-3}	2×10^{-3}	1×10^{-2}	9×10^{-1}
	il product (d L-	Ruthenium	1×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	2×10^{-3}	5×10^{-3}	1×10^{-2}	1×10^{-2}	7×10^{-3}	6×10^{-3}
	tor feed-anima	Tellurium	5×10^{-4}	4×10^{-3}	4×10^{-3}	7×10^{-3}	7×10^{-3}	2×10^{-2}	3×10^{-2}	7×10^{-2}	7×10^{-2}	6×10^{-1}	5
SYS-87.	Transfer fact	Niobium	4×10^{-7}	6×10^{-6}	6×10^{-6}	3×10^{-7}	3×10^{-7}	1×10^{-6}	2×10^{-6}	3×10^{-6}	3×10^{-6}	3×10^{-4}	1×10^{-3}
used in ECC		Zirconium	6×10^{-7}	6×10^{-6}	6×10^{-6}	1×10^{-6}	1×10^{-6}	3×10^{-6}	5×10^{-6}	1×10^{-5}	1×10^{-5}	6×10^{-5}	2×10^{-4}
oducts TFm		Iodine	3×10^{-3}	5×10^{-1}	5×10^{-1}	1×10^{-3}	1×10^{-3}	3×10^{-3}	3×10^{-3}	1×10^{-2}	1×10^{-2}	1×10^{-1}	2.8
ed-animal pr		Strontium	2×10^{-3}	1.4×10^{-2}	14×10^{-2}	3×10^{-4}	3 × 10 ⁻⁴	2×10^{-3}	2×10^{-3}	3×10^{-3}	3×10^{-3}	4×10^{-2}	2×10^{-1}
fer factors fee		Cesium	3×10^{-3}	6×10^{-2}	6×10^{-1}	1×10^{-2}	4×10^{-2}	3.5×10^{-1}	4×10^{-1}	5 × 10 ⁻¹	5 × 10 ⁻¹	4.5	3×10^{-1}
Table 11. Trans	Animal	product	Cow milk	Sheen milk	Goat milk	Reef (cnw)	Reef (hull)	Veal	Pork	Iamh	Roe deer	Chicken	Eggs

by applying correction factors for the lower body mass. Correction factors were 3 for veal, 5 for pork, and 10 for lamb.

It should be noted that the data base for the transfer of zirconium, niobium, tellurium, ruthenium, barium, cerium, plutonium, manganese, and zinc to animal food products is rather poor. Therefore, the uncertainty for these parameters is considerable. These parameters are often derived from short-time experiment 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.

Table 12. Biological half-lives $T_{b,j}$ according to the biological transfer rates $\lambda_{b,mj}$ and their contribution fractions a_{mj} applied in ECOSYS-87.

Element	Product ^a	a	$T_{h,i}$ (d)	<i>a</i> ₂	$T_{b,2}$ (d)
Cesium	milk	0.8	1.5	0.2	15
	beef (cow),	1.0	30	*	
	beef (bull)	1.0	50		
	pork	1.0	35		
	lamb roe	1.0	20		
	deer, chicken	1.0	20		
	eggs	1.0	3		
Strontium, barium	milk	0.9	3	0.1	100
	meat	0.2	10	0.8	001
	chicken	0.5	3	0.5	100
	eggs	0.5	2	0.5	20
Iodine	milk, eggs	1.0	0.7		
	meat, chicken	1.0	100		
Zirconium	milk	1.0	1		
	meat, chicken	1.0	8.000		
	eggs	1.0	3		
Niobium	milk	1.0	ĩ		
	meat, chicken	0.02	4	0.98	200
	eggs	1.0	3		
Tellurium	miłk	1.0	1		
	meat, chicken	0.1	20	0.9	5,000
	eggs	1.0	3		9
Ruthenium	milk, meat,	0.1	30	0.9	1,000
	eees	1.0	3		
Cerium	milk	0.5	ĩ	0.5	20
	meat, chicken	1.0	4.000		
* C	eggs	1.0	3		
Plutonium	milk, meat	1.0	7.000		
	chicken, eggs	1.0	2.5		
Manganese	milk, meat, chicken	0.4	40	0.6	700
	eggs	1.0	3		
Zinc	milk	0.3	4	0.7	200
	meat	1.0	700		
	chicken	0.1	10	0.9	100
	eggs	1.0	3		

^a Meat stands for pork, beef, veal, lamb, and roe deer.

