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April 1991

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Abstract. The transfer of radionuclides in the terrestrial environment have been investigated. The thesis is divided into two parts. Part I; Dynamic model for the transfer of radionuclides in the terrestrial environment. The study comprises the development of a compartment model, that simulates the dynamic transport of radioactive pollution in the terrestrial environment. The dynamic processes include, dry and wet deposition, soil resuspension, plant growth, root uptake, foliar interception, animal metabolism, agricultural practice, and production of bread. The ingested amount of radioactivity, by man, is multiplied by a dose conversion factor to yield a dose estimate. The dynamic properties and the predictive accuracy of the model have been tested. The results support the dynamics very well and predictions within a factor of three, of a hypothetical accident, are likely. Part II; Influence of plant variety on the root transfer of radiocaesium. Studies of genetic differences, in plant uptake of radiocaesium, were concluded with a pot experiment. Four varieties of spring barley and three varieties of rye-grass have been tested in two types of soil. The results for barley showed a significant difference between the four varieties. Analyses of variance confirmed a high root uptake of radiocaesium in the variety Sila and a significantly lower root uptake in the variety Apex in each type of soil. The pattern between the varieties was identical in 1988, 1989 and 1990. Similarly for the grass varieties, one variety, the Italian rye grass, was identified as having the relatively highest uptake of radiocaesium.

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PART I

Dynamic Model for the Transfer of Radionuclides in the Terrestrial Environment

1.0 INTRODUCTION

The development of nuclear weapons, nuclear energy and the applications of nuclides in medicine and industry result in a release of radioactive material into the environment.

To make an assessment of the radiological impact or consequences of such releases of radionuclides, mathematical models, which incorporate the many factors, that cause or affect the movement of radionuclides, have been widely used. Furthermore modelling is the only tool available to predict consequences of hypothetical accidental situations.

The experiences from the investigations of the fallout, originated from nuclear weapons tests in the fifties and sixties, formed the background for the development of the steady state models. These models were based on a continuous fallout, and one of the applications has been to predict the concentrations of radionuclides in the environment close to the nuclear power plants with routine discharges of radionuclides.

Steady state models can only be applied, if the rates of movement of the radionuclides and the integration periods over which results are required, are such, that the situation can be regarded as in quasi-equilibrium, i.e. the time variations can be ignored without introducing significant errors.

When discharges to the environment are discontinuous or when the release is acute, a different type of environmental models is required. Under these circumstances the changes, that occur with time, need to be represented and models must therefore be dynamic. The experience learned from the Chernobyl accident clearly demonstrated, that a more detailed modelling, including time dependent processes, is necessary.

The present study comprises the development of a compartment model, that can simulate the dynamic transport of radionuclides in the terrestrial environment, after a discrete release to the atmosphere. The model is intended to be used for predictions of the radionuclide concentrations in the main elements of the terrestrial foodchain, and subsequently estimate the dose to man.

The structure of the model is described in details in chapter 2. Following a validation in chapter 3, the aspects of a single hypothetical deposition are investigated and discussed in the chapters 4, 5, and 6. The results of several sensitivity analyses, and a discussion of the overall uncertainty of the model predictions, are presented in chapter 7.

Currently, the model contains data necessary for a simulation of the dynamic transport of the radionuclides ^{137}Cs, ^{134}Cs and ^{90}Sr within a Danish agricultural system.

2.0 GENERAL DESCRIPTION

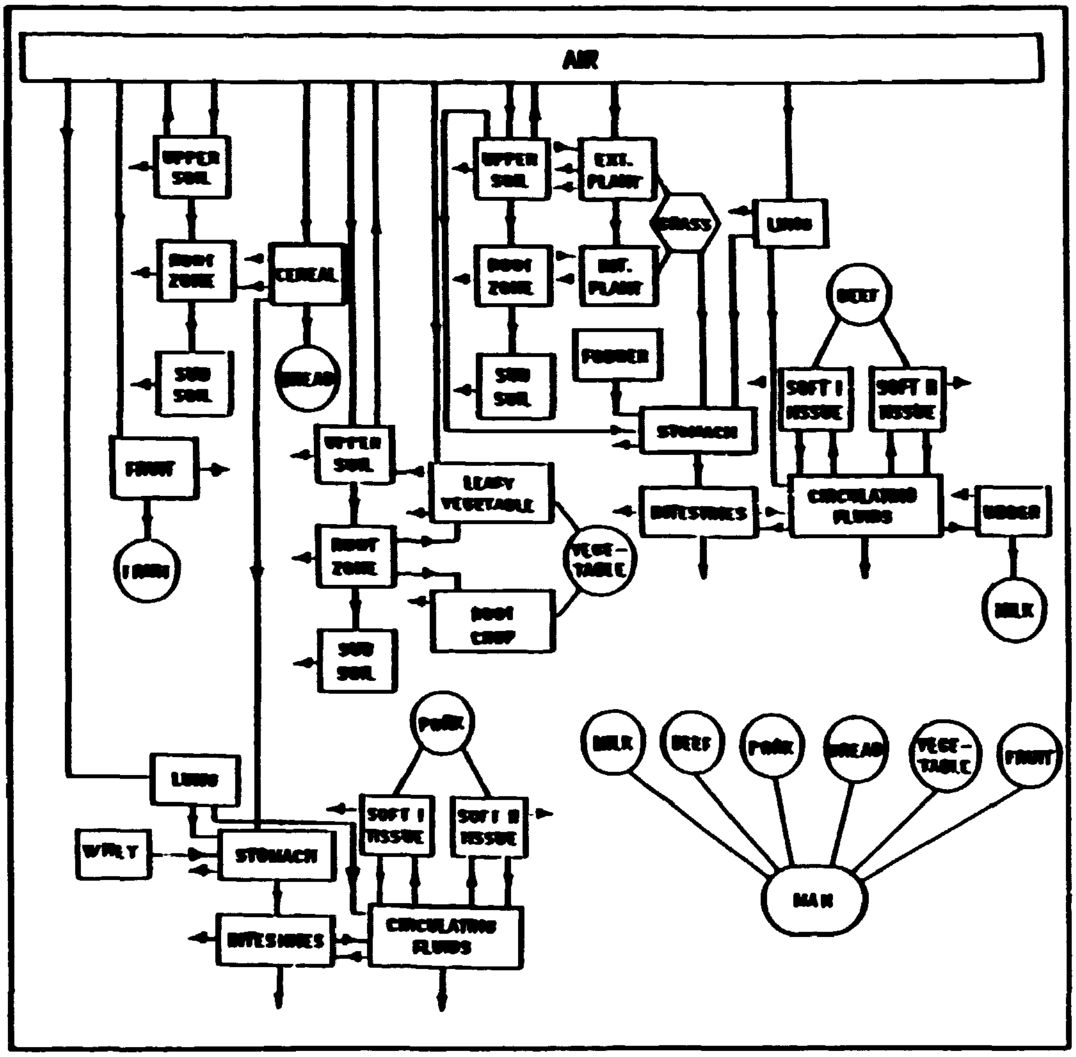

Figure 1.a
Schematic structure of the compartmentsystem.

The modelling system consists of a series of interconnected compartments, each representing different parts of the terrestrial environment. The structure of the model for caesium isotopes is shown in Figure 1.a.

The pathways between the different compartments are indicated. Each compartment is represented by a state variable, Y_j , $j = 1,\ldots,n$. These represent the quantity of the radionuclides in specific compartments. The rate of change for a given radionuclide in a compartment, is given by a system of linear differential equations:

$$\frac{dY_j}{dt} = \sum_{i \neq j} \lambda_{ij} Y_i - \sum_{i \neq j} \lambda_{ji} Y_j - \lambda_f Y_j + P_j$$

j is the compartment of reference and i designates all other compartments. λ_{ij} and λ_{ji} represents the transfer coefficient between the compartments in units of reciprocal time. The first term on the right represents the flow entering compartment j; the second term represents the flow leaving compartment j. The term P_j represents the input into compartment j from outside the system, in units of activity per unit time. The constant λ_f accounts for the physical decay of the activity in compartment j.

The resulting set of linear coupled differential equations is solved numerically, using a Runge-Kutta algorithm of order four (Kirchner 1989). Inventories are calculated in steps of one day and converted to concentration units. The air, soil and plant compartments all refer to a surface area of 1 m^2.

The model is implemented as a Fortran code and simulates the dynamic transport of several radionuclides through the Danish agricultural ecosystem. The code was made using a modelling development system for personal computers, TIME-ZERO (Kirchner 1989). The final code made for the modelling development system is listed in the appendix, including a description of the state variables and parameters.

2.1 DEPOSITION

The description of deposition of radionuclides includes the concentration X (Bq m^{-3}), of a given radionuclide, at the height of 1 meter above ground.

Based on the basic definition of the dry deposition velocity v_d (NCRP 1984), the dry deposition flux F_d to the surface is:

$$F_d = v_d \cdot X \qquad \text{Bq m}^{-2}\ \text{s}^{-1}$$

A similar expression for the wet deposition flux F_w to the surface (NCRP 1984) is:

$$F_w = w \cdot p \cdot X \qquad \text{Bq m}^{-2}\ \text{s}^{-1}$$

where w is the washout ratio (Bq l^{-1}/Bq m^{-3}), which is defined as the ratio between the concentrations of a given radionuclide in precipitation and in air (NCRP 1984), and p is the precipitation rate (m d^{-1}).

Many atmospheric and surface processes influence the dry and wet deposition, and hence a wide range of values for v_d and w have been reported for several scenarios (Nielsen 1981), (NCRP 1984) (Whicker and Schultz 1982). The values v_d = 172.8 m d^{-1} (2mm s^{-1}) and w = 10^5 (Bq l^{-1}) are used in the present model. These are based on Danish data from the weapons fallout period (Aarkrog 1979). Caesium and strontium are both attached to atmospheric particles when deposited, and an average particle size of 1 µm is assumed in the present model.

2.2 SOIL COMPARTMENTS

To account for the intensive cultivation of the Danish agricultural soil, three soil compartments are introduced: an upper soil compartment, a root zone compartment, and a sub soil compartment. For each crop a soil system containing these three compartments determines the soil to plant transfer.

The upper soil compartment, with a thickness of 1 cm, is introduced to account for the resuspension from the surface of the soil and the soil ingestion by the livestock. The resuspension process and soil ingestion are described in details in chapter 2.3 and chapter 2.8.1, respectively.

For ploughing and root uptake, an effective root zone of 25 cm is introduced. Rotation of crops, including pasture grass, is normally used in Denmark. To include ploughing, the inventory in the upper soil layer, the inventory of the root zone and what is left of the crops after harvest are mixed once a year in October in the model simulation. Ploughing provides a uniform mixing of the radionuclide contamination in this zone.

The soil compartments, accounting for the resuspension, include both the upper soil and the root zone. This reflects that the resuspended material also originates from uncultivated areas with an undisturbed soil surface.

The construction of the model makes it possible to leave ploughing out of the simulations, and simulate a scenario with undisturbed pasture instead of a well grown pasture.

The sub soil compartment accounts for the radionuclides no longer available to the crops. This is due to fixation and leaching to deeper soil layers (Nielsen and Strandberg 1988). The rate of penetration for the radionuclides from the root zone to the sub soil compartment, depends on the radionuclide and the soil type.

Due to differences in retention to clay minerals and leaching to deeper soil layers, different transfer coefficients have been introduced for ^{137}Cs and ^{90}Sr (Russell 1966), (Rogowski and Tamura 1970 a) (Livens and Baxter 1988), (Squire and Middelton 1966a, 1966b). Furthermore different transfer factors have been introduced for caesium due to differences in retention in various soil types, Table 2.2.I. The transfer factors for caesium in sandy loam and organic soil are based on results from the studies described in part II.

Table 2.2.I
Transfer coefficients providing for fixation to minerals and leaching to deeper soil layers for a given isotope and a given type of soil.

Sandy loam		Organic soil
d^{-1}	d^{-1}	d^{-1}
Strontium	Caesium	Caesium
$7\cdot10^{-4}$	$1\cdot10^{-3}$	$7\cdot10^{-4}$

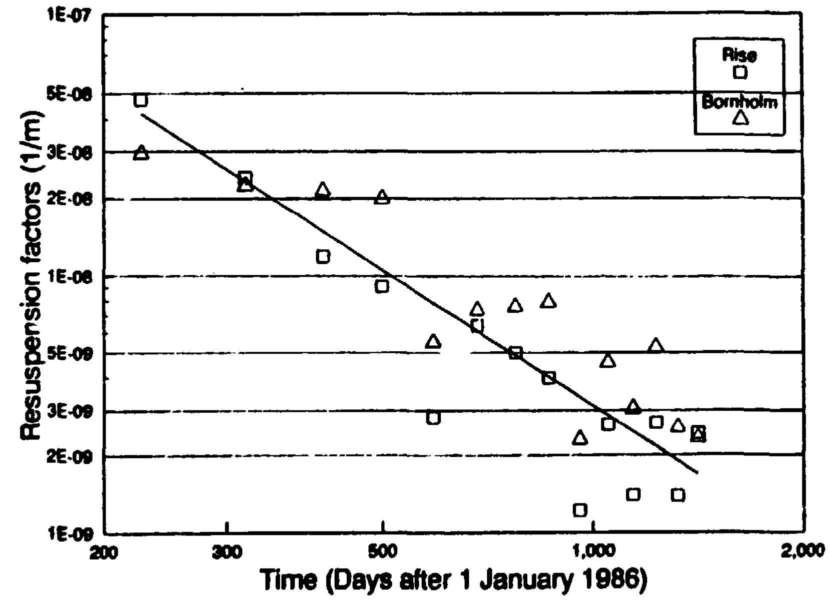

Figure 2.3.a
Measured values for the resuspension factor in Denmark after the Chernobyl accident. Data fitted with the approximation

$$RF(t) = 1.45\cdot10^{-5}\cdot t^{-1.26}\ m^{-1}$$

2.3 RESUSPENSION

Experience from the Chernobyl accident (Aarkrog et al. 1989) show that radionuclides deposited on the ground, may again be "resuspended" by wind into the air, and subsequently deposited on the ground or vegetative surfaces. Resuspended material can thus become a significant contributor to the doses to persons via the food chain, long time after the source term has ceased to exist.

To account for this resuspension, a pathway from the upper soil compartment to the air compartment is introduced (Figure 1.a).

The resuspension factor RF (m^{-1}) for a given radionuclide is defined as the ratio of the concentration in the air, at a reference height above the ground (usually one meter), to the concentration per unit surface area. Based on earlier studies, the resuspension factor RF(t) used in the present model is a function of the time t measured from the time of deposition (O.J. Nielsen 1981), (H.Hötzl et al 1989), (NCRP 1984). In agreement with Danish experience after the Chernobyl accident, the following formula for the time dependence of the resuspension factor is used:

$$RF(t) = 1.4 \cdot 10^{-5} \cdot t^{-1.26} \qquad m^{-1}$$

for the first 2000 days after a release of radionuclides, Figure 2.3.a (S.P. Nielsen 1990), (A.Aarkrog et al 1989). Based on the assumption that the resuspension factor will not decrease to less than 10^{-9} (NCRP 1984), this value is used as the resuspension factor, for the rest of the simulation period.

The amount of radionuclides resuspended into the air compartment AIR_r at time t, after the deposition, will then be:

$$AIR_r(t) = (RF(t) \cdot y_j) \qquad Bq\ m^{-2}$$

where y_j is the concentration of radionuclides in the upper soil compartment.

2.4 PLANT GROWTH

2.4.1. Root uptake

The plant uptake via the roots from the inventory in the root zone compartment, Y_r, is estimated as

$$R_{up} = Y_r \cdot (dB/dt) \cdot CR/(D_r \cdot S_b) \qquad Bq\ m^{-2}\ d^{-1}$$

where,

Y_r	: the inventory of the root zone compartment, (Bq m^{-2})
dB/dt	: the growth rate of the plant considered, (kg m^{-2} d)
CR	: the concentration ratio of the plant considered, (Bq/g plant per Bq/soil, dw.)
D_r	: the depth of the root zone, (m)
S_b	: the soil bulk density of the soil type considered, (kg m^{-3})

This equation is similar to the one used in the Pathway model (Whicker and Kirchner, 1987).

The values used for CR depend on plant species, soil type and the radionuclide considered. The CR values used in the simulations are primarily based on the experiments carried out with several crops grown in different sorts of Danish of soil (Part II, chapter 3.1 and 3.2). Concentration ratios for crops and isotopes, which are not considered in part II, have been chosen based on earlier studies. (Andersen 1967), (Steffens et al. 1988), (IUR 1989). Typical values are shown in Table 2.4.1.I.

The plant growth rate dB/dt is implemented in the model with time steps of one day. The values estimated for dB/dt depend on plant species and are further described in chapter 2.5.

Table 2.4.1.I.
Typical values for the concentration ratio CR and the soil density for strontium and caesium isotopes in different types of soil.

	Concentration ratio, CR Bq kg^{-1} plant per Bq kg^{-1} soil.			
	grass	leafy vegetables	coarse vegetables	cereals
Caesium:				
Sandy loam S_b^*:1460 kg m^{-3}	0.3	0.5	0.3	0.03
Organic soil S_b^{**}:550 kg m^{-3}	2.4	5.0	3.0	0.5
Strontium:				
sandy loam	4	8.0	3.0	0.3

* (Russel 1966),
** (Øhlenschlæger and Gissel Nielsen 1989)

2.4.2. Foliar absorption

The deposition is distributed between the soil and plant surfaces, using the foliar interception factor p introduced by A.C. Chamberlain (Chamberlain 1970),

$$p = 1 - \exp(-m \cdot d)$$

where m is the mass interception factor in units m^2 kg^{-1} and d is the density of the plants.

Various experiments, with different radionuclides, particle sizes, and varying intensity of rain, have been conducted in order to investigate the range of the interception factor (Hoffman et al. 1989), (U. Greitz et al 1974). Based on the results obtained from these studies, the value of the interception, factor used in the present model, is 0.3 for pasture grass, with an average density of 0.15 kg m^{-2} dw, and a mass interception factor of 2.3 m^2 kg^{-1}. The initial washoff, generated by the rainfall, that provides the wet deposition, is included in this value. The wet deposition is dominant, and depending of the amount and intensity of rainfall, the washoff from the surface of the plants to the soil can be substantial, and must be taken into account.

The interception factor is assumed to be the same for all nuclides transported attached to particles. The value of the interception factor included for dry deposition is the same as for wet deposition. Due to the minor importance of dry deposition no distinction has been made.

The use of p = 0.3 as the interception factor other than for pasture grass may yield erroneous results, and can only be considered on a case by case basis, depending on the type of crop. Assuming that p for vegetable crops cultivated in rows is smaller than the one for pasture grass, due to the extra soil surface exposed between rows, an interception factor p = 0.25 has been used for leafy vegetables and beet leaves (NCRP 1984).

Plant tissue incorporate the radionuclides from the foliar surfaces by absorption. It appears that the fraction of deposited material translocated into the internal parts of plants is usually small. According to Nielsen (Nielsen 1981) the average value lies between 5 and 10%.

To calculate the foliar transfer coefficient K_{ou} the following expression is used

$$K_{ou} = F_A \cdot K_W / (1 - F_A) \qquad d^{-1}$$

where,

F_A : the absorbed fraction of the surface deposit
K_W : the weathering constant, (d^{-1}) (Chapter 2.6)

The expression is similar to the one introduced by J.R. Simmonds (Simmonds et al. 1979) and Whicker and Kirchner (Whicker and Kirchner 1987).

2.5 VEGETATION

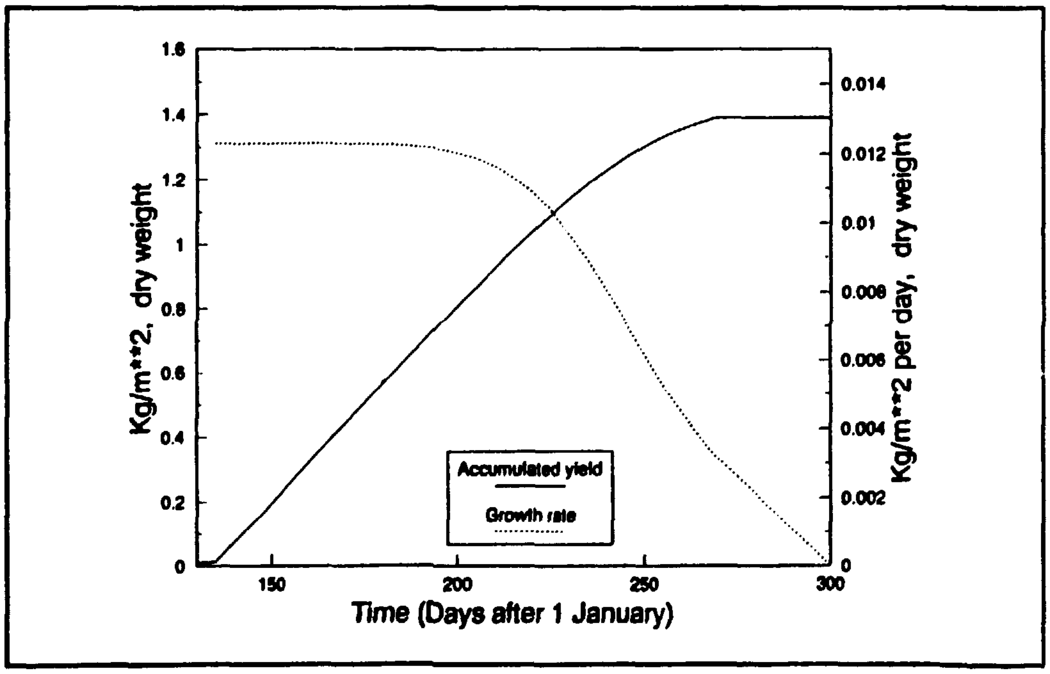

Figure 2.5.1.a
Plant growth rate, (dB/dt), for pasture grass based on experiments made by The National Institute of Animal Science (Kristensen 1987).