Processing and storage of 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-stuff or foodstuff) is calculated from the raw product by the following:

$$C_k(t) = C_{k0}(t - t_{pk})P_k \exp(-\lambda_r t_{pk}),$$
 (16)

where

- $C_k(t) =$ activity concentration (Bq kg⁻¹) in product k ready for consumption at time t;
- $C_k(t) =$ 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); and
 - t_{pk} = storage and processing time (d) for product k.

The processing factors applied in ECOSYS-87 are summarized in Table 13. The values for strontium, iodine, and cesium are based on Bunzl and Kracke (1987), Voigt et al. (1989b), and the compilation in Pröhl (1990). Due to the lack of data for all other elements, the default values in Table 13 are applied. Considering the pronounced enrichment of minerals in

 Table 13. Processing factors (raw products in brackets) applied in ECOSYS-87.

	Processing factor (Concentration in the raw product $= 1$)					
Processed product	Strontium	Cesium	Iodine	Default		
Wheat flour	0.5	0.5	0.5	0.5		
Wheat bran	3.0	3.0	3.0	3.0 ^d		
Rye flour	0.5	0.6	0.5	0.5°		
Rye bran	3.5	2.7	3.0	3.0 ^d		
Beer (spring barley)	0.04	0.1	0.1	0.1°		
Brewing residues (spring barley)	0.25	0.1	0.1	0.1 ^r		
Distillery residues (wheat)	0.3	0.3	0.3	0.3		
Potatoes, peeled	0.8	0.8	0.8	0.8		
Vegetables	0.8	0.8	0.8	0.8		
Fruit and berries	1.0	1.0	1.0	1.0		
Butter	0.2	0.2	0.5	1.0		
Cream (30% fat)	0.4	0.7	0.7	1.0		
Skim milk	1.1	1.04	1.0	1.0		
Cheese ^a	6.0	0.6	0.6	1.0		
Cheese ^b	0.8	0.6	1.4	1.0		
Whey ^a	0.4	1.05	1.05	1.0		
Whey ^b	1.04	1.05	0.95	1.0		
Condensed milk	2.7	2.7	2.7	2.7		
Milk substitute	9.3	8.7	9.4	8.0 ^g		

^a Rennet coagulation.

^b Acid coagulation.

^e For plutonium, a value of 0.2 is applied.

^d For plutonium, a value of 4.0 is applied.

^e For ruthenium, barium, and plutonium, a default value of 0.04 is applied.

^f For ruthenium, barium, and plutonium, a default value of 0.25 is applied.

⁸ For barium, a default value of 9.3 is applied.

the outer layers of the grain, a similar fractionation in milling products is assumed as for cesium and strontium. The storage times in Table 14 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.

Activity intake and exposure

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

$$A_h(t) = \sum_k C_k(t) V_k(t), \qquad (17)$$

where

- $A_h(t)$ = human intake rate (Bq d⁻¹) of activity;
- $C_k(t) =$ concentration of activity (Bq kg⁻¹) of foodstuff k; and

 $V_k(t) =$ consumption rate (kg d⁻¹) of foodstuff k.

In ECOSYS-87, age-dependent consumption rates are applied. The dietary habits can also be assumed to be time-dependent which allows the simulation of dietary changes during or after an accidental situation. The foodstuffs are assumed to be locally produced, i.e., their concentration of activity is assumed according to the input data of contamination of air and precipitation. Importation of foodstuffs from other regions with different levels of contamination can be considered by applying multiplicative correctional factors to the consumption rates for single foodstuffs.

Average German consumption rates for the age groups 1, 5, 10, 15 y, and adults were deduced from Deutsche Gesellschaft für Ernährung (1988) and Becker et al. (1982), and are given in Table 15. For leafy vegetables, it is assumed that the consumption rate in summer is higher than the mean rate, and in winter, only a small fraction of the consumed vegetables is harvested outdoors (the rest is produced in greenhouse 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 15.

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

$$D_{Ing}(T) = \int_0^T A_h(t) g_{Ing}(t) \, dt, \qquad (18)$$

where

 $D_{Ing}(T)$ = ingestion dose (Sv); and

 $g_{Ing}(t) =$ age-dependent dose factor for ingestion (Sv Bq⁻¹).