2.5.1 Pasture grass

Pasture grass is the main part of the cows´ diet in the summer, when they are outdoors. When kept indoors, which is becoming more common in Denmark, they are fed mainly with pasture grass harvested outdoors. The plant growth rate used in the model, is calculated from experiments made by the National Institute of Animal Science, Denmark (Kristensen 1987). It provides for the growth of the above-ground biomass and the subsequent dilution of the radionuclide concentrations, Figure 2.5.1.a.

2.5.2. Fodder beets

During winter, beets and beetsilage are major components of the cows´ diet in Denmark. The plant growth rate for beets is based on results obtained by Aslyng and Hansen, 1982 (Aslyng and Hansen 1982). It is possible to specify the time of harvest of the beets in the model. After the harvest and the silage production, the products are stored until use.

2.5.3 Root crops and green vegetables.

To simulate the concentration of radionuclides in coarse vegetables like potatoes, the model structure used, is the same as for fodder beets. The CR values for coarse vegetables as well as harvest time, and growth dilution were included.

For green vegetables like cabbage, spinach and lettuce, a model is used that provides for root uptake and direct deposition. The growth of the green vegetables is assumed to be similar to the growth of the green parts of the fodder beets.

Depending on the species simulated in the model, the period of growth, and the density of above ground biomass can be changed to obtain the best predictions for each type of crop.

2.5.4 Silage

The main constituents of silage are beet leaves and grass. In an average winter diet, the silage is made up of 2/3 feed unit (f.e.) beet leaves silage and 1/3 feed unit grass silage. This composition of silage is used in the model. One feed unit (f.e.) is the nutritional value of 1 kg of barley grain.

As the concentration o: radionuclides in silage made from grass is sensitive to it's harvest time, it has been made possible to specify the actual harvest time of grass used for silage in the model.

2.5.5 Cereals

Based on experimental studies at Risø, a model for barley grain has been developed. This model provides for the uptake and translocation of different isotopes after a direct contamination of barley grain, and takes the time of contamination into consideration (A.Aarkrog 1983).

Assuming no radioactive decay, the two following expressions were developed:

Caesium $$\mu_{Cs}(t) = 0.098 \cdot \exp(-0.0013(t-34)^2) \quad (1)$$

Strontium $$\mu_{Sr}(t) = 0.045 \cdot \exp(-0.00095(t-2)^2) \quad (2)$$

where $\mu(t)$ is the activity in Bq kg^{-1} in the mature grain at harvest and t is the time in days before harvest when the crop has received 1 Bq per m^{-2} barley field of strontium or caesium, Figure 2.5.5.a and Figure 2.5.5.b.

We know from earlier experiments, that there is only slight difference in the retention, and the translocation, of radionuclides between barley, rye, wheat and oats (A. Aarkrog 1969-). Hence the expression developed for barley grain has been used, in the present model, for all four species to account for the contamination level at harvest time. Furthermore, no distinction has been made between winter and spring varieties, apart from the possibility to specify the different times of harvest for the different varieties.

Testing (1) with caesium data from Risø, obtained after the Chernobyl accident in 1986, showed that it overestimated the measured radiocaesium concentrations by a factor 2 to 3 (Aarkrog et al. 1988). It is obvious that the contributions from July-August 1986 play an important role in the models. This contribution may, however not be so important in reality,

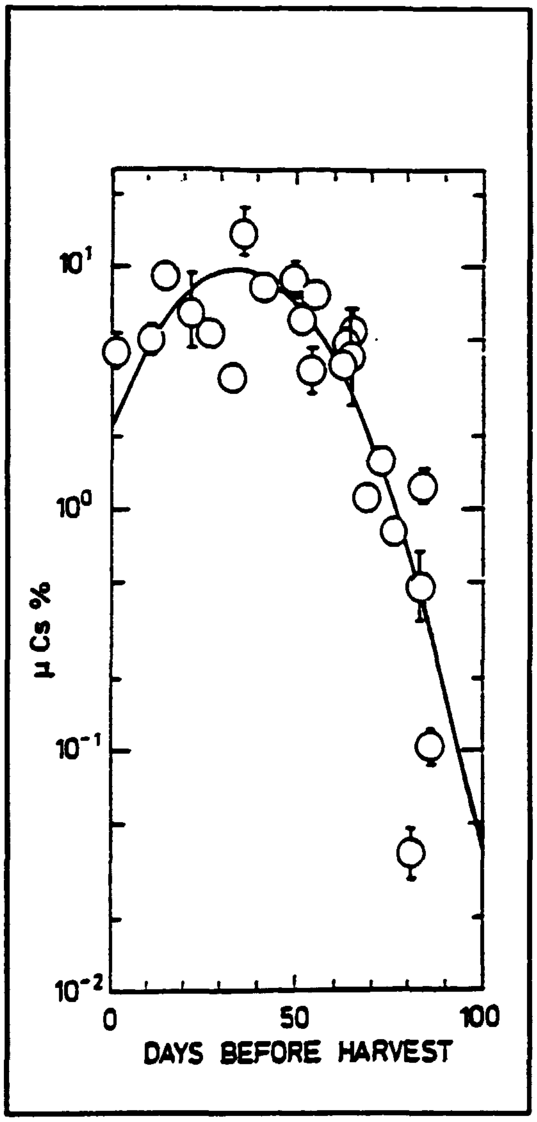

Figure 2.5.5.a
Percentage of radiocaesium, applied at various dates to 1 m^2 of barley field, recovered per kg of grain at harvest, assuming no radioactive decay (Aarkrog 1983).

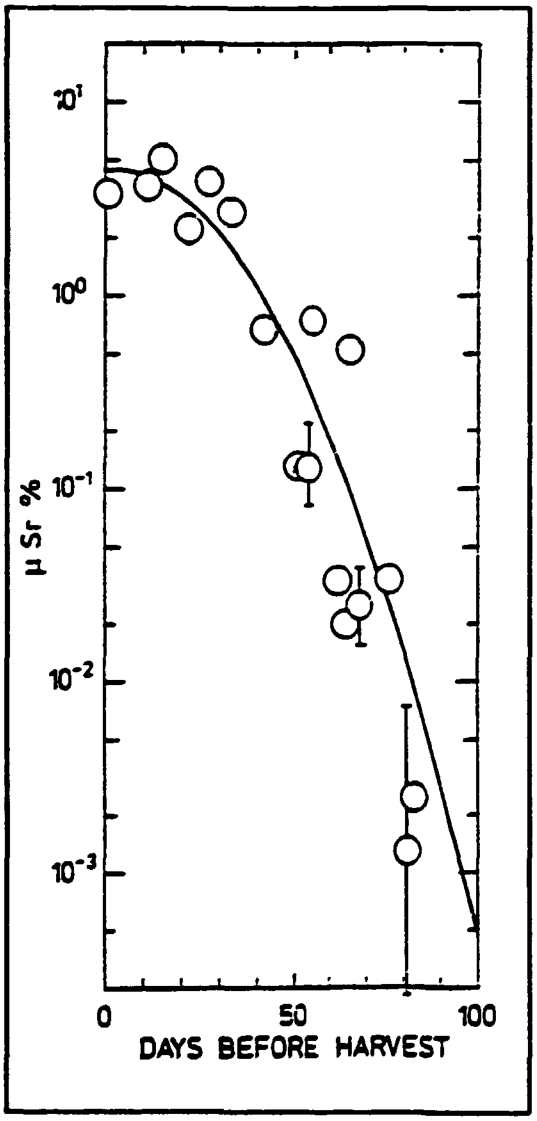

Figure 2.5.5.b
Percentage of radiostrontium, applied at various dates to 1 m^2 of barley field, recovered per kg of grain at harvest, assuming no radioactive decay (Aarkrog 1983).

since the fallout in July-August was mostly due to local resuspension. This implies that the radiocaesium was attached to soil particles, which may have retained it so efficiently, that the plants cannot get hold of it. To include this effect in the present model, the uptake of direct deposited radiocaesium $\mu_{Cs}(t)$ is reduced with a factor of 3 for resuspended radionuclides. Additional physical decay has been included.

2.6 WEATHERING

Weathering denotes the loss of radioactive material from the plant surface to the soil surface. The mechanisms are precipitation and wind. For periods longer than one month after the deposition, earlier experiments show, that it is necessary to include at least two weathering halflives (Krieger and Burmann 1969), (Nielsen 1981), because the absorption of the radionuclides, into the plant tissue from the foliar surface, will reduce the effect of weathering with time. The same authors report no significant differences between the wheatering halflife for caesium and strontium in grass grown in an exposed area.

Concentrations of ^{137}Cs measured in the grass at Risø in the year after the Chernobyl accident strongly support the use of two wheatering halflives (Aarkrog et al. 1988). Based on these data, an effective halflife of 7 days has been chosen in the model for the first 20 days after a deposition and a halflife of 30 days for the rest of the simulation period.

2.7 ANIMAL METABOLISM

2.7.1 Dairy cows and beef cattle

The structure of the cow model simulating the transport of caesium and strontium to milk and beef is based on a model previously published (Crick and Simmonds, 1984; Simmonds, 1985). A breathing rate of 90 l air per minute has been in-

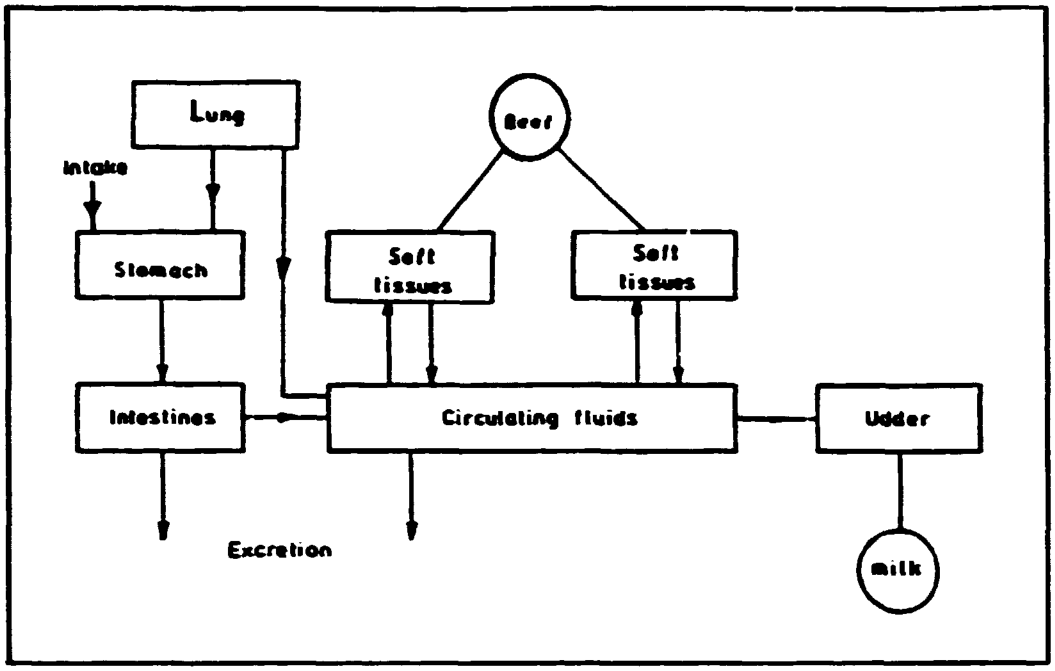

Figure 2.7.1.a
Structure of the cow model for the metabolism of the caesium isotopes.

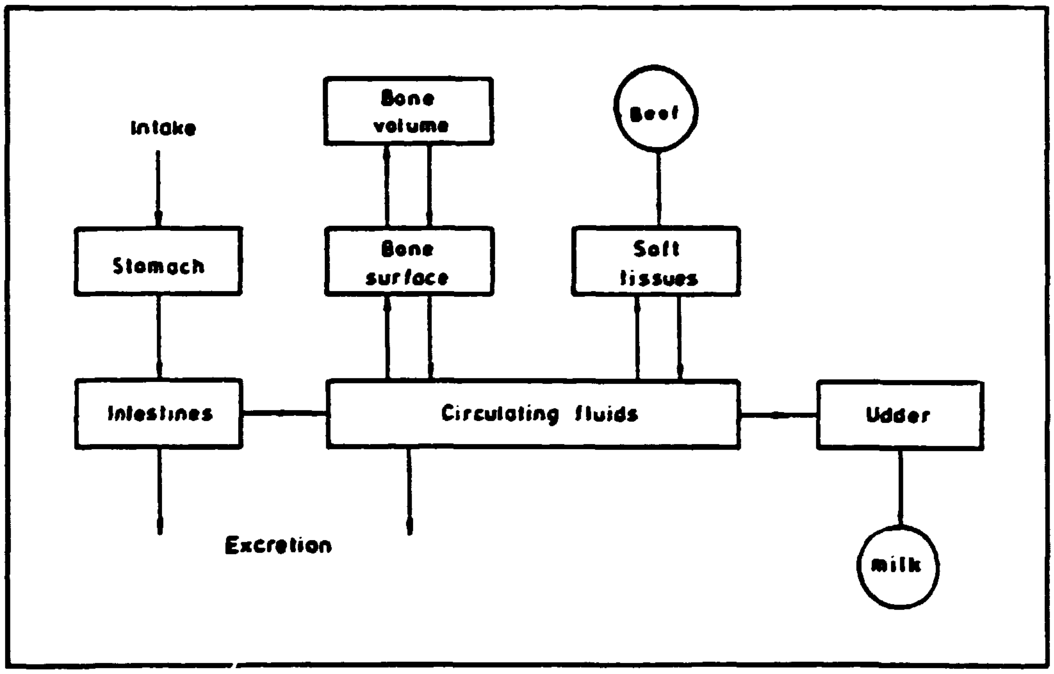

Figure 2.7.1.b
Structure of the cow model for the metabolism of strontium isotopes.

cluded (Russell 1966). The inhaled amount of radionuclides is divided between the circulating fluid and the stomach according to ICRP (ICRP 30, 1979), assuming similarities between cattle and man. According to ICRP, 25 % of the inhalated radionuclides, attached to particles, is distributed to the circulating fluids and 15 % to the stomach, the remaining 60 % is exhaled.

The model structure for the metabolic modules developed for caesium and strontium is the same, except for the organs which are considered depend on the particular radionuclide. Caesium and strontium are both readily transferred to milk, whereas only caesium is concentrated, in substantial amounts, in the meat. ^{90}Sr is thus relatively unimportant as doner to the total dose via consumption of beef. Animal bones are, however, useful indicators for a ^{90}Sr contamination of the terrestrial environment. For caesium, there are two compartments, that represent the soft tissues in the animal, with different effective biological halflives. For strontium, there are compartments, that represent bone surface and bone volume. The structure of the two parts of the model is shown in Figure 2.7.1.a and Figure 2.7.1.b.

Finally, the model representing the cow has been adjusted to Danish agricultural practice, which essentially means a high milk and beef production rate. To simplify the model, no distinction has been made between beef cattle and dairy cows.

Periodic slaughter is represented by losses from all compartments. The average lifetime for the cows is assumed to be 5.8 years which gives the value of a transfer coefficient of $4.7 \cdot 10^{-4}$ d^{-1}.

There has been some discussion (Köhler at al. 1991) whether models, with a multi-compartmental description of cow metabolism, are significantly better than steady-state models, using F_m and F_f, as the simple transfer coefficients to milk and beef

(IAEA 1982). The performance of the more complex models is not significantly better than the one of the simple ones, if we only regard the time integrated concentration of radionulides in milk and beef, (Köhler et al. 1991), (Chrick and Simmonds 1984). However a more complex model is required, if a time trend for the transfer of radioisotopes to milk and beef, especially during the first weeks after a given contamination is to be adequately predicted. There is a recycling of the radioisotopes between organs and body fluids and this has particular implications for the time dependence of the transfer to milk and beef.

2.7.2 Pigs

Approximately 80 % of the meat consumed in Denmark is pork, Table 2.10.I. Pork can thus be an important contributor to the ^{137}Cs contamination of the Danish diet after an accident.

Similar to beef, pork does not contain substantial amounts of ^{90}Sr and pork is thus relatively unimportant as ^{90}Sr doner in the total diet (Aarkrog 1979). Therefore, only a model concerning the metabolism of caesium has been included.

As for the cow model, a metabolic structure has been chosen that makes a realistic simulation of the time trend for the transfer of caesium to pork. The general structure of the model is shown in Figure 2.7.2.a. The structure of the respiratory tract is the same as for cows (chapter 2.7.1). A breathing rate of 6 l air per minute is used for pigs (Russell 1966). The transfer coefficients between the different compartments are partly based on a model previously published (Kliment 1991).

Periodic slaughter is represented by losses from all compartments. The average lifetime for the pigs is assumed to be five months which gives a transfer coefficient of $6.7 \cdot 10^{-3}$ d^{-1}. The average lifetime is actually some weeks longer, but five months have been chosen because of a different feeding habit

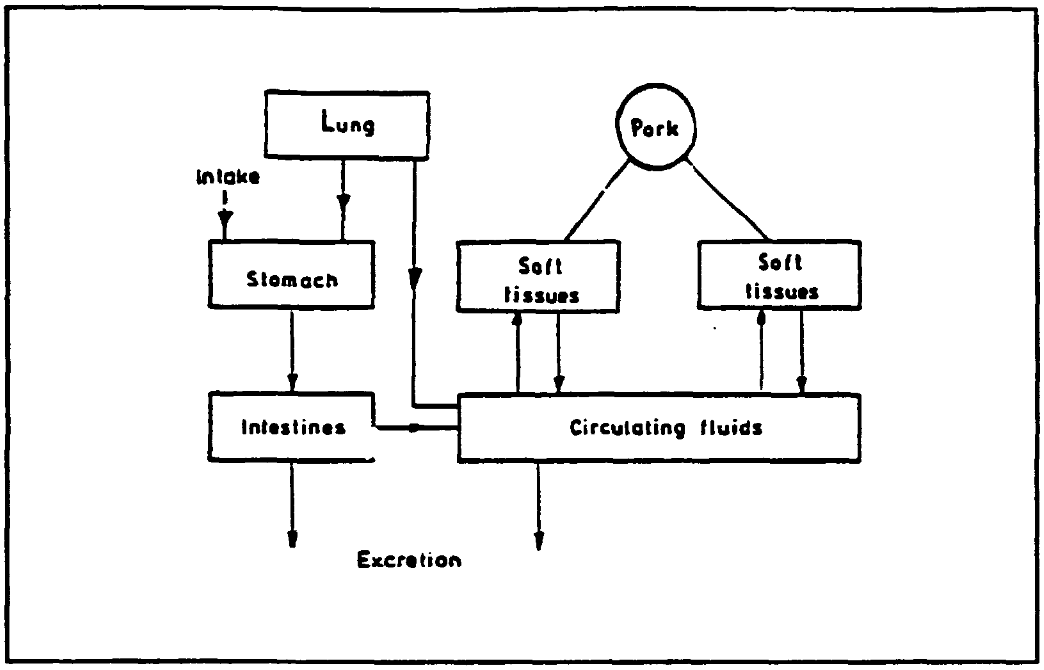

Figure 2.7.2.a
Structure of the model for the metabolism of caesium isotopes in pigs.

for younger pigs.

While the models for cattle and pigs are able to account for important metabolic processes, it should be emphasized that they have been developed for the assessment of the radiological significance of releases, and not for the purpose of providing a detailed description of element metabolism.

2.8 FODDER PLANS

2.8.1 Cows' diet

The cows' diet is the main determinant for the levels of contamination in milk and beef. The diet specified in the present model, is based on common Danish agricultural practice (Østergaard et al.1983), (Håndbog for Driftsplanlægning 1990), (Pedersen 1988). A typical diet is shown in Figure 2.8.1.a.

Several options regarding agricultural practice, described in the following, have been included in the model.

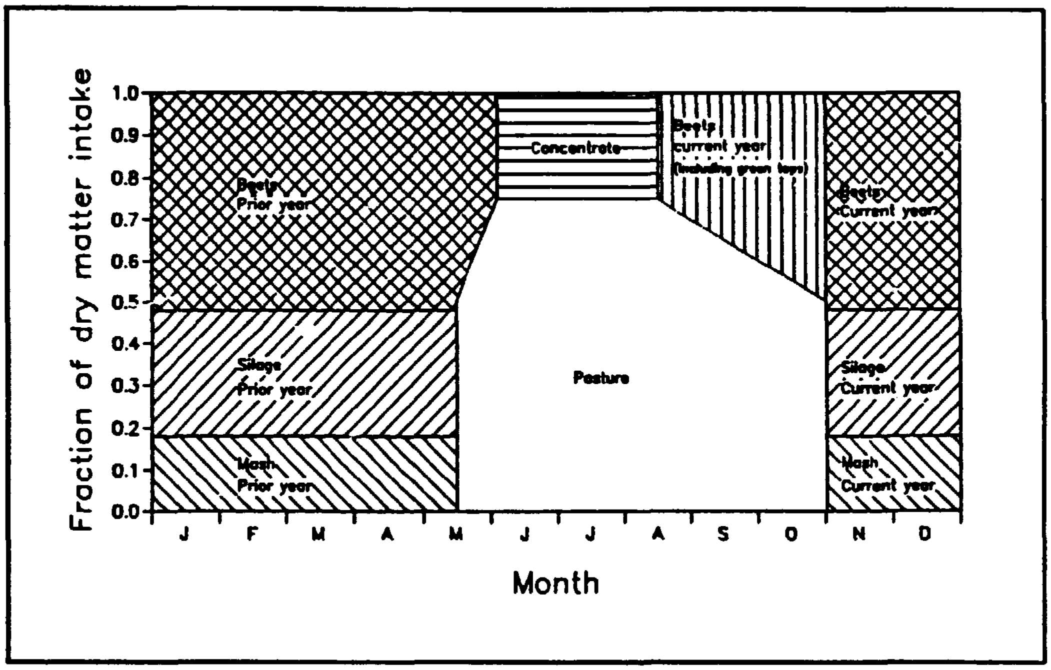

Figure 2.8.1.a
Diet used in the model for Danish cows.

During the summer period, it is possible to specify the period that the cows are on pasture and the fraction of concentrate given in addition to pasture grass. It is also possible to introduce a period in which the cows are on stable eating uncontaminated fodder. This to simulate the possible counter-measures taken, to reduce the uptake of radionuclides after an accidental release.

Contrary to feeding practice in other European countries, hay is not very common in the cows winter diet in Denmark. Instead fodder beets and beetsilage are the major components. It is possible to specify the different fractions of beets, silage and concentrate in the winterdiet.

According to G.F. Fries (Fries et al. 1982) the average soil intake by dairy cattle is about 2-3% of their dry matter intake, when the cows are kept on well grown pastures and fed with supplementary concentrates. The radionuclides ingested with soil may not, however, be in the same chemical form as the radionuclides in the fodder. As for caesium, it may be firmly fixed to the clay minerals in the soil and thereby less available for transfer through the gastrointestinal tract to the milk, and thus of minor importance compared to the contamination of milk and beef by other pathways.

For cows pasturing on land with poor plant growth, like in areas with extensive farming, the intake of surface soil during the pasture season may be up to 14 % of the dry matter intake, and this pathway has therefore to be taken into special account (Healy 1968).

The plant growth rate, described in chapter 2.5.1, provides a well grown Danish pasture. Consequently a soil ingestion of 2%, of the cows dry matter intake, is included.

The Danish cows are supplied with uncontaminated ground water, consequently the supply of drinking water is not included in the model (H. Hansen and A. Aarkrog 1990).

2.8.2 Pigs' diet.

The fodder for pigs mainly consists of barley, rye, wheat and crushed soya. Normal practice for feeding pigs (FAF 1991) makes 60 % of their fodder intake cereals. The amount of fodder increases during the period of feeding. The total intake during 5 months of feeding is about 240 kg. This gives an average of 1 kg cereals per day, which is included in the model.

The cereals used for feeding include grain from the previous harvest, and this will continue until harvest the following year, when the newly harvested grain will be included in the fodder. The crushed soya is imported and considered not contaminated.

A constant ratio of whey, 10 % of the total diet, was included in the fodderplan used in the calculations. The structure of the model makes it possible to include a fraction of whey, where the concentration of a given radionuclide is given by the concentration of the radionuclide in milk, assuming a whey production time of one month.

2.9 BREAD

The contamination levels in bread depend on the contamination in grain. Danish experience from nuclear weapons fallout, show ratios between bread and grain to be 0.74 for ^{137}Cs in rye bread and 0.37 for ^{137}Cs in white bread. Similarly, the ratios for ^{90}Sr are 0.74 in rye bread and 0.15 in white bread (Aarkrog 1979).

It has been found (Aarkrog et al. 1963), that the atmospheric fallout during a calendar year in Denmark, clearly affects the grain levels at harvest, but does not affect the levels in bread until the last part of the year. For that reason, the production of bread, in the model, starts 1 December with flour from the previous harvest, and continues until 1 December the following year, when a new harvest is included in the production. It is assumed, that no bread is prepared from grain older, than from the last harvest.

2.10 DOSES

The consumption by man of the various food types contaminated with radionuclides will give rise to an individual dose. To estimate the effective dose equivalent commitment to man, based on the amount of consumed radioactivity, typical Danish food habits have been introduced in the model.

The composition of the human diet; used in the present model is based on results from a nationwide dietary survey, made by the National Food Agency, and on statistical information on the consumption of food (Haraldsdóttir et al. 1986), (Danmarks

Table 2.10.I
The average annual intake of food per capita in Denmark.

Type of food	Annual quantity (kg)
Milk products	174
Rye bread	39
White bread	29
Potatoes and coarse vegetables	82
Leafy vegetables	16
Fruit	56
Beef	9
Pork	35

Statistik 1987). The average annual intake of food used in the model is given in Table 2.10.I. Only foodproducts of terrestrial origin, that are of significant importance for the total dose, are included.

The model may be extended to incorporate specific information about sex, age and food habits, in order to get a more precise dose assessment for a specific group of people, but it is considered to be beyond the scope of this project.

The time-integrated amount of radioactivity consumed is calculated, and converted to effective dose equivalent commitment by multiplication with the relevant dose factor, reported by the UNSCEAR committee (UNSCEAR 1988).

The effective dose equivalent per unit of ingested activity (nSv Bq^{-1}) is shown in Table 2.10.II.

While caesium is assumed to be uniformly distributed throughout all organs and tissues of the body, strontium is assumed to be distributed mainly to bone marrow and bone surfaces. The doses calculated for ^{90}Sr, can be converted to organ doses by dividing with w_T, the ICRP (ICRP 1979) weighing factor: 0.12 for bone marrow and 0.03 for bone surfaces.

Due to the chemical similarity, the transfer of strontium

Table 2.10.II
Dose factors from UNSCEAR 1988.

	nSv Bq^{-1} adults
^{90}Sr	21*
^{134}Cs	20
^{137}Cs	14

* The dose factor for ^{90}Sr is based on Danish data (Aarkrog 1979). Until 1986 the dose factor was for ^{90}Sr 15.6 nSv Bq^{-1}.

within the body is largely determined by the quantity of calcium present. Earlier studies show, that a decrease in the intake of calcium, and no correspondingly reduce in the intake of strontium, will increase the uptake of strontium and subsequently give a higher dose (Russel 1966).

From 1958 to 1986 $CaCO_3$ was added to the Danish flour, according to a Government Notice, giving an annual intake of 0.62 kg Ca Y^{-1} (Aarkrog et al. 1989). The annual intake of Calcium with Danish diet is estimated to 0.47 kg y^{-1} after 1986 (Aarkrog et al. 1989). According to this, the dose factor for ^{90}Sr was 15.6 nSv Bq^{-1} until 1986 and raised to 21 nSv Bq^{-1} from 1986 and on.

2.11 RADIOECOLOGICAL SENSITIVITY

Infinite time-integrated concentrations per unit deposit, distributed like global fallout throughout the year in a given item of the food chain is defined as the radioecological sensitivity (Aarkrog 1979). In the present work, the term radioecological sensitivity has been widened to include infinite time-integrated concentrations per unit deposit from a single event, in a given item of the food chain. Four years have been used as integration period for the infinite time-integrated concentrations, because this period accounts for more than 95 % of the infinite time-integration values.

The radioecological sensitivity is a very useful tool, when comparing the response to a unit deposition for different scenarios.

3.0 VALIDATION

3.1 CHERNOBYL

The observations of the dynamics of several radionuclides after the accident at Chernobyl in the USSR, in 1986, provided a rare opportunity to test models that sinulates the dynamic transport of radioactive materials in the terrestrial environment after a discrete release of radioactive material.

The present model was validated and discussed with regard to Danish data and the result is presented in the following chapters.

3.1.1 Grass, milk and beef.

The Chernobyl accident was characterized by its release of radiocaesium. It has been estimated that approximately 100 PBq of ^{137}Cs and about 50 PBq of ^{134}Cs were released (Aarkrog 1990), two thirds of the release were deposited outside the European part of the USSR. The boiling point for caesium is 671 °C and thus caesium is very volatile, at the temperatures that were reached in the reactor, at the accident. A substantial part was thus transported over long distances, before it was deposited on the ground. During 1986, the average concentration of ^{137}Cs in the air over Denmark increased by a factor of nearly 2000, compared to 1985 (Aarkrog et al. 1988).

The model input were the ^{137}Cs concentrations (Bq m^{-3}) in the air, measured at Risø, in the weeks after the accident (Aarkrog et al., 1988). The daily precipitation rates, measured at Risø from April 1986 up to and including 1989, provided for the rainfall in the simulations.

In Figure 3.1.1.a the, actual measurements of the ^{137}Cs concentrations in the grass, and the concentrations predicted by the model, from 1986 up to and including 1989, are shown.

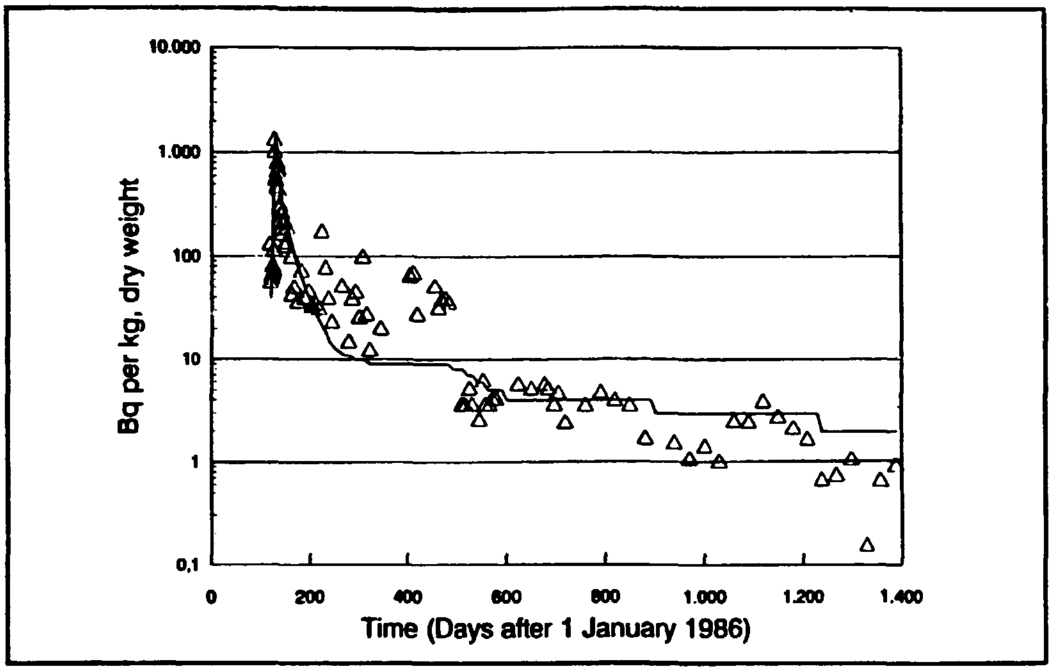

Figure 3.1.1.a
Calculated and measured concentrations of ^{137}Cs in grass at Risø after the Chernobyl accident in 1986 (Bq kg^{-1}).

The time trend and the predictions of the actual concentrations of ^{137}Cs in the grass, are fairly consistent with the measured levels, during the first years after the contamination.

Calculating the P/O ratio, i.e. dividing each Prediction by the corresponding Observed value, provides another measure of the uncertainty, and a possible adverse bias, of the predictions.

The geometric mean GM and the geometric standard deviation GSD have been calculated for the P/O ratios. GM = 1.1 and GSD = 2.5 which emphasize the agreement between predictions and observations shown in Figure 3.1.1.a, where no general tendency, of either overestimate or underestimate the concentrations, is seen.

In order to prevent high concentrations of Iodine in the milk after the accident, the Danish authorities ordered the farmers

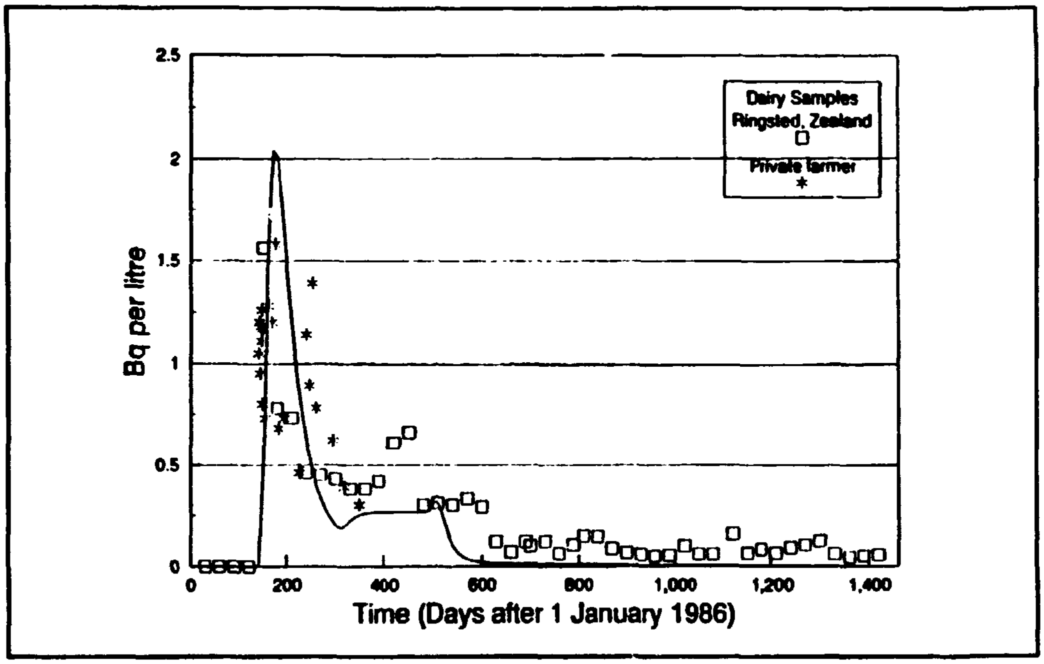

Figure 3.1.1.b
Calculated and measured concentrations of ^{137}Cs in milk after the Chernobyl accident in 1986 (Bq l^{-1}).

to keep their cows stabled until the 11 of May. The found concentrations of ^{137}Cs in milk and the concentrations predicted by the model are shown in Figure 3.1.1.b. The period, the cows were kept on stable, during the normal pasturing period in 1986, is simulated by feeding the cows uncontaminated fodder.

A private farmer, who delivered fresh milk samples in 1986, has been interviewed. Feeding habits for his livestock, as well as information on the actual period, he kept his cows on stable, and fed them uncontaminated fodder, are included in the model simulations. This gave an opportunity to simulate a well described scenario in the pasture-cow-milk pathway. A later interview with the farmer revealed that during the period of stabeling the cows had been partly fed with fodder, which has been stored outdoors and consequently slightly contaminated. However this extra contribution from supplementary fodder had no effect, on the concentrations of ^{137}Cs in the milk, during the first days after the accident. Measurable concentrations was first seen after the 11 May, when the cows went to pasture.

In addition to the concentration of ^{137}Cs in samples, delivered by the farmer, concentrations of ^{137}Cs measured in dried milk samples, collected monthly from a dairy at Ringsted, Zealand, are shown. These milk samples are bulked samples and reflect differences in agricultural practice based on size of farm, feeding habits etc.

The time trend of the predicted levels in milk fits the observed levels reasonably well. There is a tendency to underestimate the concentrations of caesium in milk through the years following a contamination. The actual concentrations of caesium in milk in 1988 - 1989 are however so small, that even minor additions of concentrate in the fodder, imported from areas with a higher level of contamination, will have an effect on the concentrations of ^{137}Cs in the milk.

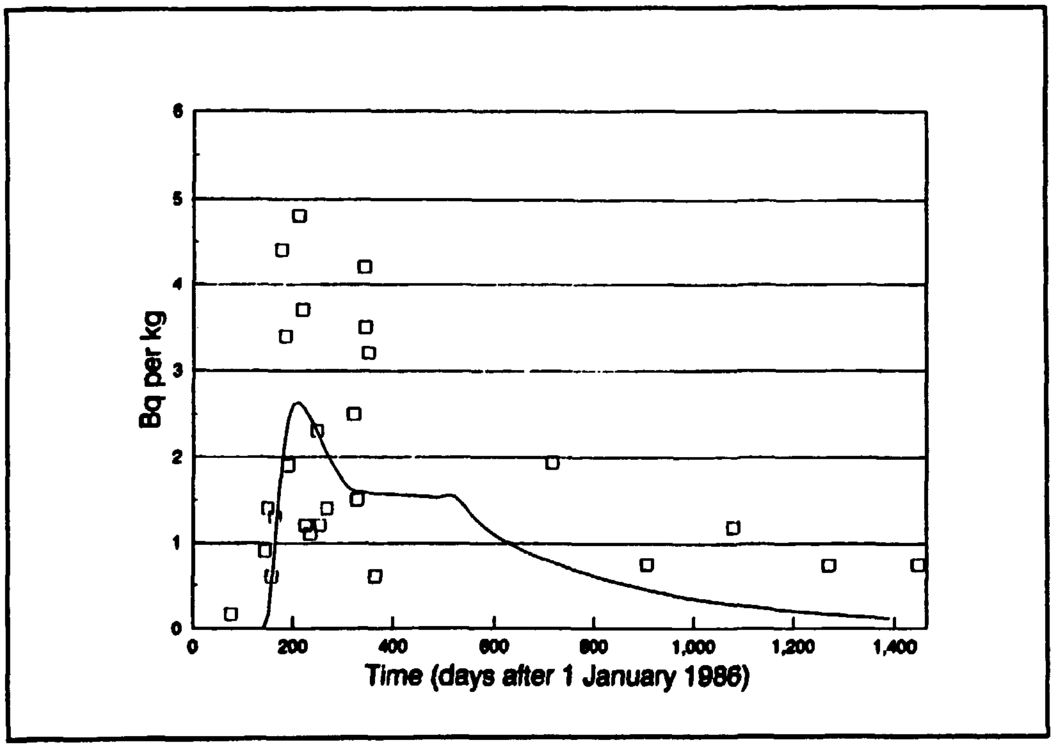

Figure 3.1.1.c
Calculated and measured concentrations of ^{137}Cs in beef from Zealand after the Chernobyl accident in 1986 (Bq kg^{-1}).

There is a wide variation in the caesium concentrations measured in beef during the summer 1986, and this blurs the expected time trend. This is because the beef samples represents animals from all over Zealand, and just as the milk samples they also reflect differences in agricultural practice. The tendency is again to underpredict the concentrations of caesium in beef in the years following an accident. Due to the strong correlation between milk and beef, given in the structure of the model, this was to be expected, (chapter 2.7.1).

Table 3.1.1.I
The geometric mean and geometric standard deviation calculated for the P/O ratios for the ^{137}Cs concentrations in milk and beef.

	Geometric mean P/O	Geometric standard deviation
milk	0.3	2.8
beef	0.7	2.1

The geometric mean, GM, and the geometric standard deviation, GSD, for the P/O ratios have been calculated for the caesium concentrations in milk and beef, and the results are shown in Table 3.1.1.I. The concentrations of ^{137}Cs in milk are predicted within a factor of three and the concentrations of ^{137}Cs in beef within a factor of 1.5 and these results emphasize the tendency of the model to underpredict the concentrations, in the years following the accident.

Because of the meteorological conditions, the deposition in Denmark from the Chernobyl accident was low. For this particular contamination, keeping the cows on stable had a minor effect, but for a more serious accident, such a countermeasure can be of considerable importance. The aspects of keeping the cows on stable, for a certain period of time after a given contamination, are discussed in chapter 6.0.

3.1.2 Pork

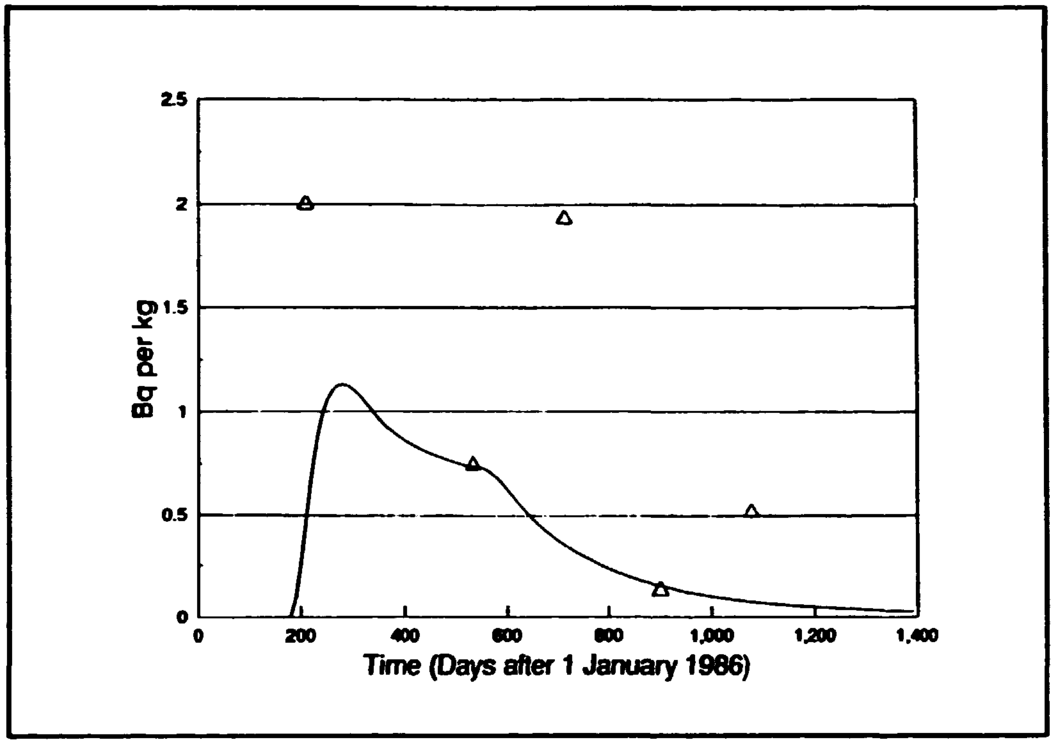

Figure 3.1.2.a
Calculated and measured concentrations of ^{137}Cs in pork after the Chernobyl accident in 1986 (Bq kg^{-1}).