The dose factors applied in ECOSYS-87 are taken from Henrichs et al. (1985a.b.c,d) and No β ke et al. (1985) which are based on the metabolic models de-

Table 14. Storage and processing times $t_{\rho k}$ applied in ECO-SYS-87.

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, roe deer	2
Chicken, lamb	7
Eggs	2

Table 15. Age-dependent German consumption rates V_k in ECOSYS-87.

Consumption rate (g d ⁻¹))	
Foodstuff	1 y	5 y	Age grou 10 y	ир: 15 у	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
Rve, whole grain	2.2	4.8	6.0	6.9	8.7
Rve, 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
Roe deer	0	1.1	1.2	1.3	1.7
Eggs	5.0	18	25	36	43
Beer	0	0	12	130	610

scribed in ICRP Publication 30 (ICRP 1979) considering age-dependent organ masses and, as far as possible, age-dependent biokinetic data. They give the dose committment for an individual from its age at ingestion until the age of 70 y. For individuals >20 y, the 50-y dose committment is calculated.

INTERNAL EXPOSURE FROM INHALATION

The dose D_{Inb} , 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 agedependent dose factor for inhalation (Henrichs et al. 1985a,b,c,d; Noßke et al. 1985). In addition, a reduction factor can be applied that considers the lower activity in air inside houses:

$$D_{Inh} = C_a I_{Inh} g_{Inh} R_{Inh}, \tag{19}$$

where

 D_{Inh} = inhalation dose (Sv);

 $C_a =$ time-integrated activity concentration in air (Bq h m⁻³);

 I_{Inh} = inhalation rate (m³ h⁻¹);

 g_{Inh} = dose factor for inhalation (Sv Bq⁻¹); and

 R_{Inh} = reduction factor for staying indoors.

The inhalation rates applied for the five age groups at light corporeal activity are 0.18, 0.42, 0.60, 0.90, and 1.2 m³ h⁻¹ for the age groups 1–, 5–, 10–, 15–y, and adults, respectively, according to Documenta Geigy (1976) and ICRP Publication 23 (ICRP 1975).

EXTERNAL EXPOSURE FROM THE CLOUD

The gamma exposure due to radiation from the cloud is calculated assuming a semi-infinite homogeneous cloud. This assumption is justified for locations far away (at least several kilometers) from the emission source. Then, the external gamma exposure is given by the following:

$$D_c = C_a g_c R_c, \tag{20}$$

where

- D_c = dose due to external radiation from the cloud (Sv);
- C_a = time-integrated activity concentration in air (Bq s m⁻³);
- $g_c = \text{dose factor for exposure from the cloud (Sv m³)} Bq^{-1} s^{-1}$; and
- R_c = reduction factor for staying at different locations.

The age-dependent dose factors g_c for exposure from the cloud are taken from Jacob et al. (1990). The reduction factor R_c for staying at different locations considers the fractions of time during which people stay at different locations and the shielding of the gamma radiation at these locations, as follows:

$$R_c = \sum_i f_i c_{c,i}, \qquad (21)$$

where

- f_i = fraction of time staying at location *i*; and
- $c_{c,i}$ = correction coefficient for the gamma dose rate at location *i* relative to that in a semi-infinite homogeneous cloud.

Default values of $c_{c,i}$ for the different locations applied in the model are based on Meckbach and Jacob (1988) and are summarized in Table 16.

EXTERNAL EXPOSURE FROM NUCLIDES DEPOSITED ON THE GROUND

The exposure due to radiation from radionuclides deposited on the ground is calculated on the basis of **a** horizontally homogeneous distribution of radionuclides over grassland. Correction factors for different locations considering shielding and deposition patterns (e.g., in urban areas) are applied. The dose by gamma radiation from deposited radionuclides is calculated by the following:

$$D_g(T) = A_s R_g \int_0^T y(t) g_g(t) \exp(-\lambda_r t) dt, \quad (22)$$

where

- $D_g(T) = \text{dose (Sv)}$ from gamma radiation of deposited nuclides from time of deposition up to time T;
 - A_s = total deposition to grassland (Bq m⁻²);
 - $g_g(t)$ = age-dependent dose factor for exposure from ground (Sv m² Bq⁻¹ s⁻¹);
 - R_g = reduction factor for staying at different locations; and
 - y(t) = corrective function for shielding due to migration of the radionuclides into deeper soil layers.