The contamination of Danish pork after the Chernobyl accident was only of minor importance. This because the release of caesium into the Danish environment took place at a very early stage of the growing season. The major part of pigs' diet is cereals. If the accident had occurred about a month before the harvest of barley, the situation would have been different, due to the translocation of caesium to grain described in chapter 2.5.5. Aspects of a contamination that happens later in the growing season are discussed in chapter 4.0.

The concentrations of ^{137}Cs, the time trend in pork predicted by the model for 1986 and 1987, and the actual measured concentrations, are shown in Figure 3.1.2.a. The model predicts the observations reasonable well. A more detailed study, on the radiocaesium content in pigs, must however be done to further validate this part of the model.

3.1.3 Cereals and bread

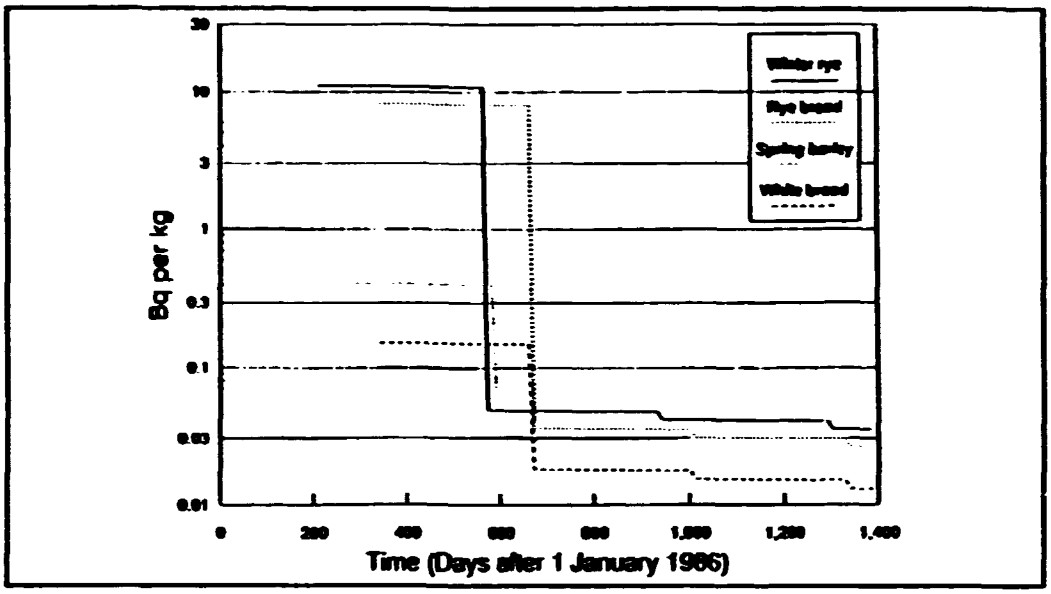

Figure 3.1.3.a
Calculated concentrations of ^{137}Cs in cereal, rye-bread and white bread after the Chernobyl accident in 1986 (Bq kg^{-1}).

The concentrations of ^{137}Cs, and the time trend in cereals and bread predicted by the model, from 1986 up to and including 1989, are shown in Figure 3.1.3.a. Comparisons between the predicted concentrations, and the actually measured values are shown in Table 3.1.3.I. The harvest time for winter rye has been set as July 24 (Day no. 205) whereas the harvest time for spring barley, representing all the spring varieties has been set as August 8 (Day no. 220). Bearing in mind, that the cereals are very sensitive to the time span between the time of contamination and the time of harvest (Chapter 2.5.5). The difference between predicted and observed concentrations is within a factor of two. Although the modelling for production of bread is fairly rough (Chapter 2.10) the discrepancy between predicted and observed concentrations are within a factor of two. A more specific distinction between the different varieties of cereals and a more detailed modelling of the production of bread might give a better agreement between

Table 3.1.3.I
Calculated and measured concentrations of ^{137}Cs in cereals and bread after the Chernobyl accident (Bq kg^{-1}).

	1986	1987	1988	1989
Winter rye				
P	11.3	0.05	0.04	0.03
O	9.9	0.07	0.07	0.03
P/O	1.1	0.7	0.6	1.0
Rye bread				
P	7.8	7.8	0.3	0.3
O	6.3	4.8	0.3	0.3
P/O	1.2	1.6	1.0	1.0
Spring barley				
P	0.4	0.05	0.04	0.03
O	0.2	0.08	0.05	0.03
P/O	2.0	0.6	0.8	1.0
White bread				
P	0.2	0.2	0.02	0.02
O	0.3	0.4	0.05	0.03
P/O	0.7	0.5	0.4	0.7

predicted and observed values. The significant effect of a variation in the time of harvest would, on the other hand, indeed suppress gain of such a detailed modelling.

3.1.4 Vegetables

The calculated and measured concentrations of ^{137}Cs in leafy vegetables and potatoes are shown in Table 3.1.4.I. The differences between the predicted and measured concentrations are within a factor of two except for the potatoes from 1986. This indicates, that there is a translocation of caesium from the leaves to the potato tubes, which dominates the root uptake in the first year after a direct contamination. This translocation has to be further investigated in field experiments to include the proper transfer coefficient providing for this process in tne model.

Table 3.1.4.I
Calculated and measured concentrations of ^{137}Cs in leafy vegetables and potatoes after the Chernobyl accident in 1986 (Bq kg^{-1}).

	1986	1987	1988	1989
Leafy vegetables				
Density: 1.5kg m^{-3}				
P	0.13	0.10	0.08	0.07
O	0.19	0.08	*	*
P/O	0.7	1.3		
Potatoes				
Density: 3.5kg m^{-3}				
P	0.003	0.06	0.05	0.05
O	0.03	0.05	0.03	0.03
P/O	0.1	1.2	1.7	1.7

* No samples.

3.1.5 Doses.

Using the calculations described in the previous paragraphs, an estimate was made of the contribution from ^{137}Cs to the individual dose after the first year and to the total effective dose equivalent commitment from the Chernobyl accident.

The daily intake of ^{137}Cs, per individual, during the period from 1986 up to and including 1990, estimated from observed concentrations in various Danish food products, is shown in Figure 3.1.5.a. Based on this daily intake the time-integrated amount of ^{137}Cs consumed was calculated and converted to effective dose equivalent commitment, as described in chapter 2.10.

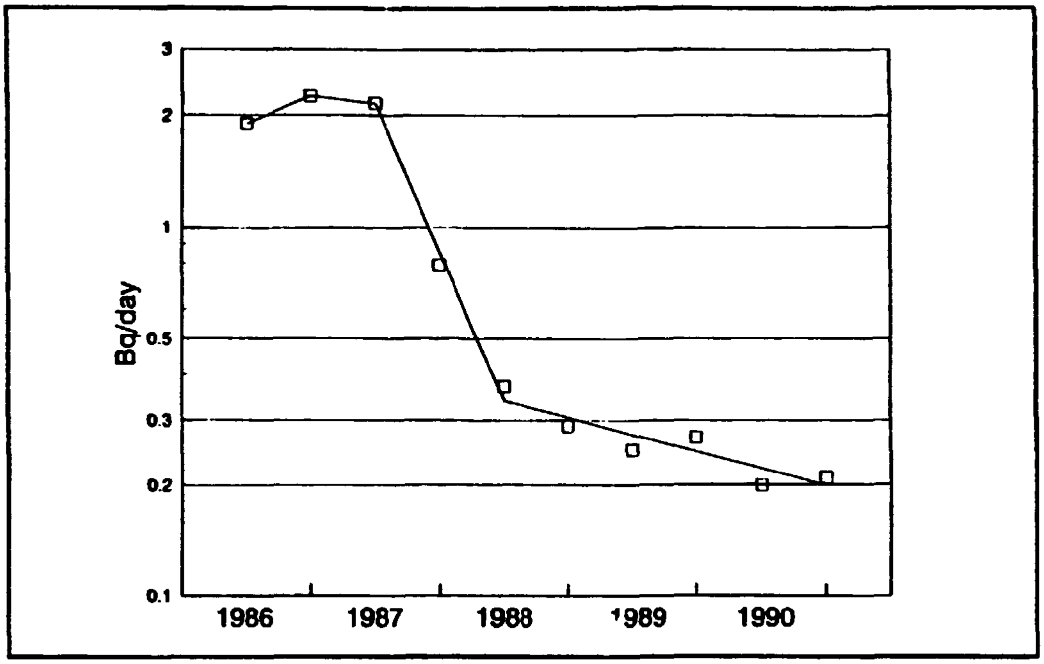

Figure 3.1.5.a
The daily intake of ^{137}Cs, per individual, estimated from observed concentrations in various Danish food products.

The results, of these two ways of predicting the individual dose from ^{137}Cs, agree within a factor of two. The calculated doses are shown in Table 3.1.5.I.

The time-integration, based on the measurements in food products, was made assuming no change in the decline pattern of ^{137}Cs from 1990 and on. This might underestimate the individual effective dose equivalent commitment, because a decrease in the ^{137}Cs concentrations towards a constant value may be more realistic.

The agreement between model simulations and predictions, based on observed values, seems to be a very good support of the structure and dynamics of the model as well as of its ability to give a realistic estimate of the consequences of a possible future accident involving ^{137}Cs.

Table 3.1.5.I
Individual doses from the Chernobyl accident to the Danish population, based on the deposition of ^{137}Cs.

	dose first year	effective dose equivalent commitment
	μSv	μSv
model predictions	22	36
predictions, based on measurements in foodproducts	13	29

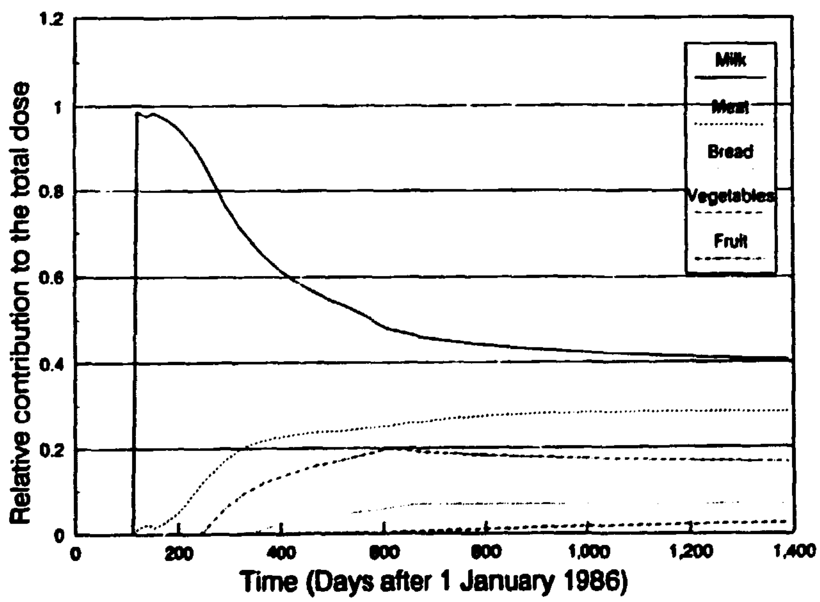

Figure 3.1.5.b
Time course of the relative importance of different foodproducts to the total dose from ^{137}Cs.

The time trend of the relative contributions to the total dose are shown in Figure 3.1.5.b for the most important foodproducts. Meat is the sum of beef and pork, and bread is the sum of rye bread and white bread.

3.1.6 Sr-90

Due to the minor importance in Denmark of ^{90}Sr from the Chernobyl accident, only a few simulations of the ^{90}Sr dynamics were made. The ^{90}Sr activity, in the air over Denmark, increased two orders of magnitude after 1985. The total release of ^{90}Sr was 8 PBq, a factor of 12 lower than for ^{137}Cs (Aarkrog 1990). The boiling point for strontium is 1377 °C and this makes ^{90}Sr less volatile than caesium, and it will deposit on the ground close to the source.

Already by September 1986 the ^{90}Sr levels were again back to the values seen in 1985. (Aarkrog et al. 1988)

The ^{90}Sr inventory, still present from the weapons fallout, in the upper 25 cm soil layers were approximately 1 Bq kg^{-1} soil in 1978. (Aarkrog et al. 1981). Corrected for fixation due to ageing and physical decay, the concentration of strontium, that is still available for root uptake in the soil, was added to the soil compartments, and provided part of the initial conditions. Strontium is, unlike caesium, not strongly fixed to soil particles, and therefore available for root uptake when present in the soil layers (Russel 1966).

The concentrations of ^{90}Sr in the air at Risø were measured only during a few days after the accident in 1986. These concentrations were used, in addition to the concentration of ^{90}Sr in the soil, as input to the present model for simulating the dynamics of ^{90}Sr after the Chernobyl accident.

The results of the predictions, made by the model, of the concentrations and the time trend of the ^{90}Sr contamination in

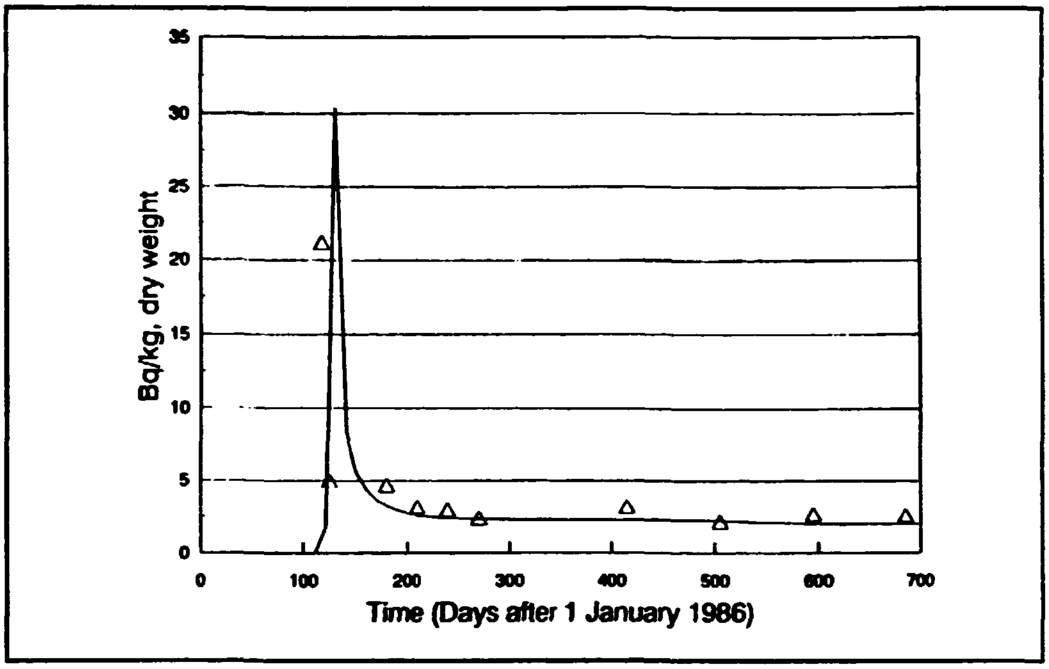

Figure 3.1.6
Calculated and measured concentrations of ^{90}Sr in grass after the Chernobyl accident in 1986 (Bq kg^{-1}, dry weight).

grass are shown in Figure 3.1.6.

Similar to the results for ^{137}Cs, the time trend in the deposition pattern is very well predicted, as well as the concentrations of ^{90}Sr in the grass. The concentrations in the grass were however so low, that an increase of ^{90}Sr in the foodproducts hardly was detectable (Aarkrog et al. 1988). Because of this, no further effort has been done to simulate the strontium dynamics after the Chernobyl accident.

The predictions of the time trend and the concentrations of ^{137}Cs and ^{90}Sr in the Danish environment, and the predictions of the ^{137}Cs contribution to the total dose after the Chernobyl accident, made by the present model, agree with the observations within a factor of two. The results are considered supporting the structure and dynamics of the model to a very high degree. Furthermore its ability to give a realistic estimate of the consequences of a possible future accident involving radioactive materials, is considered very fine.

3.2 WEAPONS FALLOUT

Another way of validating the present dynamic model is to use it predicting the effect of the heavy fallout from the atmospheric nuclear tests in the early sixties.

3.2.1 Grass, milk and beef.

The input were the daily ^{137}Cs and ^{90}Sr concentrations in the air measured at Risø during the years 1963, 1964, 1965, and 1966, (Aarkrog and Lippert, 1964, 1965, 1966 and 1967). In addition, a daily precipitation rate, based on the average rainfall from the same area, was included.

Due to fallout from years prior to 1963, strontium and caesium were present in the upper soil layers in 1963. The amount of strontium in the root zone in 1963 was assumed to be 1350 Bq (Aarkrog et al. 1964). The strontium was considered to be "fresh" fallout, available for root uptake. Opposed to strontium, the fraction of caesium in the soil from fallout prior to 1963 was not included, due to the minor importance of root uptake compared to the direct deposition of caesium.

Calculated and measured concentrations of ^{90}Sr in grass are shown in Figure 3.2.1.a. The calculated and measured concentrations are of the same order of magnitude. However the model fails to predict the time trend for the period. This is probably partly due to the growth rate of the grass (chapter 2.5.1), which might overestimate the concentration in pasture grass during the winter period. Only three measurements of caesium in grass have been done during a four years period, so no comments can be made on the prediction of the time trend. Nevertheless, the few calculated and measured caesium values were within a factor of three.

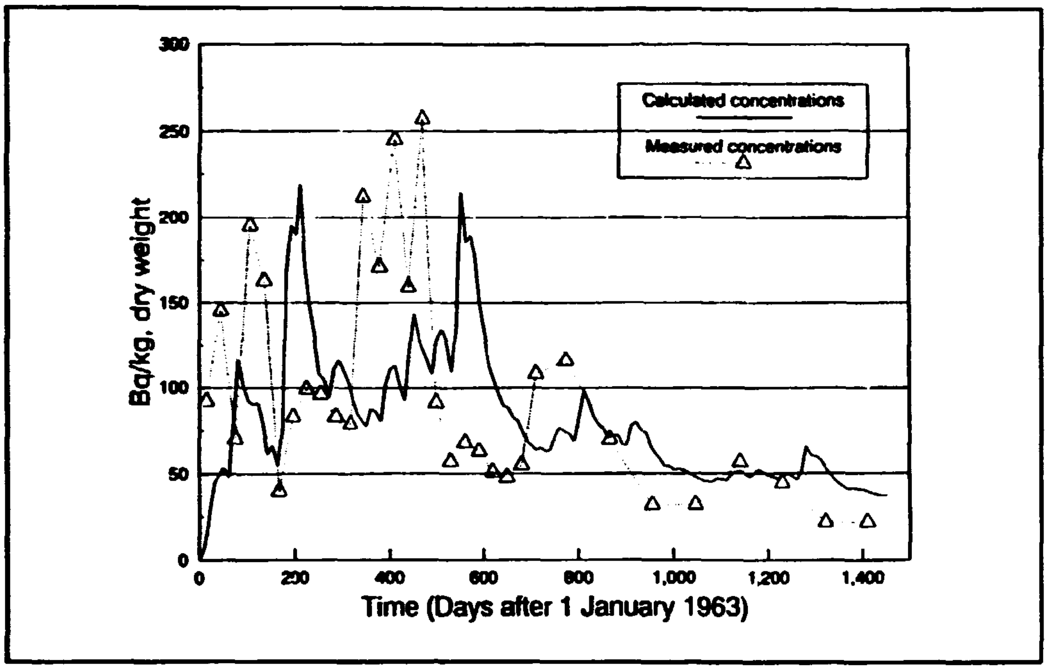

Figure 3.2.1.a
Calculated and measured concentrations of ^{90}Sr in grass during the fallout period 1963 - 1966 (Bq kg^{-1}, dry weight)

The cows' diet has been adjusted to agricultural practice in the early sixties. Thirty years ago, the dairy cows produced only half as much milk per day as now in the nineties. This due to the now more intensive feeding and the breeding methods. A change in feeding habits essentially means that grass now is only a minor part of the total fodder intake by cattle. Averaged over a year, grass was about 50% of the fodder in the early sixties, while in the nineties, it is only about 30% of the total fodder intake (Aarkrog 1979), (Østergaard et al. 1983).

The results of the simulation compared with the actual measured concentrations of ^{137}Cs and ^{90}Sr in milk and beef in the years 1963, 1964, 1965 and 1966 are shown in Figure 3.2.1.b and Figure 3.2.1.c. The failure in the prediction of the deposition pattern (Fig 3.2.1.a) is recognized especially in the model predictions of the time trend for the milk samples.

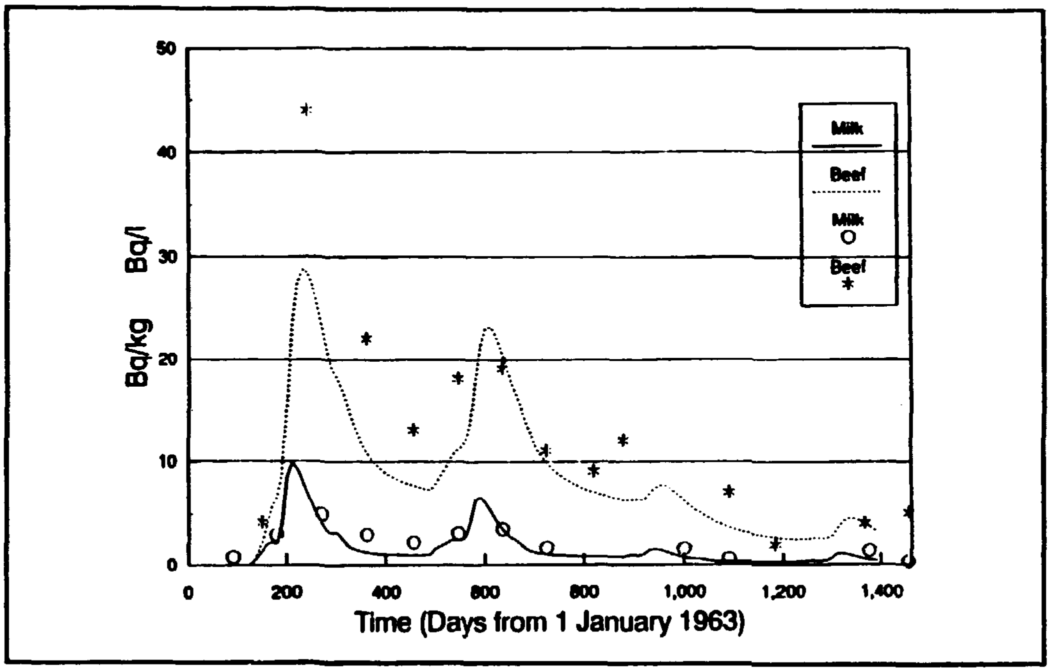

Figure 3.2.1.b
Calculated and measured concentrations of ^{137}Cs in milk and beef during the fallout period 1963-1966 (Bq l^{-1} and Bq kg^{-1}).

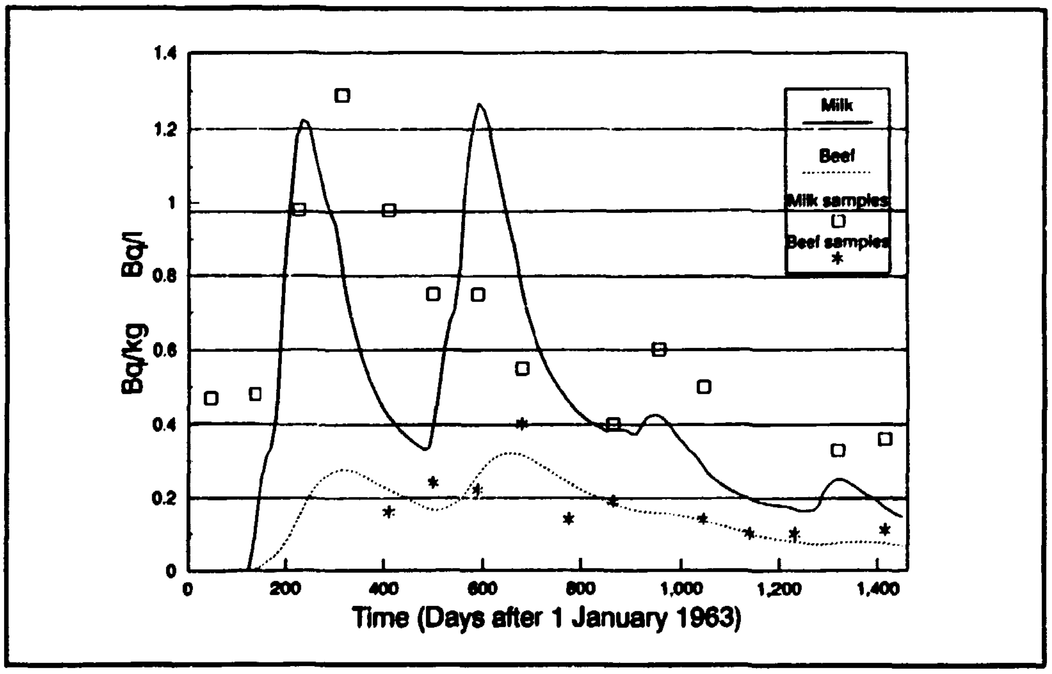

Figure 3.2.1.c
Calculated and measured concentrations of ^{90}Sr in milk and beef during the fallout period 1963-1966 (Bq l^{-1} and Bq kg^{-1}).

Table 3.2.1.I
The geometric mean and geometric standard deviation calculated for the P/O ratios for the ^{137}Cs and ^{90}Sr concentrations in milk and beef.

	Geometric mean P/O	Geometric standard deviation
^{137}Cs		
milk	0.59	1.4
beef	0.71	1.4
^{90}Sr		
milk	0.70	1.7
beef	0.97	1.4

The predictions and the observations are slightly staggered. Nevertl ..ess calculations of the geometric mean and geometric standard deviation for the P/O ratios, Table 3.2.1.I, show that the predicted and measured concentrations are within a factor of two.

3.2.2. Cereals

The concentrations of ^{137}Cs and ^{90}Sr in cereals, predicted by the present model, for the fallout period 1963 - 1966 are shown in Table 3.2.2.I. In addition, comparisons between the predicted concentrations and the observed concentrations are shown.

Generally speaking the model seems to handle the fallout situation fairly well, although it was made solely for single events. The results seem to support the dynamics of the model very well.

Table 3.2.2.I
Calculated and measured concentrations of ^{137}Cs and ^{90}Sr in cereals during the fallout period 1963-1966 (Bq kg^{-1}).

	1963	1964	1965	1966
^{137}Cs				
P	29	17	6.7	2.5
O	43	24	4.6	3.8
P/O	1.5	1.4	0.7	1.5
^{90}Sr				
P	6.1	5.1	2.4	2.0
O	5.4	4.3	3.2	3.0
P/O	0.9	0.8	1.3	1.5

Simulating the fallout situation revealed the importance of including a realistic rainfall in the model. Including an average daily amount of rainfall, calculated from the monthly averages during the period from 1963 up to and including 1966, failed to simulate the dynamics. The actual rainfall for the period had to be used, including days without any rain as well as rainy periods. Due to the structure of the wet deposition (chapter 2.1), a daily amount of an average rainfall made too few radionuclides, from the air compartment, to deposit on to the surface compared to the actual deposition pattern.

Especially, the prediction of radionuclide concentrations in cereals, was sensitive to the "correct" amount of rain. Using an average daily amount of rain, the concentrations were underpredicted up to a factor of ten.

A more realistic rainfall pattern, including days without any rain as well as rainy periods, based on measurements of rain in the period from 1986 up to and including 1989, was permanently included in the general structure of the model.

4.0 DIFFERENCES IN THE EFFECT OF ACCIDENTS HAPPENING AT VARIOUS TIMES OF THE YEAR

The transfer of radionuclides through the terrestrial environment, following an accidental release, will vary markedly, depending on the season of the year at which the release occurs.

As described in chapter 2.0 a considerable effort has been made to make this model include all the aspects of a seasonal variation: weather conditions, plant growth, and agricultural practice. This enables the model to make realistic predictions of the consequences of an accident happening at any time of the year.

4.1 ^{137}Cs deposited in each of the four seasons

The year was divided in four seasons and the effect of a single deposition of 1 Bq m^{-2} ^{137}Cs in each of the four seasons has been investigated.

The scenario for the deposition was assumed to be the typical Danish environment described in chapter 2.0, and the isotope considered was ^{137}Cs. The precise times of the depositions were chosen to be January 15, April 15, July 15 and October 15, in an arbitrary year. The cows were on pasture from May 1 to October 27. Cereals were harvested August 8, vegetables August 28, fruit September 1 and beets October 27.

The concentration of ^{137}Cs in milk and milk products depends very much on the time of year of a given contamination as shown in Figure 4.1.a. As expected, due to pasturing season, the highest concentrations in the milk will occur after an accident happening in the summer period. This of course if no countermeasures are taken. Furthermore, the radioecological

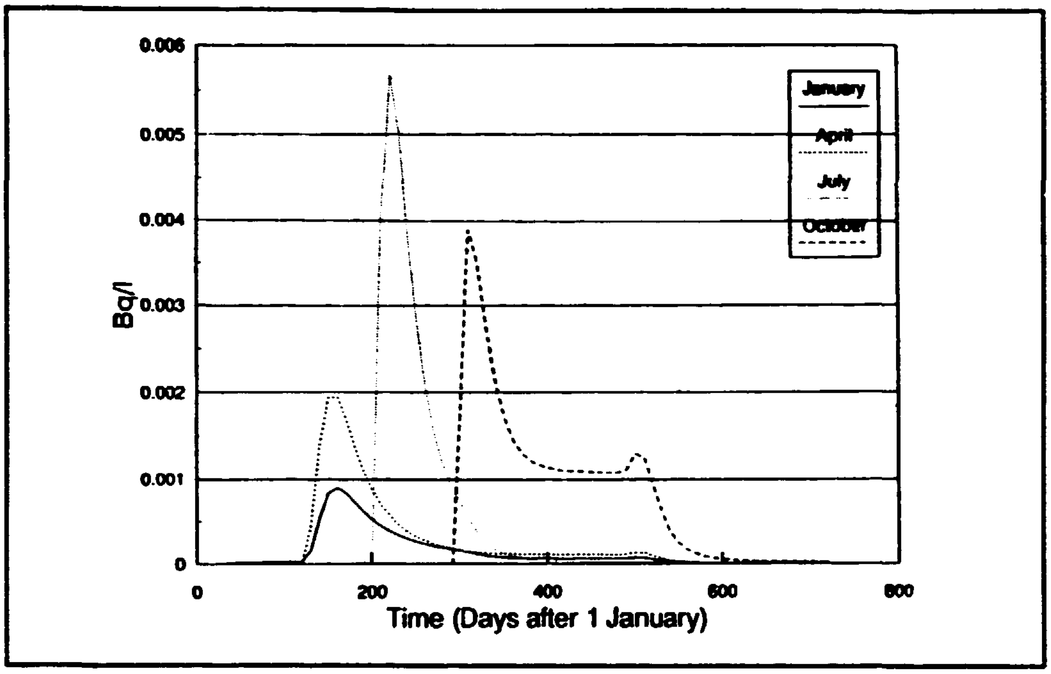

Figure 4.1.a
Seasonal variation in the ^{137}Cs concentration in milk due to a single deposition of 1 Bq m^{-2} at various times of the year.

sensitivity of milk, appeared to be higher for a single deposition in October than for a single deposition in July, Table 4.1.III. This is due to the harvest time for beets twelve days after the deposition in October, which gives a contribution of contaminated beet leaves used in the silage production. Similar patterns are seen for the ^{137}Cs concentrations in beef, due to the strong correlation between the concentration of ^{137}Cs in milk and beef as described in chapter 2.7.1.

The maximum concentrations of ^{137}Cs in cereals are shown in Table 4.1.I. As expected from the expression for the uptake and translocation of ^{137}Cs in cereals described in chapter 2.5.5, the contamination of cereals will be substantial only if the contamination takes place in the summer, and less than a month before harvest. The timing of a given contamination, will influence the concentrations of ^{137}Cs in flour and bread following the same pattern.

The main part of pigs diet consists of cereals, described in

Table 4.1.I
Maximum concentration of ^{137}Cs in cereals, due to a single deposition of 1 Bq m^{-2} at various times of the year.

Time of deposition:	January	April	July	October
		10^{-5} Bq per kg		
first harvest	1.0	1.3	4463	3.7
second harvest	4.3	3.8	4.5	3.0

Table 4.1.II
Calculated doses to adults from a single deposition of 1 Bq m^{-2} ^{137}Cs at various times of the year.

Time of deposition:	January	April	July	October
		nSv		
dose first year	10	19	377	37
effective dose equivalent commitment	21	28	493	48

chapter 2.8.2. Consequently only a deposition happening in July will give rise to a substantial contamination of pork, Table 4.1.III.

The variations in doses to adults, after a single deposition of 1 Bq m^{-1} at different times of the year, are shown in Table 4.1.II. The doses to an individual after one years intake of contaminated food, and the effective dose equivalent commitment based on several years intake of contaminated food have been calculated . Four years were used as the integration period for the effective dose equivalent commitment, because this period of time accounts for more than 95 % of the infinite time integration values.

The predictions made by the model are in agreement with earlier studies (Simmonds 1985). An accident, that gives a deposition of ^{137}Cs in the middle of the summer, at the height of the growing season, will result in the highest dose; the effective dose equivalent commitment will be a factor of ten higher than for a deposition in January. The dose from a deposition in the fall will be slightly higher than the dose from a deposition in the winter or in the early spring. This difference will only occur, if the cows are still on pasture in October, or if the harvest of beets, for the winter diet, is not finished at the time of the deposition.

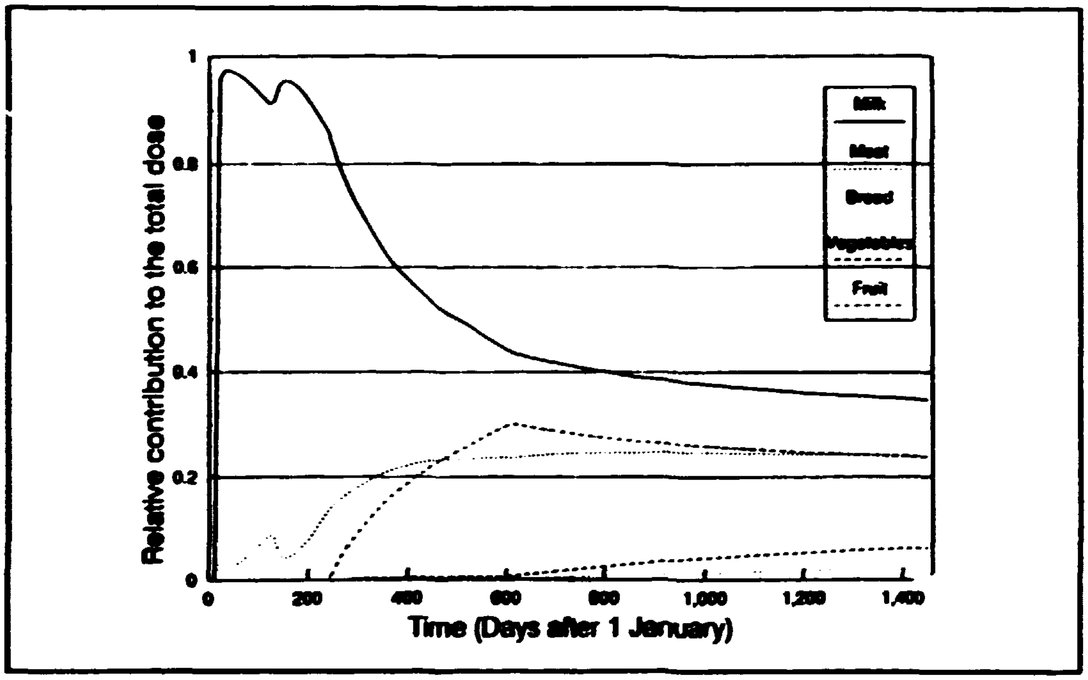

Figure 4.1.b
Time course of the relative importance for different foodproducts to the total dose from a single deposition of 1 Bq m^{-2} of ^{137}Cs in January.

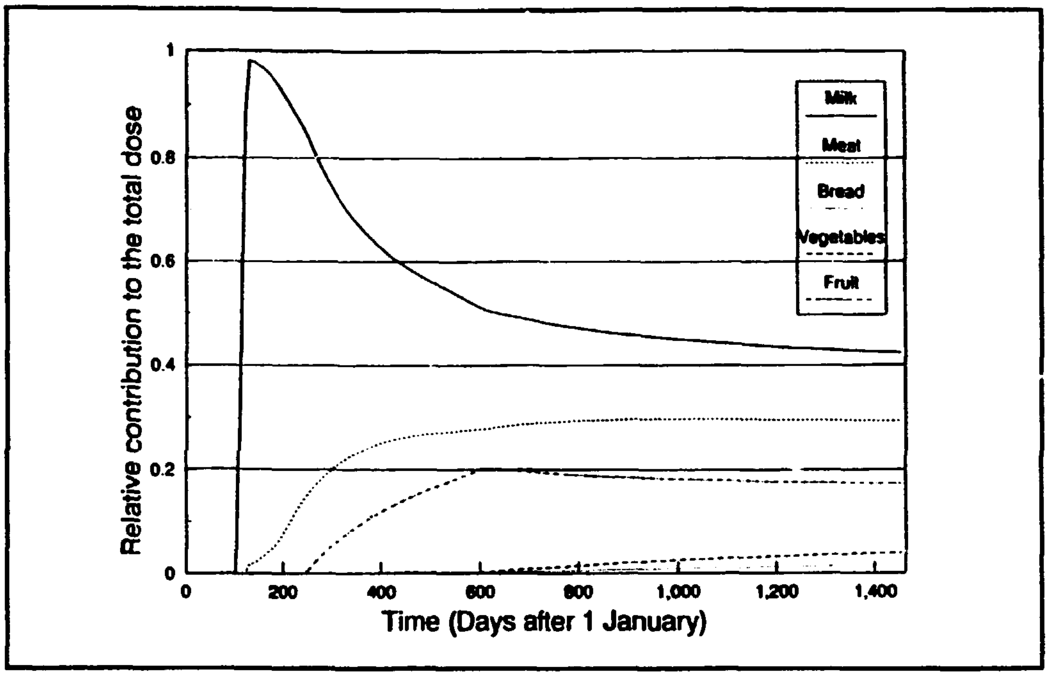

Figure 4.1.c
Time course of the relative importance for different foodproducts to the total dose from a deposition of 1 Bq m^{-2} of ^{137}Cs in April.

The time courses of the relative importance for different foodproducts to the total dose, calculated for different times of a single deposition, are shown in Figure 4.1.1 b, Figure 4.1.c, Figure 4.1.d and figure 4.1.e respectively. Meat is the sum of beef and pork products and bread is the sum of rye bread and white bread.

The predictions follow what was to be expected from the agricultural practice in the different seasons. Milk is the main contributor to the dose, from an accident happening in the winter or in the early spring. Although the total dose is low, the relative contribution from milk, contaminated via the cows' inhalation of contaminated air, is dominating. Vegetables and cereals have not yet emerged and will only contribute via root uptake to the total dose. The contribution from fruit seems to be rather high. A translocation of ^{137}Cs from the tree and the early buds has been assumed, based in the experience from the Chernobyl accident.

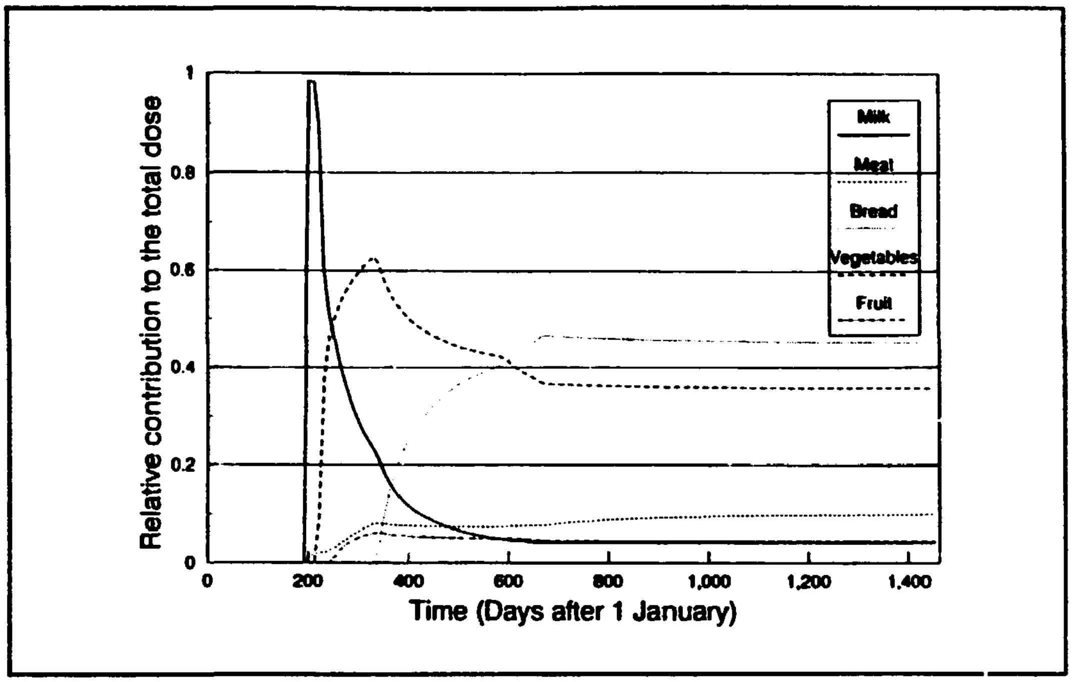

Figure 4.1.d
Time course of the relative importance for different foodproducts to the total dose from a deposition of 1 Bq m^{-2} of ^{137}Cs in July.