Table 16. Correction coefficients $c_{e,i}$ and $c_{g,i}$ for external exposure at different locations.

	Correction coefficients for exposure from:		
Location	Cloud	Ground	
Outdoors:			
suburban	1.0	1.0	
urban	0.6	0.3	
Single family houses:			
above ground	0.3	0.1	
basement with windows	0.05	0.01	
basement, no windows	0.01	0.001	
Large buildings:			
above ground	0.05	0.01	
basement	0.001	0.0005	



Fig. 3. Structure of the ECOSYS-87 program system. Words in capital letters indicate programs; boxes indicate data files.

The dose factors g_g for external exposure from deposited radionuclides are taken from Jacob et al. (1990). The reduction factor R_g is calculated in the same way as for external exposure from the cloud [see eqn (21)], but instead of the correction coefficients $c_{c,i}$, the respective coefficients $c_{g,i}$ are used. These coefficients, which give the gamma dose rate from deposited nuclides at location *i* relative to that over grassland, are also based on Meckbach and Jacob (1988) and are given in Table 16.

The following approach (Jacob 1989) is used for the corrective function for shielding y(t):

$$y(t) = a_1 \exp(-\lambda_1 t) + a_2 \exp(-\lambda_2 t),$$
 (23)

where

- $\lambda_1, \lambda_2 = \text{migration rate} (\lambda_1 = 1.46 \times 10^{-3} \text{ d}^{-1}, \lambda_2 = 3.87 \times 10^{-5 \text{ d}^{-1}}); \text{ and }$
- $a_1, a_2 =$ contribution fractions of the migration rates $(a_1 = 0.36, a_2 = 0.64).$

STRUCTURE OF THE PROGRAM SYSTEM

ECOSYS-87 is a modular system of several FORTRAN-77 programs; each of these modules performs one step of the calculations and stores its results in one or more disk files which are the input for the subsequent module(s). This has the advantage that the intermediate results can be compared with and, if necessary, replaced by measured data. Fig. 3 schematically shows the structure of the program system with the most important programs, input data, and intermediate and final results. All model parameters are kept in external, editable data files so that they can easily be exchanged or modified without changing the programs.

The radionuclide transfer in food chains can be regarded as independent of the amount of deposited activity. This allows the ability to precalculate the nuclide transfer in food chains for a normalized shortterm deposition of 1 Bq m⁻² deposition onto the leaves of the plants and 1 Bq m^{-2} onto the soil. The precalculation is done in program NORA.[†] The resulting normalized time-dependent functions of the activity concentrations in primary products (i.e., plant and animal products at time of harvesting before storage and processing) have a very high time resolution in the first 2 y since, here, the most pronounced changes of the activity concentration in foods are to be observed. The time steps increase later since there is only little variation with time. Up to 751 time steps are used to represent the time dependence during the 70 y since deposition.

For the dose calculation in an actual case (characterized by activity in air and precipitation, amount of precipitation, and time of the year), the dry and wet deposition onto soil and onto the foliage of the different plant types (according to the plants' development) is calculated in program DEPOS. In program ACTI, the normalized activity concentration functions are multiplied by the actual deposition values in order to achieve the actual functions of activity in food- and feedstuffs. For contaminations of air and precipitation lasting for more than 1 d, or for several separated single deposition events, the effects of these events are superimposed in program ACTI. The doses via all pathways are calculated in the program module DOSIS.

The results of the program ACTI and DOSIS are very comprehensive, therefore only the most important results are given as routine output. For the output of additional information, the programs ACTOUT and DOSOUT allow the user to select those results that are of interest.

Due to the normalization process in program NORA, only simple standard feeding diets for domestic animals can be assumed. For calculating the concentration of activity in animal products for more complex feeding diets, the additional program ANIMAL is available. In this program, the diet can consist of any mixture of the feedstuffs considered in the model. The feeding rates can be time-dependent to simulate seasonal effects, and substitutions in feed for limited time periods can be specified to represent countermeasures. The feedings rates can also change with the age of the animals, thus allowing users to consider the effect of feeding less-contaminated fodder during a certain time period before slaughtering.

The program LIMITS estimates the reduction of the ingestion dose due to introducing intervention levels for consumed foodstuffs. It is possible to apply activity limits for single nuclides or for groups of nuclides for all considered foodstuffs independently.