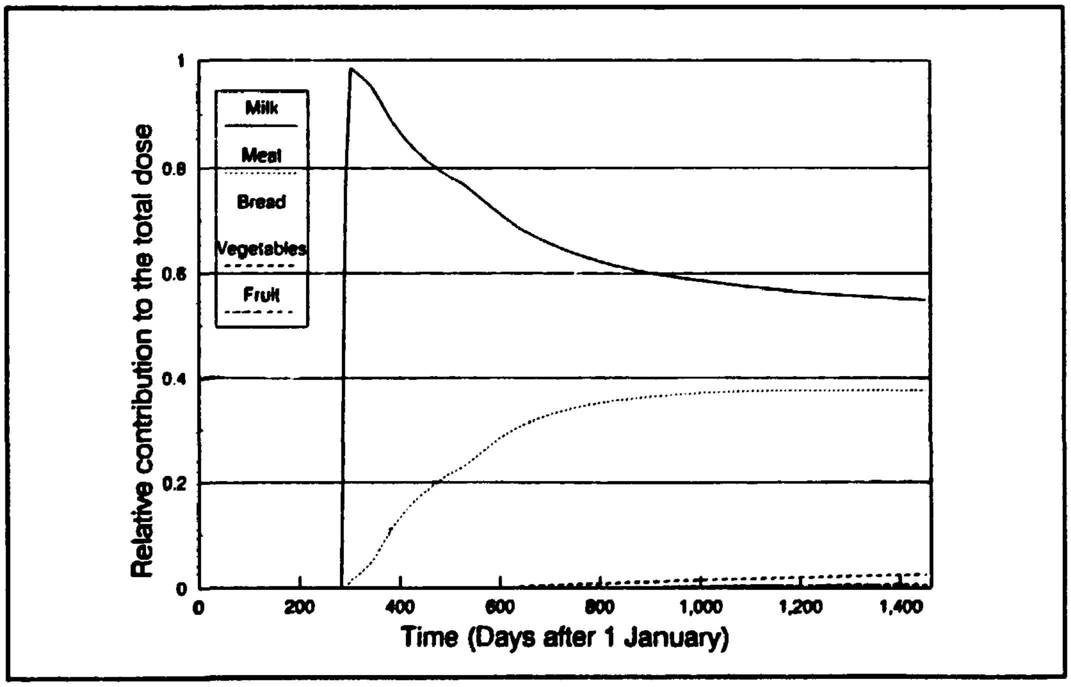

Figure 4.1.e
Time course of the relative importance for different foodproducts to the total dose from a deposition of 1 Bq m^{-2} of ^{137}Cs in October.

After an accident in the summer, at the height of the growing season, milk will be the dominating contributor to the total dose, in the first months after the deposition, due to the cows´ pasturing. The contribution from vegetables will dominate in a period after harvest, until the contaminated cereals is used in the production of bread.

As for the winter and early spring, the animal products dominate the contribution to the total dose from an accident happening in October. The small contribution from vegetables and cereals originate from root uptake the following year.

The radioecological sensitivities for ^{137}Cs in milk, beef, pork and grass have been calculated for each of the four different times of the deposition. The results are shown in Table 4.1.III. Results from other studies have been included for comparison.

The calculations made by A. Aarkrog (Aarkrog 1979), assume a deposition of 1 Bq m^{-2}, distributed like global fallout throughout the year, whereas calculations made by the present model, Pathway (Whicker and Kirchner 1987) and Simmonds (J. Simmonds 1985) assume a unit deposit at various times of the year.

The radioecological sensitivity, predicted by the model, supports the results shown earlier in this chapter. The surprisingly high values for milk and beef in October are due to the fact that the cows are still on pasture, and that the harvest of beets is not finished when the deposition occurs. The radioecological sensitivity of grass is highest in the winter due to the lack of growth dilution.

The model predictions for milk and beef are in the same order of magnitude as the ones calculated in the Pathway model. On the other hand, the calculations made by Simmonds are more

Table 4.1.1.III
Radioecological sensitivity for ^{137}Cs. Milk (Bq y l^{-1} per Bq m^{-2}), beef and pork (Bq y kg^{-1} per Bq m^{-2}), grass (Bq y kg^{-1} per Bq m^{-2}, dw).

	Milk	Beef	Pork	Grass
		10^{-3}		
Model predictions				
January	0.29	1.5	0.03	130
April	0.5	2.5	0.03	78
July	0.86	4.4	7.1	53
October	1.0	5.3	0.03	41
Pathway*				
July	2.5	4.4		68
Simmonds**				
January	2.5	13		
April	16	75		
July	18	74		
October	2.5	13		
Aarkrog***				
fallout	4.3	27	34	178

* (Whicker and Kirchner 1987), ** (J Simmonds 1985), *** (Aarkrog 1979).

than an order of magnitude higher than the present model predictions and on average nearly the same as for the fallout situation.

This discrepancy is assumed to be due to differences in the agricultural practice used in the two models. The fodder plan, used by Simmonds, include hay and grass silage in the winter time. The present model uses fodder beets and beetsilage with a lower concentration of radionuclides per feed unit, than grass. Furthermore, the milk and beef production rate, used by Simmonds, is less than for Danish cows.

Due to the difference between the deposition pattern for a single event and the continuous fallout situation, one should expect a higher radioecological sensitivity for the weapons fallout.

In summary, one can state that the worst time of a deposition of ^{137}Cs will be in the middle of the summer, at the height of the growing season, when cattle are grazing pasture. In addition the results presented in this chapter, can be used to identify the most effective countermeasures, able to reduce the dose given to man in case of a future accident. This is further discussed in chapter 6.0.

5.0 APPLICATIONS OF THE MODEL IN A SCENARIO REPRESENTING THE FAROE ISLANDS

In the previous chapters, the scenarios used in the model simulations have been limited to the area around Risø, characterized by the rainfall, a sandy loam soil and an average diet for the livestock stated by the local farmers.

Previous studies (Aarkrog 1979) showed shown that the averages of the radiological sensitivities for ^{137}Cs and ^{90}Sr are 1.3 times and 1.6 times higher, for ^{137}Cs and ^{90}Sr, respectively, in the western part relative to the eastern part of Denmark; the averages were calculated for grain, vegetables and milk. This reflects differences in weather conditions, soil type and, agricultural practice for the two regions.

The present model is able to simulate any combination of rainfall, soil type and agricultural practice. This makes it possible to investigate differences in radioecological sensitivity for different regions. To illustrate the possibilities of the model, an area known to show very different radioecological sensitivities from the area around Risø (Denmark) has been selected for further investigations. The Faroe Islands has been selected for this purpose.

Parameters characterizing average rainfall, types of soil, and agricultural practice for the Faroe Islands are used according to previous studies (Aarkrog 1979), to simulate the dynamic transport of ^{137}Cs in the terrestrial environment of the Faroe Islands.

The average precipitation is high, approximately 1500 mm yr^{-1}, about twice the average precipitation in Denmark. The mineral content of the soil is relatively low and the organic matter content is high. Consequently, the soil is assumed to be a typical organic soil, and characterized by the parameters given in Table 2.2.I and Table 2.4.1.I.

The pasturing season on the Faroe Islands is shorter than in Denmark and the main part of the cows fodder is grass products. During the winter, the fodder consists of hay, silage made of grass, and imported concentrate.

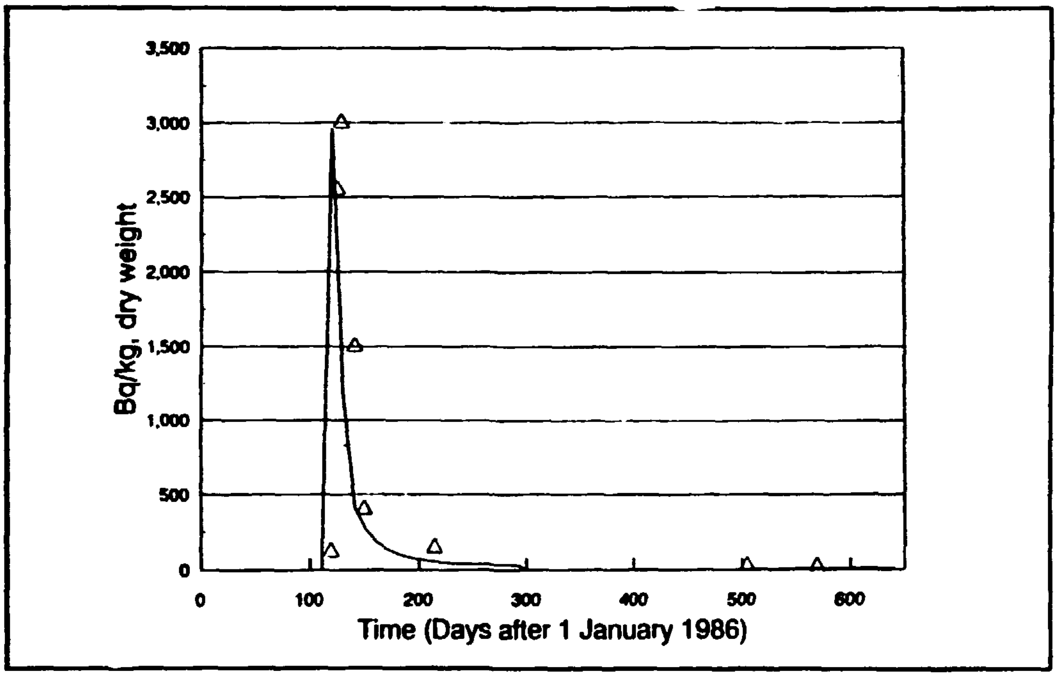

Figure 5.a
Calculated and measured concentrations of ^{137}Cs in grass at the Faroe Islands after the Chernobyl accident (Bq kg^{-1}).

The calculated and measured concentrations of ^{137}Cs in grass and milk, in the period following the Chernobyl accident, are shown in Figures 5.a and 5.b. It shows, how the changes in the model input reflect the dynamics of ^{137}Cs on the Faroe Islands. The time trend in the deposition pattern and the concentrations in the grass during 1986 and 1987 are very well predicted. The time trend and the concentrations of ^{137}Cs in the milk are predicted within a factor of two, revealing that the cows get relatively more contaminated fodder during the winter, and that feeding with fodder, partly made from grass harvested in 1986, continues through the summer of 1987. The structure of the model has to be changed, to include fodder from the previ-

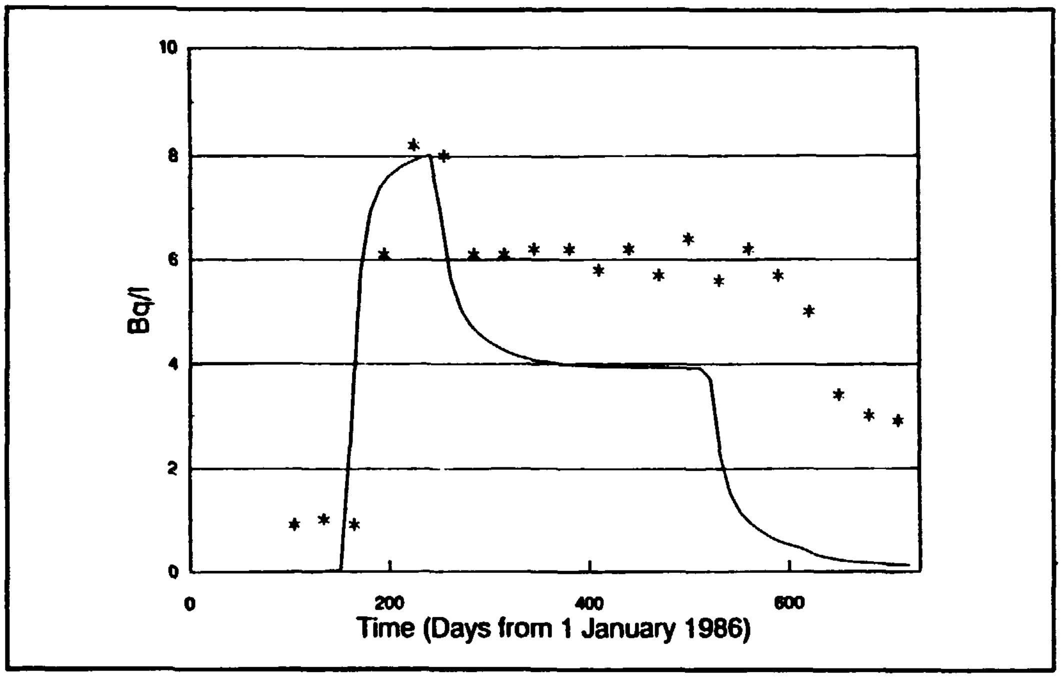

Figure 5.b
Calculated and measured concentrations of ^{137}Cs in milk at the Faroe Islands after the Chernobyl accident ($Bq\ l^{-1}$).

ous harvest in the following pasturing season (chapter 2.8.1). Previous studies (Aarkrog 1979) have shown significant local variations in the ^{137}Cs content of milk. For the present study, grass and milk data from a location near Thorshavn was chosen as representative.

Given a ground deposition of 1 Bq m^{-2} on January 15 and July 15 for the two different areas, the radioecological sensitivities have been calculated, and the results are shown in Table 5.I. Additionally, the ratios between the corresponding values for the Faroese and Danish environment, F/D, have been calculated. The differences are highest for a deposition in the summer period, nearly a factor of 20. The differences for milk and beef are mainly due to differences in agricultural practice.

Table 5.I
Radioecological sensitivity for The Faroe Islands and Denmark predicted by the model. Milk (Bq y l^{-1} per Bq m^{-2}), beef (Bq y kg^{-1} per Bq m^{-2}) and grass (Bq y kg^{-1} per Bq m^{-2}, dry weight).

	milk	beef 10^{-3}	grass
The Faroe Islands			
January	1.9	10	175
July	16	84	102
Denmark			
January	0.29	1.5	130
July	0.88	4.4	53
F/D			
January	6.6	6.6	1.4
July	18	19	1.9

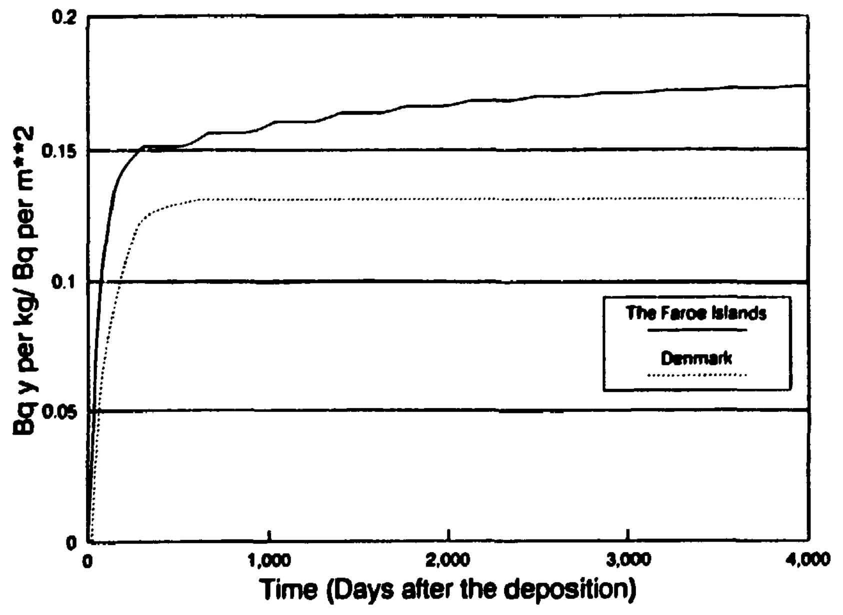

Figure 5.c.
Time course of the radioecological sensitivity for grass in Denmark and the Faroe Islands.

Pasture grass for dairy cows is assumed to be grown intensively in both areas. The differences between radioecological sensitivities for grass, is solely due to the difference in root uptake, from the two types of soil, as illustrated in Figure 5.c. The contribution, from a direct deposition suppresses the relative small contribution from the root uptake the following years. However, calculations have shown that the difference in the radioecological sensitivity for pasture grass, due only to root uptake, can go up to a factor of 50.

6.0 COUNTERMEASURES

Based on the results presented in chapter 4.0, a number of effective countermeasures can be introduced to reduce the dose, given to a population, after an accident, that involves a deposition of radioactive material.

The actual reduction of the dose has been calculated for several optional countermeasures for an accident happening in July or in October, described below:

Deposition in July:

- I.a: No countermeasures
- I.b: Keeping cows on stable for two weeks after the deposition and feeding them uncontaminated fodder during the time of the maximum concentrations of radionuclides in the grass.
- I.c Import of uncontaminated cereals and bread during the first year after the deposition.
- I.d Introducing both I.b and I.c.
- I.e Import of leafy vegetables
- I.f Introducing I.b up to and including I.d.

Deposition in October:

- II.a No countermeasures
- II.b Sending the cows on stable to feed on uncontaminated fodder immediately after the deposition.
- II.c Prohibiting silage made of beetleaves in addition to II.b.

The decreases in the total dose, due to the introduction of countermeasures after a deposition of 1 Bq m^{-2} ^{137}Cs in July and October, are shown in Table 6.I.

Table 6.I
Doses to adults from a single deposition of 1 Bq m^{-2} of ^{137}Cs.
Calculated after introducing countermeasures described in the text.

	dose first year	effective dose equivalent commitment
	nSv	nSv
I.a	377	493
I.b	220	330
I.c	74	88
I.d	56	68
I.e	210	310
I.f	25	33
II.a	37	48
II.b	11	16
II.c	2	7

The responsible authorities, who may have to introduce countermeasures after an accident, must make their decision based on a cost benefit analysis, comparing the economical expenses and the corresponding reductions of the dose. Import of uncontaminated foodproducts, for instance, will be very expensive. A thorough discussion of the economic aspects of countermeasures is considered beyond the scope of the present project.

Calculations show, that it is possible to reduce the contribution to the total dose from ^{137}Cs by more than a factor of ten by introducing several countermeasures. There are of course, several steps between I.a and I.f., e.g. importing only a part of the cereals, bread and vegetables, needed for food products, reduces the effect of the countermeasures correspondingly, but will also be less expensive.

Introducing similar countermeasures after an accident in the winter or in the spring, will also give a reduction in the total dose. However, the doses, from a deposition in the winter or in the spring, are more than a factor of ten less, than the doses from a deposition in the summer, without introducing any countermeasures, Table 4.1.1.II. Only a very serious accident will thus involve reasonable countermeasures.

In summary, it is possible to simulate countermeasures in the present model and to predict the corresponding reduction in the dose. The results of the most effective countermeasures are shown.

7.0 SENSITIVITY ANALYSES AND AN ESTIMATE OF THE UNCERTAINTY IN THE MODEL PREDICTIONS.

7.1 SENSITIVITY ANALYSES

Several sensitivity analyses were performed. These sensitivity analyses made it possible to focus on critical parts of the model and thus emphasize where the future effort should be concentrated to improve the predictions made by the model.

The parameter values were treated as independent variables and the respective output variables as the dependent variables. All the parameters were permitted to vary within a normal distribution with a standard deviation, SD, amounting to 10 % of the nominal value. The nominal value, used for a given parameter, was chosen to be the one used in the model when simulating the dynamics of ^{137}Cs.

Latin hypercube sampling (IAEA 1989) of all the involved parameter values precedes each model run. The values of the output variables for each of the simulations were saved for later analysis. To be sure of a stable estimate, of the output distribution, 500 simulations have been chosen.

Grass, milk, beef and cereals were chosen as dependent output variables. Pork and bread were not included, due to the strong dependence on cereals. A multiple regression procedure was employed to calculate correlation coefficients for each of the independent parameters. The squared correlation coefficients provide a measure for the the relative contribution of each parameter to the total variability of the output variables, assuming that parameters vary independently (IAEA 1989), (Whicker et al. 1990). Simulations have been made for four different periods of time after a given accident, to see whether the mutual importance of the different parameters changes with time. Additionally, a sensitivity analysis has been made for the radioecological sensitivity.

The statistical tools for these calculations are included and described in the modelling development system TIME-ZERO, (Kirchner 1989).

Reflecting the results in chapter 4.0, the start condition was chosen to be the deposit of 1 Bq m^{-1} July 15 in an arbitrary year.

Parameters, that contribute with more than five percent to the total variability of the output variables, are listed in Table 7.1.I.

The sensitivity analyses identify the foliar interception factor as the most critical parameter. This is in agreement with earlier studies. (Whicker et al. 1990), (Köhler and Peterson 1991). As expected, due to the structure of the model, the mutual importance of the parameters changes with time. In the years following a deposition, the parameter governing the fixation of the radionuclides in the soil and the model structure of the metabolism in the cow, become more and more important, for the accuracy of the time trend, in the model predictions.

The sensitivity analyses thus reveal, that the main effort, needed to improve the model, should be given to further studies of the foliar interception factor, its dependence on particle size, climatic conditions, and vegetation characteristics. For a better prediction of the concentration of radionuclides in food products, in the years following an accident, the metabolism of radionuclides in the cow and the fixation processes in different types of soil and the characteristics of resuspension should be further investigated.

The mutual importance of the parameters 30 days after the deposition is almost the same as for the radioecological

Table 7.1.I
The square of the correlation coefficients R^2 (in percent) showing the sensitivity of model output to variable input parameters, assuming parameters vary independently.

Time after the deposition	30d	1y	2y	3y	rad.sen*
Output variable Input parameter					
Grass					
interception	73	65	48	27	93
washout		12	8	6	
weathering	26				8
soil fixation			26	50	
resuspension		17	11	6	
Milk					
interception	63	60	34	20	69
weathering	9	8			7
soil fixation				5	
cow metabolism	16	30	48	62	10
Beef					
interception	70	46	20	12	65
weathering		7			
cow metabolism	15	31	65	65	19
Cereals					
washout		47	27	18	
resuspension		52	34	16	
soil fixation			40	65	

* Radioecological sensitivity.

sensitivity. This was to be expected due to the the dominating effect of the initial direct deposition.

The amount of direct deposition and a realistic amount of rainfall are of significant importance for an estimation of the radionuclide concentrations in cereals (chapter 3.2.2). The sensitivity analyses have identified the washout ratio and the resuspension factor as critical parameters in agreement with this. Finally, the soil fixation, which influence the resuspension and the root uptake, is identified as a critical parameter.

The identified parameters all represent simplified expressions simulating much more complex processes. Although identifying critical parameters in a sensitivity analysis makes it possible to focus on critical parts of the model, the "correct" choice for a specific parameter is not easy and should be considered and motivated carefully.