The estimation of the uncertainty of the model

results is performed together with the program package PRISM (Gardner et al. 1983). Input for PRISM are the distribution functions for the model parameters used in ECOSYS-87. From them, the program PRISM1 produces N sets of model parameters for the ECOSYS-87 model. The next step is to run the ECOSYS-87 model. The next step is to run the ECOSYS-87 model N times using these N sets of parameters, and storing all results of interest. The statistical analysis of these results is performed by the program PRISM3, leading to probability distributions of the model results.

MODEL RESULTS

Based on the measurements of activity concentration in air and the activity deposited with rain at Munich-Neuherberg after the Chernobyl accident (Hötzl et al. 1987), the ¹³⁷Cs concentration in foodstuffs has been calculated using ECOSYS-87 (Pröhl 1990). These data are compared with measurements of activity in foodstuffs during 1986 in Southern Bavaria (StMLU 1987) in Table 17. For this comparison, it must be noted that the deposition of Chernobyl activity in Southern Bavaria showed considerable variation (roughly a factor of 2, in some cases a factor of 3, higher and lower than at Munich-Neuherberg).

The activities in animal products cover a wide range due to different feeding practices associated with the measured data and with the predictions. Most of the predictions are within the range of observed values given in Table 17, but some differences are obvious. For veal, the calculated activities greatly exceed the measured. The reason is that the veal pathway was recognized as a critical one very early on, so highly contaminated milk was not used for the production of whole milk substitute. For spring cereals, the measured activities are below the calculated values. This is due to the fact that, in spring 1986, the development of the plants was slower than in average years due to low temperatures. If, in the calculations, the time of deposition is assumed to be 1 wk earlier, the agreement between calculated and observed values is much better.

For fruit and berries, the model predictions agree rather satisfyingly with the observed values given in Table 17, though due to subsummation of quite different plant species in one compartment ("fruit"), a large range of observed values occurs that makes the comparison difficult. In contrast to these findings, during the application of ECOSYS-87 to another region (Central Bohemia) in the VAMP study (Linsley et al. 1990), the application of eqn (9) and the parameters for fruit given in this paper lead to considerable overestimation of the contamination of apples and pears in 1986 and underestimation in the following years. Thus, for fruit and berries, the model given here obviously needs to be improved.

The model performance can be demonstrated in a better way by making comparisons for special situations which have circumstances that are well described. Fig. 4 shows the ¹³⁷Cs activity of milk from a dairy farm in

Table 17. ECOSYS-87 prognosis of ¹³⁷Cs concentration in feed and foodstuffs in the year 1986 and measured concentrations in Southern Bavaria (from Pröhl 1990).

×.	Activity concentration (Bq kg ⁻¹)		
Product	Calculated	Measured	
Grass ^a	2,700	2,000-4,000	
Winter wheat	31	10-50	
Spring wheat	8	<5	
Winter barley	110	30-200	
Spring barley	19	<5	
Rye	130	50-300	
Oats	12	<5	
Potatoes	0.5	<5	
Leafy vegetables ^a	3,000	2,000-4,000	
Fruit vegetables	2	<5	
Root vegetables	2	<5	
Fruits	40	10-200	
Berries	110	20-400	
Milk ^a	280	-400	
Beef (cow) ^a	480	10-600 ^b	
Beef (bull) ^a	3-880°	10-600 ^b	
Vealª	950	20-300	
Pork ^a	13-750°	10-800	
Roe deer*	2,300	-3,000	

^a Maximum value.

^b There is no differentiation between cows' and bulls' meat in the measured data.

e Range due to different feeding regimes.



Fig. 4. Comparison of measured 137 Cs-concentration in milk (dots) with that predicted by ECOSYS-87 (solid line = deterministic calculation; bars = 5%, 50%, and 95% percentile of frequency distribution due to parameter ranges given in Table 18).

the vicinity of Munich. The cows were fed on fresh grass in summer and on hay and grass silage in winter. In early May 1986, they were kept indoors for some days and fed on uncontaminated fodder. The time-

March 1993, Volume 64, Number 3

dependent concentration of activity in milk, and its estimated range of uncertainty, was calculated with ECOSYS-87 and the PRISM package, and considered the estimated ranges of uncertainty of the respective model parameters (see Table 18).