7.2 ESTIMATION OF THE UNCERTAINTY IN THE MODEL PREDICTIONS

A considerable effort has been made to subject the present model to a critical review and to test its predictive accuracy and dynamic properties. This involved the verification of model predictions against different sets of data, as described in chapter 3.0. The deviations between predictions and observations for the present model went up to a factor of two. The results are considered to be a good support for the structure and dynamics of the model, as well as its ability to give a realistic estimate of the consequences of a possible future accident involving radioactive materials. However, the testing of the model against the data from Chernobyl and the fallout data was retrospective; the exact weather conditions as well as the agricultural practice were well described.

Predictions of the consequences for a hypothetical accident, are assumed to be valid within a factor of three, given the significant influence of weather conditions and agricultural practice. Estimates must to be done, similar to what was done in chapter 4.0, and this will increase the uncertainty of the model output.

Considering the magnitude of uncertainty to be expected in the output of complex food-chain models (Köhler and Peterson 1991), the uncertainty within a factor of three for the present model seems very reasonable.

8.0 SUMMARY AND CONCLUSIONS

The experiences from the investigations of the fallout, originated from the nuclear weapons tests in the fifties and sixties, have formed the background for the development of steady-state models that describe the transfer of radioactive material in the environment. These models are based on a continuous fallout. One of the applications has been to predict the concentrations of radionuclides in the environment close to nuclear power plants with routine discharges of radionuclides to the environment.

However, especially the experience learned from the Chernobyl accident has shown, that a more detailed modelling of the effects of a discrete event, including dynamic processes, is necessary.

This study comprises the development of a compartment model, that simulates the dynamic transport of radioactive pollution released to the atmosphere in a single event, and subsequently transported to man, giving rise to an individual dose.

The model uses a set of linear, coupled differential equations to estimate the concentrations of radionuclides in soil, vegetation, animal tissue, and animal products as a function of time. Additionally the radioecological sensitivity was calculated to compare the response to a unit deposition for different scenarios.

Dynamic processes in the model include: dry and wet deposition, soil resuspension, plant growth, root uptake, foliar interception, foliar absorption, weathering and soil fixation, animal metabolism, agricultural practice, and production of bread.

To estimate the effective dose equivalent commitment to man, based on the amount of consumed radioactivity, typical Danish food habits have been used.

Currently, the model contains data necessary for a simulation of the dynamic transport of ^{137}Cs, ^{134}Cs and ^{90}Sr within the Danish agricultural system. Other isotopes of these radionuclides can be handled by simply entering the appropriate radioactive decay constants.

The accident at Chernobyl in the USSR, on April 26 1986, and the subsequent observations of the dynamics of the deposited radioactive material, provided an opportunity to test various models of the dynamic transport of radioactive materials in the terrestrial environment, after a discrete release of radioactive material.

The present model has been validated and discussed for Danish data. The predictions of the time trend, the concentrations of ^{137}Cs and ^{90}Sr in the Danish environment and the predictions of the ^{137}Cs contribution to the total dose after the Chernobyl accident, agree with the observations within a factor of two.

During the period of weapons fallout in the sixties and until today, comprehensive measurements were made of the activity of different isotopes in the terrestrial environment. The present model has been validated and discussed with regard to Danish data from the period 1963 - 1966. The predicted and measured concentrations in grass, milk, beef and cereals were within a factor of two, thus the model handles the fallout situation fairly well, even though it was made solely for single events.

The results of the validation are considered to be a very good support for the structure and dynamics of the model as well as its ability to give a realistic estimate of the consequences of a possible future accident, involving radioactive materials.

Following the validation several aspects of a single hypothetical deposition of 1 Bq m^{-2} ^{137}Cs has been investigated and discussed.

Considerable effort has been done to include all aspects of a seasonal variation in weather conditions, plant growth and agricultural practice in this dynamic model. The year was divided in four seasons, and the effect of a single deposition of 1 Bq m^{-2}, in each of the four seasons, has been investigated and discussed. In summary, the worst time of a deposition will be in the middle of the summer, in the height of the growing season, when cattle are grazing pasture.

Application of the model in a scenario representing the Faroe Islands has been made and the results were discussed and compared with results from a Danish scenario.

The results presented in the chapter 4.0, dealing with the differences in the effect of accidents happening at various times of the year, were used to identify the most effective countermeasures, that can be introduced to reduce the dose given to man, in case of a future accident. The actual reduction of the dose has been calculated for several countermeasures, implemented after a single deposition of 1 Bq m^{-2} in July or in October. The calculations showed, that it will be possible to reduce the contribution to the total dose from ^{137}Cs, after a deposition in July, by more than a factor of ten, by keeping the cows on stable for two weeks after the deposition eating uncontaminated fodder, and importing all the cereals, vegetables, and bread, used for human consumption and food products for the livestock, from areas that are not contaminated. Such efforts will be very expensive and a thorough discussion of the economic aspects will be necessary. Importing only part of the cereals, bread, and vegetables reduces the effect of the countermeasures correspondingly, but will also be less expensive.

Several sensitivity analyses have been performed and discussed. The sensitivity analyses made it possible to focus on critical parts of the model, and emphasize where the future effort should be concentrated to improve the model. In agreement with earlier studies, the foliar interception factor was identified as the most critical parameter. In the years following a deposition, the estimation of the parameter governing the fixation of the radionuclides in the soil as well as the model structure of the metabolism in the cow, become more and more important, for the accuracy in the model predictions.

Considerable effort has been made to test the predictive accuracy and dynamic properties of the present model. Predictions and observations agree within a factor of two. However, the testing the model against data from Chernobyl and weapons fallout data is retrospective; the exact weather conditions and the agricultural practice are well described. Based on this, predictions within a factor of three, of the consequences, for a hypothetical accident are likely, due to the lack of exact knowledge of the weather conditions and agricultural practice in the period following the accident.

PART II

Influence of Plant Variety on the Root Transfer of Radiocaesium.

1.0 INTRODUCTION

The contamination of vegetation with nuclear fallout takes place through a direct contamination, i.e. adsorption on the aerial parts of the vegetation often followed by an absorption, and an indirect contamination, i.e. absorption through the root system of radionuclides that have entered the soil. While all radionuclides in nuclear fallout play a role in direct contamination, it is among the long-lived nuclides that absorption via the roots can be substantial.

In areas with intensive farming, as in Denmark, it is of great interest to identify possible countermeasures to be taken in order to reduce the long-term effects of radioactive contamination of arable land.

The aim of the present study was to identify varieties of different crops with relatively high or low ability to absorb caesium through the roots. Radiocaesium was the most important radioisotope at long distances from the Chernobyl accident.

Although such differences may be small, a shift in varieties might be a cost-effective way to reduce collective doses.

2.0 MATERIALS AND METHODS

A pot-experiment was started in the summer of 1988 (Øhlenschlæger and Gissel-Nielsen 1989). 56 pots were seeded on 10 May with spring barley (Hordeum vulgare L) varieties: Golf, Apex, Anker, Sila; Perennial rye grass (Lolium perenne L.) varieties: Darbo (early), Patoro (late) and Italian rye grass (Lolium multiflorum) variety: Prego.

Soil type	Content of organic matter %	Particle size in mm%				pH	mg K pr. 100 g soil
		0.002 mm<	0.002-0.02 mm	0.02-0.2mm	0.2-2.0 mm		
Sandy-loam	2.0	6.7	10.5	37.9	42.1	7.0	10.7
Organic	66	4.4	7.7	15.9	6.0	5.2	8.0

Table 2.I
Characteristics of the soil.

Each crop was grown in two types of soil, a typical Danish sandy-loam from Risø, and an organic soil from Gävle, in Sweden, the area of the largest deposition of radiocaesium in Scandinavia following the Chernobyl accident. Characteristics of the two soils are given in Table 2.I. The soil is characterized according to the official Danish methods for soil analysis (Elling 1972).

All pots received a basic fertilization of 20 g of a formula fertilizer (NPK 16-5-12). After each harvest of grass, the pots were fertilized with 4g N as a solution of NH_4NO_3.

Cs-137 was experimentally added to the sandy-loam. The organic soil that was contaminated with Cs-137 from the Chernobyl accident was supplied with Cs-134. The Cs-137 solution was added to sand which, was dried and mixed up in 28 kg sandy-loam. This was divided into 28 portions, each of which was mixed with 19.5 kg sandy-loam. A total of 20.5 kg sandy-loam was then added to each pot. The Cs-134 solution was added similarly to the organic soil. Both isotopes were added as $CsNO_3$ with 10 μg stable Cs ml^{-1} as carrier. The pots were seeded immediately after the isotopes were added to the soil. Because of the lower density of the organic soil, only 11 kg were placed in each pot. The diameter of the pots was 25 cm and the volume 20 l. The concentration of caesium in each pot, at the beginning of the study, was 343± 1% kBq Cs-137 kg^{-1} soil in the sandy-loam, and 24.7± 2% kBq Cs-134 kg^{-1} and 2.12± 2% kBq Cs-137 kg^{-1} soil in the organic soil, dry weight. Each value is the mean of twenty-eight replicates ±1SE.

The pots were systematically placed within four blocks, each representing a replicate. Border-pots were placed at the end of the rows. The experiment was carried out in an outdoor cage and the pots were supplied daily with deionized water, up to 80 % of the waterholding capacity.

The barley was harvested on 30 August 1988. The samples were cut 5 cm above the soil surface, divided into grain and straw, and dried at 80°C for 24 hours. For the grass, five successive cuts were taken at appropriate stages of the development: 14 June, 28 June, 19 July, 8 September, and 21 October. The samples were cut 4 cm above the soil surface and dried at 80°C for 24 hours.

This part of the experiment was repeated in 1989 and 1990 in the same pots. The upper 10 -15 cm soil of the pots with the barley in 1988 was mixed in the spring 1989 and resown 3 May with the same varieties as in 1988. The barley was harvested 16 August. The soil in the pots was again treated in the same way in the spring 1990 and resown 9 May with the same varieties as in 1988 and 1989. The barley were harvested 8 August. The pots were placed indoors during the winter 1988 - 1989 and 1989 - 1990. The samples were treated in the same way as in 1988.

The pots containing the grass varieties were placed indoors after the last cutting in October 1988, until early april 1989. During the summer 1989 four successive cuts were taken at appropriate stages of the development: 9 May, 20 June, 3 August, 19 September. The samples were cut and dried in the same way as in 1988.

In order to confirm the results obtained in 1988, the part of the experiment carried out in sandy loam was repeated in exactly the same way in 1989. Two additional varieties Gunnar and Ida of spring barley (Hordeum vulgare L) were introduced and one rye grass variety Patoro (late, Lolium Perenne L.) was excluded. The barley was harvested on 16 August 1989 and treated as described above. Four successive cuts were taken of the grass on 20 June, 11 July, 16 August and 19 September 1989 and treated as described above.

The yields of the samples were registered and the radiocaesium concentrations were determined with gamma-spectrometric equipment using germanium detectors.

2.1 Data treatment

The concentration ratio (CR) is defined as the ratio of the plant to soil concentration, Bq per g plant/Bq per g soil on dry weight basis.

The statistical analyses were performed on the log-transformed concentration ratios, as the data showed log-normal rather than normal distributions. Comparisons were made based on two- or three-factorial analyses of variance, including two or three of the following factors: varieties, time of harvest, soil types and isotopes.

The results were corrected for the decay of the isotopes. Calculations showed that during the summer of 1988 the Italian rye grass removed 10 percent of the activity from the organic soil. For this particular combination of variety, soil and isotope, corrections were made to account for the activity removed from the soil during the period of growth. The other varieties grown in organic soil removed less than 4 percent. For the sandy-loam less than one percent of the activity was removed from the soil; consequently, no corrections were made.

3.0 RESULTS

3.1 Barley

Soil and isotope	Variety	1988	1989	1990
Organic soil experimentally added Cs-134	Apex	100± 7 %	100± 8 %	100±15 %
	Golf	101±10 %	105± 7 %	82±12 %
	Anker	128± 7 %	150±13 %	120±11 %
	Sila	136± 7 %	121±19 %	167±20 %
Organic soil Chernobyl Cs-137	Apex	100± 7 %	100±13 %	100±20 %
	Golf	102±10 %	84± 8 %	82±11 %
	Anker	132± 6 %	115±13 %	114± 5 %
	Sila	154± 9 %	112±16 %	159±18 %
Sandy-loam experimentally added Cs-137	Apex	100± 9 %	100±10 %	100± 7 %
	Golf	109± 5 %	140± 5 %	112± 3 %
	Anker	116± 7 %	152± 4 %	124± 4 %
	Sila	134± 4 %	204± 7 %	139± 5 %
Sandy-loam experimentally added Cs-137, 1989	Apex		100± 3 %	
	Golf		110± 9 %	
	Anker		137± 7 %	
	Sila		148±12 %	
	Gunnar		134± 5 %	
	Ida		132± 2 %	

Table 3.1.I
Root uptake of radiocaesium in barley grain expressed relative to the concentration ratio for the variety Apex in each group (Year-soil-isotope category). Each value is the mean of four replicates ±1SE.

The results for barley grain are shown in Table 3.1.I and Table 3.1.IV. In Table 3.1.I they are shown relative to the value of the concentration ratio for the variety Apex for each category, given by soil, isotope and year. This was done in order to emphasize the differences in root uptake among the varieties and to exclude the effect of soil type and fixation of caesium in the soil over the growing seasons. Table 3.1.IV provides the actual concentration ratios of the variety Apex for each category.

Table 3.1.II
Analyses of variance of ln(CR) for barley grain during the three years of experiment.

Soil and isotope Nature of effect	Source	SSD	f	s^2	F	Significance P %
Organic soil experimentally added ^{134}Cs						
Main factors	Year (Y)	13.582	2	6.791	109.181	100.00
	Variety (V)	1.194	3	0.398	6.406	99.86
Interaction	Y x V	0.430	6	0.072	1.154	64.72
Replication	Residual	2.175	35	0.062		
Organic soil Chernobyl ^{137}Cs						
Main factors	Year	0.348	2	0.174	2.735	92.26
	Variety	1.334	3	0.445	7.035	99.92
Interaction	Y x V	0.227	6	0.038	0.599	27.10
Replication	Residual	2.213	35	0.063		
Sandy loam experimentally added ^{137}Cs						
Main factors	Year	1.515	2	0.758	57.426	100.00
	Variety	1.077	3	0.359	27.207	100.00
Interaction	Y x V	0.165	6	0.027	2.079	91.91
Replication	Residual	0.462	35	0.013		

Analyses of variance of these results showed a significant difference between the four varieties in each type of soil, for each isotope and for each year, thereby confirming a high root uptake of caesium in Sila and a significantly lower root uptake in Apex. Additional analyses of variance, made for barley grain for each type of soil and each isotope as given in Table 3.1.II, show no significant interactions between varieties and years, which confirms that the distribution pattern among the different varieties was identical in 1988, 1989 and 1990 for each category.

Soil and isotope	Variety	1988	1989	1990
Organic soil experimentally added Cs-134	Apex	100± 9 %	100± 5 %	100± 8 %
	Golf	89±12 %	100±14 %	93± 5 %
	Anker	91± 9 %	124±11 %	112±15 %
	Sila	120± 9 %	134± 9 %	176±10 %
Organic soil Chernobyl Cs-137	Apex	100±11 %	100±26 %	100±13 %
	Golf	110±12 %	113±11 %	105± 5 %
	Anker	110± 8 %	133±13 %	115± 9 %
	Sila	157± 9 %	188± 4 %	117±12 %
Sandy-loam experimentally added Cs-137	Apex	100± 8 %	100±11 %	100± 2 %
	Golf	127± 5 %	175±15 %	114± 4 %
	Anker	101±10 %	138± 7 %	118± 4 %
	Sila	161± 7 %	214± 5 %	168± 6 %
Sandy-loam experimentally added Cs-137, 1989	Apex		100± 2 %	
	Golf		100± 9 %	
	Anker		100± 9 %	
	Sila		160±12 %	
	Gunnar		106± 3 %	
	Ida		116± 6 %	

Table 3.1.III
Root uptake of radiocaesium in barley straw expressed relative to the concentration ratio for the variety Apex in each group (year-soil-isotope category). Each value is the mean of four replicates ±1SE.

The results for barley straw are shown in Table 3.1.III and Table 3.1.IV, reported in the same way as for barley grain. Analysis of variance show, for all categories, a significant difference between the varieties and no interaction between varieties and years. As for the grain, Sila dominates with the highest uptake and Apex with the lowest uptake.

In agreement with earlier experiments, Gissel-Nielsen and Andersen (1967), Steffens et al. (1988), Grogan (1984), the uptake in the straw is somewhat greater than in the grain. In 1988 the ratio straw/grain (Bq/kg per Bq/kg, dry weight) was about 1.5 to 2, in 1989 and 1990 the ratio had decreased to about 1 to 1.5. The higher ratio in 1988 might be due to resuspension.

Soil and isotope	Apex	1988	1989	1990
Organic soil experimentally added Cs-134	grain straw	0.471± 7% 0.764± 9%	0.140± 8% 0.118± 5%	0.174±15% 0.223± 8%
Organic soil Chernobyl Cs-137	grain straw	0.117± 7% 0.219±11%	0.128±13% 0.196±26%	0.146±20% 0.203±13%
Sandy-loam experimentally added Cs-137	grain straw	0.031± 9% 0.065± 8%	0.018±10% 0.027±11%	0.020± 7% 0.038± 2%
Sandy-loam experimentally added Cs-137 1989	grain straw		0.060± 3% 0.107± 2%	

Table 3.1.IV
Concentration ratios for the barley variety Apex, (Bq per g plant/Bq per g soil, dry weight). Each value is the mean cf four replicates ±1SE.

Because of the chemical similarity between Cs and K, the Cs uptake from contaminated soil is related to the uptake of K, e.g. (Gissel-Nielsen and Andersen 1967), (Nielsen and Strandberg 1988). The barley samples have been analyzed for K and no significant differences in the uptake of K between the varieties were identified.

The Chernobyl caesium was "added" to the soil in April 1986, whereas the experimentally added caesium was added in the spring 1988 respectively 1989. The Chernobyl caesium has thereby been subject to fixation for two more years than the experimentally added caesium.

Differences in root uptake between the two soil types can be investigated comparing the results originated from the part of the study that deals with experimentally added caesium. A the study of whether the root uptake is influenced by the origin and/or the chemical form of the contamination can be done by comparing the behavior of the two caesium isotopes of different origin in the organic soil.

The results given in Table 3.1.IV which show that the uptake of experimentally added caesium from the soil rich in organic matter is about a factor of ten higher than the uptake of experimentally added caesium from the sandy loam, are in agreement with the results from previous studies (Squire and Middelton 1966), (Andersen 1967), (Nielsen and Strandberg 1988).

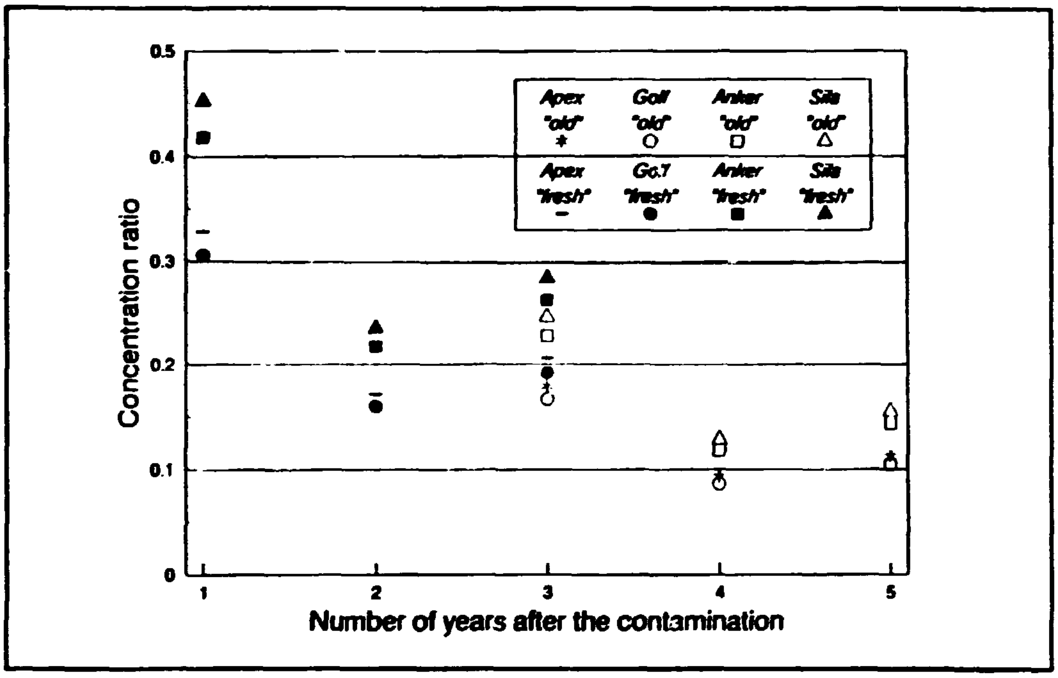

Figure 3.1.1
The concentration ratios (CR) for barley grain versus the number of years since the contamination.

Assuming no difference between experimentally added caesium and Chernobyl caesium, the two values of the concentration ratio (CR), for crops grown in the organic soil, should decline in a similar way. In order to examine this further the CR values are plotted against the number of years since the contamination of the soil, for each of the four barley varieties. The results are shown in Figure 3.1.1 for barley grain.

Although only one year, the third year after contamination, can be used for comparison, the assumption seems to be plausible. In order to investigate this further, the experiment will continue and differences in the fixation trend for the two isotopes will be studied.

Among the varieties of barley, there occurred no significant difference in the yield of dry matter. Consequently, this yield is not considered in the discussion.