Fig. 4 shows the curve resulting from a deterministic calculation using the standard parameters (as given in Tables 2–12), as well as the 5%, 50%, and 95%percentiles of the frequency distribution resulting from the uncertainty estimation. The comparison of the measured activities in milk with the predictions of the model shows good agreement, especially during the first year after deposition, which is most relevant for human exposure. Only the increase of activity due to winter feeding occurs later in the measurements as compared to the model predictions; this is due to unusually mild weather conditions in November 1986. At later times, when root uptake is the dominating pathway, the observed values are slightly higher than predicted. This can be explained by different reasons: A small amount of hay prepared in 1986 was fed even in summer 1987 to the cattle, and the transfer factor soil-pasture is relatively high (due to relatively acid soil) at the site of measurements. Moreover, it is possible that the assumed total deposition (which was estimated from measurements of soil samples nearby) underestimates the real one at the area of grass production, since considerable small-scale spatial variability of deposition was observed.

Another reason could be that the transfer of cesium from fodder to milk was higher in 1987, compared to 1986, due to increased bioavailability. Such an effect has been reported by several other authors (e.g., Ward et al. 1989), and an increased milk transfer factor had been measured in the milk of this dairy farm in 1990.

To demonstrate the parameter sensitivity and uncertainty calculations, a scenario similar to the Chernobyl fallout at Munich has been chosen: The time-integrated ¹³⁷Cs activity concentration in the nearground air is 300 Bq h m⁻³, the wet deposition is 16 kBq m⁻² with 5 mm of rainfall, and this deposition occurs on 1 May. A spatial variability of the deposition is not considered, furthermore, it is assumed that all foodstuffs consumed are produced locally and that all animal foodstuffs are produced using the standard feeding diets given in Table 10.

For this scenario, the lifetime ingestion dose for an adult person is calculated. In a first step, the most sensitive (with respect to the ingestion dose) of the more than 400 model parameters have been identified (see Table 19). In a second step, an uncertainty estimation of the resulting ingestion dose was performed using the estimated distribution functions for these most sensitive parameters given in Table 19. These distributions are intended to represent the uncertainty of the mean dose to population under the given conditions, not the variability of individual doses. For all other parameters with a low sensitivity for this endpoint, the standard values given in Tables 2-15 were used. Fig. 5 shows the resulting cumulative frequency distribution for the mean lifetime dose. It indicates that 90% of the results are within a range of about a factor of 2, and there is a factor of 3 between the minimum and maximum. This range seems to be surprisingly small. However, it should be noted that the boundary conditions for this estimation are idealized with respect to the assumption of homogeneous deposition, the consumption of locally produced food, and use of standard feeding regimes.

In reality, the exposure scenario is much more complex; it is influenced by factors that are qualitatively known but very hard to be quantify, such as the impact of food distribution, psychological factors resulting from information of the mass media, and countermeasures recommended by both competent and incompe-

Table 18. Assumed	distributions of the	sensitive parameter	rs for the cal	lculation of t	he range of	f uncertainty	in
Fig. 4.							

Parameter	Distribution	Mean (SD) or median	Minimum	Maximum
Deposition velocity on grass (mm s ⁻¹)	normal	1.5 (1.0)	0.0	4.0
Retention coefficient for wet deposits (mm)	normal	0.2 (0.2)	0.05	0.4
Weathering half-life for grass (d)	triangular	25.0	15.0	30.0
Fraction of activity translocated to root-zone	triangular	0.95	0.90	0.99
Half-life due to growth dilution in May (d)	triangular	18.	13.	23.
Half-life (d) due to root-zone translocation	triangular	60.	40.	80.0
Maximum leaf area of grass achieved (date)	triangular	15.5.	30.4.	30.5.
Transfer factor soil-grass	uniform	0.03	0.01	0.05
Begin of feeding fresh forage (date)	triangular	21.4.	11.4.	1.5.
Full fresh forage feeding achieved (date)	triangular	11.5.	1.5.	21,5.
Begin of feeding hay and silage (date)	triangular	21.10.	11.10.	31,10.
Full hav and silage feeding (date)	triangular	10.11.	31.10.	15.11.
Start of preparing hay and silage (date)	triangular	16.5.	11.5.	30.5.
Feeding rate (kg d ⁻¹ f.w.)	uniform	70.0	60.0	80.0
Transfer factor feed milk (d kg ⁻¹)	triangular	0.003	0.002	0.008
Mass of pasture soil (kg m^{-2})	uniform	140.0	100.0	180.0
Long biological half-life for milk (d)	uniform	15.0	10.0	20.0
Fraction of short biological half-life	uniform	0.8	0.7	0.9

Parameter	Distribution	Mean (SD) or median	Minimum	Maximum
Retention coefficient for wet deposits (mm)	normal	0.2 (0.1)	0.05	0.4
Weathering half-life for grass (d)	triangular	25	15	30
Fraction of activity translocated to root-zone	triangular	0.05	0.10	0.01
Half-life (d) due to root-zone translocation	triangular	60	40	80
Maximum leaf area of grass achieved (date)	triangular	15.5.	30.4.	30.5.
Begin of feeding fresh forage (date)	triangular	21.4.	11.4.	1.5.
Full fresh forage feeding achieved (date)	triangular	11.5.	1.5.	21.5
Begin of feeding hay and silage (date)	triangular	21.10.	11.10.	31.10.
Full hay and silage feeding (date)	triangular	10.11.	31,10.	15.11.
Grass feeding rate (kg d ⁻¹ f.w.) for cattle	uniform	70	60	80
Start of preparing hay and silage (date)	triangular	16.5.	11.5.	31.5.
Transfer factor feed milk (d kg^{-1})	triangular	0.003	0.002	0.008
Harvesting winter wheat (date)	triangular	5.8.	26.7.	15.8.
Harvesting winter rye (date)	triangular	31.7.	21.7.	10.7.
Processing factor for wheat flour	uniform	0.5	0.4	0.6
Processing factor for rye flour	uniform	0.6	0.5	0.7
Processing factor for leafy vegetables	uniform	0.8	0.6	1.0
Consumption rate for milk $(g d^{-1})$	uniform	230	115	345
Consumption rate for wheat flour (g d^{-1})	uniform	130	65 -	195
Consumption rate for rye flour $(g d^{-1})$	uniform	35	18	53
Consumption rate for leafy vegetables (g d ⁻¹)	uniform	94	47	141



Fig. 5. Cumulative frequency distribution of the effective lifetime ingestion dose for an adult resulting from the deposition scenario given in the text and parameter uncertainty ranges given in Table 19 (the symbols indicate minimum and maximum value).

tent advisers. This means that the description of the scenario is more or less inaccurate and incomplete, causing a discrepancy between model and reality. This has also been identified as another major source of uncertainty (besides the uncertainty of the model parameters) during the multiple pathway exercise of the VAMP study (Linsley et al. 1990).

In Fig. 6, the dependency of the radiological con-



Fig. 6. Dependence of the ingestion dose (integrated over 50 y) on the time of deposition. A time-integrated activity concentration in air of 1×10^6 Bq s m⁻³ for each radionuclide has been assumed.

sequences on the time of deposition is demonstrated: It shows the lifetime ingestion dose of a person age 20 y at time of deposition. Time-integrated air concentrations of 1×10^6 Bq s m⁻³ for each of the radionuclides ¹³⁷Cs, ⁹⁰Sr, and ¹³¹I (1/3 of ¹³¹I is aerosol-bound, 1/3 is organic, and 1/3 is elemental) are assumed, and only dry deposition is considered.

The time of deposition varies from January to December (from April to October, the 1st, 11th, and

Table 20. Total lifetime dose for an adult and contribution of the different exposure pathways resulting	from
a time-integrated activity concentration in air of 1×10^6 Bq s m ⁻³ ("—" means <0.5%).	

0			2.63		S. 32M
	 ¹³⁷ Cs	90Sr	¹³¹ I	¹⁰⁶ Ru	²³⁹ Pu
Deposition 1st January:					
Total dose (mSv)	2.8×10^{-2}	1.7×10^{-1}	5.8×10^{-3}	4.6×10^{-2}	$4.0 \times 10^{+1}$
Ingestion (%)	21	31	52	4	1
Inhalation (%)	10	69	47	95	99
Cloud (%)			<u> </u>		*
Ground (%)	69	_		1	76
Deposition 1st July:					
Total dose (mSv)	8.8×10^{-1}	5.5×10^{-1}	6.7×10^{-2}	7.8×10^{-2}	$4.3 \times 10^{+1}$
Ingestion (%)	93	79	96	42	6
Inhalation (%)		21	4	55	94
Cloud (%)		<u> </u>)	
Ground (%)	7		÷	2	<u></u>

21st day of each month; for the remaining months only the 1st day of the month is chosen). Fig. 6 gives the ingestion dose for each of the three radionuclides as a function of the time of deposition. The largest variation can be observed for the ¹³⁷Cs dose: The maximum is reached in June when the initial contamination and the translocation is highest for many plants. For ⁹⁰Sr, the difference between deposition in summer and winter is much smaller for two reasons: 1) the root uptake for strontium during the 50 y following the deposition is higher than for cesium, leading to higher doses for depositions during winter; and 2) the low translocation of strontium as compared to cesium causes many crops to be less affected by summer depositions. The curve looks quite different for the short-lived ¹³¹I. Only the foodstuffs with continuous harvesting and short storage and processing times (e.g., milk, leafy vegetables, and, to a smaller degree, fruit vegetables) contribute significantly to the ingestion dose. Consequently, a pronounced difference exists between summer and winter deposition but nearly no variation exists during the vegetation time period.

The dependency on the time of deposition is only of importance for the ingestion pathway. The external radiation from deposited radionuclides has only a weak dependency on the deposition time since, as described earlier, the dose estimation starts from the deposition onto grassland. The relative importance of the different exposure pathways thus changes with the radionuclides considered and with the time of deposition. To demonstrate this, dose calculations have been performed starting with time-integrated activity concentrations in air of 1×10^6 Bq s m⁻³ on 1 January and 1 July for the radionuclides ¹³⁷Cs, ⁹⁰Sr, ¹³¹I, ¹⁰⁶Ru, and ²³⁹Pu (assuming only dry deposition). Table 20 gives the resulting lifetime doses to adults (20 y at time of deposition) and the relative contributions of the different exposure pathways. In these examples, the ingestion and inhalation, as well as the external dose from ground-deposited nuclides, can play the dominant role,

dependent on the radionuclide and the time of deposition.

DISCUSSION

The comparisons of model results with measured concentrations of activity in feed- and foodstuffs after the Chernobyl accident show that, in general, the model gives realistic estimations of the foodstuff contamination. Of course, the overall satisfying model performance with Chernobyl data is partly due to the model parameters being deduced from post-Chernobyl observations. It cannot be excluded that in a future accident, radionuclides are released in other chemical forms under different conditions, causing a different behavior in the food chains and, subsequently, less agreement.

An important example for this is the fodder-milk transfer factor for cesium: The value of 0.003 d L^{-1} which has been observed after the Chernobyl accident at many locations [(e.g., in the BIOMOVS study (Köhler et al. 1991)] and which is used in ECOSYS-87, is about a factor of 2 to 4 lower than the value observed in earlier experiments. For radionuclides different from cesium and iodine, the data base for model validation is much poorer causing higher uncertainties in the model parameters and results.

It has been demonstrated that the dose from ingestion shows a very pronounced seasonality. This underlines the high importance to consider the time-dependency of the plants' development in radioecological modeling. Moreover, this causes the dose predictions after depositions during the vegetation time period to be associated with a considerable inherent uncertainty due to the regional and year-to-year variations of the plants' development. As a further consequence, the relative importance of the different exposure pathways depends strongly on the time of deposition. After an accidental release of radioactivity into the air, the ingestion, inhalation, and the external dose from grounddeposited nuclides or from the cloud can be the dominating pathway, dependent on the radionuclide spectrum and the time of the accident. Therefore, it is one of the main tasks of a dose assessment program to give a quick overview on all potentially relevant exposure pathways in a certain accidental situation.

A practical advantage of the modeling approaches of ECOSYS-87 is that parameters are used that can be easily deduced from measurements. Thus, the model can be adapted to different regions with different radioecological conditions. This approach also facilitates the verification of the model and an iterative improvement of model predictions in the course of an emergency.

The estimation of the uncertainty of the model results due to parameter uncertainty gives an indication about the reliability of the results. But it is important to remember that this uncertainty estimation is limited by the fact that there are sources of uncertainty that can hardly be quantified. This is due to the limited knowledge about the scenario (e.g., food distribution, farming practices, or the dietary habits of the population). These factors, especially, may change in an unpredictable way during an emergency.

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