Soil and isotopes	Variety	1988	1989
Organic soil experimentally added Cs-134	Italian	100±13 %	100±14 %
	Early Perennial	52±21 %	71±11 %
	Late Perennial	48±16 %	61±12 %
Organic soil Chernobyl Cs-137	Italian	100±19 %	100±31 %
	Early Perennial	57±30 %	64±25 %
	Late Perennial	52±26 %	64±25 %
Sandy-loam experimentally added Cs-137	Italian	100±21 %	100±10 %
	Early Perennial	37±19 %	66±17 %
	Late Perennial	41±25 %	66±17 %
Sandy-loam experimentally added Cs-137, 1989	Italian		100±13 %
	Early Perennial		61±16 %

Table 3.2.I
Root uptake of radiocaesium in rye grass expressed relative to the Italian rye grass, averaged over the growing season. (year-soil-isotope category). Each value is the mean of four replicates ±1SE.

3.2 Rye-grass

The results for the grass varieties are shown in Table 3.2.I and Table 3.2.II. The results in Table 3.2.I are shown relative to the concentration ratio for Italian rye grass for each category, given by soil, isotope and year. Each value is averaged over all cuts of each growing season. As for the barley, this was done in order to emphasize the differences in root uptake among the varieties. Table 3.2.II provides the actual concentration ratios for the Italian rye grass for each category.

Soil and isotopes	1988	1989
Organic soil experimentally added Cs-134	3.41±13%	2.65±14%
Organic soil Chernobyl Cs-137	1.37±19%	2.33±31%
Sandy-loam experimentally added Cs-137	0.257±21%	0.200±10%
Sandy-loam experimentally added Cs-137, 1989		0.382±13%

Table 3.2.II
Concentration ratios for the Italian rye grass, averaged over the growing season (Bq per g plant/Bq per g soil, dry weight). Each value is the mean of four replicates ±1SE.

For all the categories, in 1988 as well as in 1989, the Italian rye grass shows a significantly higher root uptake than the other varieties. As stated earlier, the Cs uptake is related to the uptake of K. Differences in the use of K could explain the differences in the uptake of Cs among the Italian rye grass and the other varieties, but an analysis of variance shows no significant differences in the uptake of K between the different varieties.

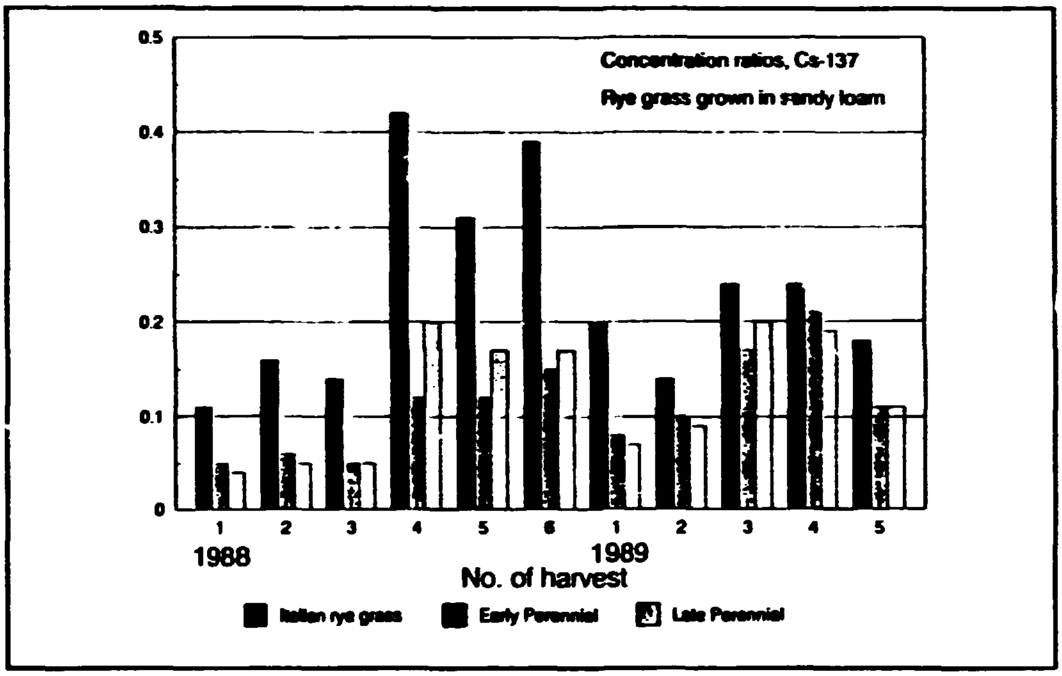

Figure 3.2.1
Root uptake of radiocaesium in rye grass grown in sandy loam given as concentration ratios.

The differences among the concentration ratios of the rye grass varieties, grown in sandy loam, during two growing seasons are shown in Figure 3.2.1. The concentrations of caesium in the Italian rye grass are 2 to 3 times higher than for the perennials through 1988. These differences decrease in 1989 partly due to plant base absorption (Russell 1966), which is typical for the perennials and not for the Italian rye grass. Thus, the caesium concentrations in the perennials are the same as in 1988 due to absorption of caesium accumulated in the plant base. The concentrations in the Italian rye grass reflect that the main part of caesium in the sandy-loam is firmly fixed already during the first year after the contamination (Squire and Middelton 1966), (Rogowski and Tamura 1970). A similar pattern is seen for the rye grass varieties grown in the organic soil contaminated with Cs-134. For the rye grass grown in organic soil contaminated with Cs-137 from the Chernobyl accident no such decrease in differences between the concentration ratios for the different varieties were observed. This is due to the fixation of the Chernobyl caesium from april 1986, given no differences in the caesium concentration in the plant base and in the soil.

4.0 SUMMARY AND CONCLUSIONS

Other elements than plant nutrients, such as heavy metals and fallout products, are taken up by crop plants. A study of these processes is therefore important in the elucidation of the plant-soil environment. Studies on genetical differences in plant uptake of radiocaesium were based on a pot experiment.

Ten different combinations of soil type, caesium isotope and age of the caesium contamination were studied in the experiment with indirect contamination. The pattern was the same for all combinations, the differences in root uptake for different barley varieties were in the order of 30 - 40%. We have identified a barley variety Sila with a high root uptake and a barley variety Apex with a significantly lower root uptake of caesium for all ten combinations. Similarly, for the grass varieties the Italian rye grass was identified as the one with the relatively highest uptake of caesium for all the combinations. The uptake of caesium was almost a factor two higher for the Italian rye grass than for the other two varieties, averaged over a growing season.

In summary, it might be possible to reduce the radiological consequences after a nuclear accident by efficient agricultural planning of countermeasures, comprising changes of agricultural practices towards the use of plant species and varieties with a low sensitivity to a given contamination. The countermeasures can contribute to a significant reduction of the contamination levels, perhaps even below a critical level. It is worth noting that such countermeasures have no adverse side effects like pollution, e.g. compared with countermeasures such as heavy fertilizing with potassium, sodium etc.

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DANSK RESUMÉ

Denne afhandling består af to dele:

I. Udvikling af en model, der kan beskrive den dynamiske transport af radioaktiv forurening, i det terrestriske miljø.

og

II. Identificering af byg- og græssorter med stort, henholdsvis lille rodoptag, af radioaktivt cæsium, fra forurenet jord.

I.

Denne del af afhandlingen omfatter udvikling af en model, der beskriver den dynamiske transport af en radioaktiv forurening fra et hypotetisk udslip til atmosfæren, videre via fødekæden til mennesket.

Modellen includerer dynamiske processer såsom: tør- og våddeponering, resuspension, plantevækst, rodoptag, absorption gennem blade, stofskifte i kreaturer for radionuklider, landbrugspraksis og brødproduktion. Den individuelle dosis til mennesker beregnes på baggrund af det totale indtag af radionuklider. En detaljeret beskrivelse af modellen findes i kapitel 2.

I kapitel 3 er beskrevet, hvorledes modellen kan simulere transporten af ^{137}Cs i det danske miljø efter Chernobylulykken i 1986. Derudover er modellen anvendt til at simulere transporten af radioaktivt nedfald fra kernevåbenforsøgene i tresserne. Resultatet af modelsimuleringerne er sammenlignet med faktiske målinger fra de to perioder. Beregninger og observationer ligger inden for en faktor 2. Dette er en udmærket overensstemmelse, på baggrund af, at usikkerheder på forudsigelser baseret på komplekse miljømodeller, kan være flere størrelsesordener.

I kapitel 4 indgår en undersøglese af, hvorledes kontaminationstidspunktet influerer på konsekvenserne af et eventuelt uheld og dermed på den endelige dosis til mennesket. Undersøgelsen viste, at det værst tænkelige tidspunkt for et uheld med radioaktivt materiale, vil være midt på sommeren en måneds tid før kornet høstes, mens køerne stadig er på græs.

I kapitel 6 er beskrevet, hvorledes følgerne af en radioaktiv forurening afhænger af det miljø, den indtræffer i.

På bagrund af resultaterne i kapitel 4, er der, i kapitel 6, udført beregninger på, hvorledes den endelige dose til mennesket kan reduceres efter et uheld med radioaktivitet, ved indførelse af forskellige modtiltag. Dette kan f.eks. være restriktioner for anvendelse af lokale produkter, forbud mod at lade kvæget græsse udendørs etc.

For at fokusere på svage dele i modellen er der udført adskillige sensitivitetsanalyser, som beskrevet i kapitel 8. Resultatet af sensitivitetsanalyserne gør der muligt at pege på de dele af modellen, det er nødvendigt at arbejde yderligere med fremover for at opnå større nøjagtighed i forudsigelserne.

Med baggrund i validering af modellen skønnes det, at resultaterne af en modelberegning vil ligge inden for en faktor 3 i forhold til, hvad man vil kunne observere i tilfælde af et virkeligt uheld. Det er nødvendigt at nævne, at simuleringen af hændelsesforløbet efter Chernobyl giver bedre overensstemmelse mellem beregninger og observationer end man kan forvente for et eventuelt fremtidigt uheld. Det skyldes, at såvel vejrforholdene som lokal landbrugspraksis for 1986 var velkendte ved modelsimuleringen.

II.

Denne del af afhandlingen beskriver et forsøg udarbejdet i samarbejde med sektionen for plantebiologi på Risø. Hovedformålet med dette forsøg var at identificere afgrøder med stort henholdsvis lille rodoptag af cæsium fra forurenet jord.

Forsøget blev gennemført som et karforsøg over 3 år. I forsøget indgik fire vårbygsorter og tre sorter af rajgræs, der alle blev dyrket i to forskellige jordtyper. Resultaterne viste, at der mellem de fire forskellige bygsorter var signifikant forskel på optaget af cæsium. Bygsorten Sila havde det største rodoptag mens bygsorten Apex havde det mindste. For græs skilte en enkelt sort sig tilsvarende ud med et stort rodoptag, nemlig den Italienske rajgræs.

På baggrund af disse resultater kan man konkludere, at det vil være muligt at reducere de radioøkologiske konsekvenser af et uheld med radioaktivt materiale ved at anvende plantesorter, inden for en given art, med det laveste forureningspotential.

Resultaterne af denne undersøglese har et videre perspektiv, idet man kan forestille sig at planter vil udvise samme mønster over for f.eks tungmetaller eller gødningsprodukter. Dette bør imidlertid undersøges nærmere.

Appendix

The Fortran code for the model is made using the modelling development system TIME-ZERO (Kirchner 1989). TIME-ZERO provides an interactive code generator that minimizes the amount of code one needs to write in order to create a simulation model. The system has an extensive set of menus to help run models, examine graphical or tabular output and perform sensitivity analyses.

TIME-ZERO structures the final code for the model by inserting the code into subroutines. TIME-ZERO provides the call to these routines automatically. A diagram representing the flow between each of the subroutines is shown in Figure A.

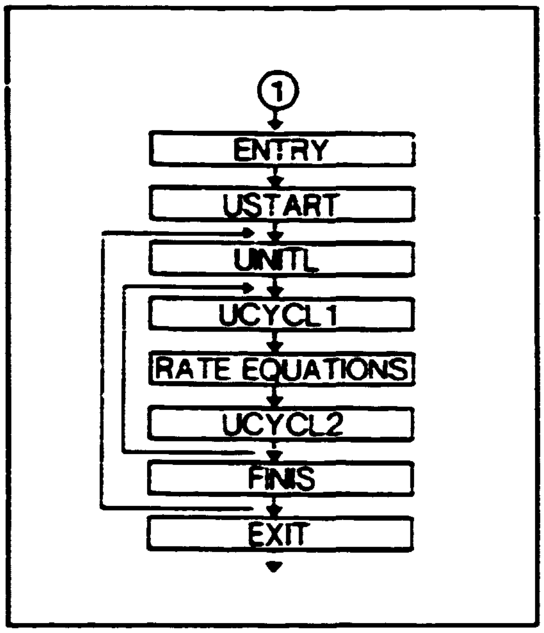

Figure A

The flow of execution starts at point 1 on the first simulation of the model. The inner loop is executed once per time step to solve the rate equations. The outer loop is executed whenever more than one simulation is required to produce a result, as in performing sensitivity analyses. Only those routines to which code is added will appear in the model.

The subroutines in which the rate equations are defined differ from the other subroutines. Each of these subroutines has its own time step parameter, in which the sets of rate equations are solved at different time steps.

On the following pages is listed the Fortran code with the information TIME-ZERO uses to build the model described in the main text.

The code required for each of the subroutines is listed. The state variables and parameters are defined. Additionally is listed the initial value for each state variable and for each parameter necessary for the simulation of ^{137}Cs.

SUBROUTINE UINITL

```
Character   evfil*10, rain*10

Write(6,*) 'Enter the day of the event:'
Read(5,*)   event
Write(6,*) 'Enter the name of the eventdata:'
Read(5,'(a)') evfil
Write(6,*) 'Enter the name of the raindata:'
Read(5,'(a)') rain
Write(6,*) 'Enter the first day the cows are on pasture:'
Read(5,*)   tpast
Write(6,*) 'Enter the last day the cows are on pasture:'
Read(5,*)   tstabl
Write(6,*) 'Enter the period cows were in stable during
summer:'
Read(5,*)   timbeg, timend
Write(6,*) 'Enter the first day the cows get fresh beets:'
Read(5,*)   fbeet
Write(6,*) 'Enter the day when the beetleaves emerge:'
Read(5,*)   beetem
Write(6,*) 'Enter the day for the beet uptake:'
Read(5,*)   beetup
Write(6,*) 'Enter harvest time for cereal crops:'
Read(5,*)   harvst
Write(6,*) 'Enter the day when the vegetables emerge:'
Read(5,*)   vegem
Write(6,*) 'Enter the harvest time for vegetables:'
Read(5,*)   vegcut
Write(6,*) 'Enter the density of vegetables at harvest
time,'
Write(6,*) 'kg per square metre:'
Read(5,*)   vegden
Write(6,*) 'Enter harvest time for fruits'
Read(5,*)   fruhar
Write(6,*) 'Enter the harvest day for silage:'
Read(5,*)   siday
Write(6,*) 'Enter the silage-rate, during winter:'
Read(5,*)   silar
Write(6,*) 'Enter the beet-rate, during winter:'
Read(5,*)   beetr
Write(6,*) 'Do you want to sow grass every year?'
Write(6,*) 'Yes = 1, No = 0'
Read(5,*)   answer

Open(10,file='grassdom')
Open(20,file='beetdom')
Open(30,file=rain)
Open(40,file='vegdom')
Open(50,file=evfil)
Open(60,access='direct',recl=50)


m=0
n=0
```

```
      i=1
      grasac=0
      milkac=0
      beefac=0
      brotac=0
      porkac=0
      rbrtac=0
      wbrtac=0
      vegac =0
      fruac =0
.END


SUBROUTINE UCYCL1

      IF (abs(time-nint(time)).le.0.0005) THEN

c     Deposition og resuspension

      read(50,*) Y0
      read(30,*) regn
      regn=regn/1000


      dep = (v+w*regn)*Y0

      if((time-event).gt.0.0) then
      rf = 1.4e-5*((time-event)**(-1.26))
      endif

      if((time-event).gt.2.000) rf = 1e-9
      air = rf*(y2g+y3g)


      fv = 1 - fs

      sdep = fs*((v+w*regn)*air+dep)
      pdep = fv*((v+w*regn)*air+dep)
      bdep = fvb*((v+w*regn)*air+dep)
      vdep = fvv*((v+w*regn)*air+dep)

c     Weathering

      If(abs(time-event).le.20.005.and.
      abs(time-event).gt.0.0) then

      k52 = wh1
      else
      k52 = wh2
      endif

c     Resowing
      If((abs(time-(300+n*365)).le.0.0005).and.
     +(answer.eq.1)) then
      m = 0.0
```

```
      y3g = y2g+y3g+y5+y6
      y2g = y3g/(xr*100)
      y5 = 0.0
      y6 = 0.0

      y3b = y2b + y3b
      y2b = y3b/(xr*100)

      y3v = y2v + y3v
      y2v = y3v/(xr*100)

      endif


c     Grass
      Read(10,*) day,dilu,dbs
      If(abs(time-event).le.0.0005) grocor = dilu
      If(time.gt.tpast.and.time.lt.event) dilu = 0.1
      If(time.ge.event.and.answer.eq.0) dilu = dilu - grocor
      If(time.gt.event.and.time.le.500.and.answer.eq.1) dilu=dilu-grocor

      grass = (y5+y6)/(0.14+dilu+m*1.391)

c     Beets

      If(abs(time-(beetem+n*365)).le.0.0005) then
      y20 = 0
      y21 = 0
      bleave = 0
      broot = 0
      endif

      if(abs(time-(beetup+n*365)).le.0.0005) then
      blewin = bleave
      browin = broot
      endif

      If(time.gt.(beetem+n*365).and.time.le.(beetup+n*365)) then

      read(20,*) dbb


      bleave = (y20/3.5)
      broot = (y21/6.5)

      else

      bleave = blewin
      broot = browin

      endif

      If(time.gt.fbeet.and.time.lt.tstable) then
      beetc = (broot*5 + bleave*10)/2
      else
      beetc = broot*5
```

```
      endif

c     Silage

      If(abs(time-(siday+n*365)).le.0.0005) sigra=grass

      silac = (bleave*10*1.96)*2/3+(sigra*1.3)*1/3

c     Cereals and bread

      if(time.eq.((harvst-130)+n*365)) cereal = 0

      if(time.gt.((harvst-130)+n*365).and.time.lt.(harvst+n*365)) then
      cereal=(9.8e-2*exp(-0.0013*(((harvst+n*365)-time)-34)**2))
     +*pdep/(fv*3)+cereal
      endif

      if(event.gt.(harvst-90).and.time.gt.event.and.
      time.lt.harvst) then
      cereal=(9.8e-2*exp(-0.0013*((harvst-time)-34)**2))
      *pdep/fv+cereal
      endif

      if(abs(time-(harvst+n*365)).le.0.0005) then
      pcer = 0
      cereal=crc*y3g/(xr*ps)+cereal
      pcer = cereal
      endif



      If(abs(time-((n+1)*335)).le.0.0005) then

      cercon = cereal

      rbread = 0.74*cercon
      wbread = 0.37*cercon

      endif

c     Vegetables

      if(time.ge.(vegem+n*365).and.time.le.(vegcut+n*365)) then
      if(time.eq.(vegem+n*365)) veg = 0
      Read(40,*) dbv
      vegcon = veg/vegden
      endif

      if(abs(time-(vegcut+n*365)).le.0.0005) veghar = vegcon


c     Fruits

      if(abs(time-(fruhar+n*365)).le.0.0005) then
```

```
      fruit = grass*0.05

      endif

c     Animal produce

      beef = (y14+y15)/beefpr
      milk = y17/milkpr
      excr = y18
      urin = y19/30
      pork = (ys1+ys2)/75

      y17 = 0
      y18 = 0
      y19 = 0

      write(60,rec=i) milk

      If(time.gt.30) then
      j=i-30
      read(60,rec=j) pimilk
      endif

      i=i+1

c     Radioecological sensitivity

      If(time.ge.event) then

      grasac=(grass+grasac)
      milkac=(milk+milkac)
      beefac=(beef+beefac)
      brotac=(broot+brotac)
      porkac=(pork+porkac)
      rbrtac=(rbread+rbrtac)
      wbrtac=(wbread+wbrtac)
      vegac =(veghar+vegac)
      fruac =(fruit+fruac)


      grasen =grasac/365
      milsen =milkac/365
      befsen =beefac/365
      poksen =porkac/365
      brosen =brotac/365
      wbrsen =wbrtac/365
      rbrsen =rbrtac/365
      vegsen =vegac/365
      frusen =fruac/365

      endif

      ENDIF

c     Fodderplans
```

```
      If(time.ge.(tpast+n*365).and.time.le.(tstabl+n*365)) then
      If(time-(tpast+n*365).le.21) then
      fodder=((time-(tpast+n*365))*((0.5-adfod)/21))*
     +grass*ain*fvg*dtc+
     +0.5*grass*ain*fvg*dtc+(0.5-(((time-(tpast+n*365))/42)))*
     +silac*ain*dtc

      else if((time-(tpast+n*365)).gt.21.and.time.le.
     +(fbeet+n*365)) then
        fodder=grass*ain*fvg*(1-adfod)*dtc+adfod*ain*adfodc
      else if(time.gt.(fbeet+n*365)) then
        fodder=((1-adfod)+((time-(fbeet+n*365))*
     +  (adfod-0.5)/(tstabl-fbeet)))*grass*ain*fvg*dtc+
     +  ((time-(fbeet+n*365))/2/(tstabl-fbeet))*beetc*ain*dtc

      endif

      else

      fodder = (beetr*beetc+silar*silac+mashr*mashc)*ain*dtc

      endif

      If(time.le.event.or.(time.ge.timbeg.and.time.le.timend))       then
      fodder = zero
      endif

      pfod = cerq*pcer + whey*pimilk


c     Inhalation

      inh = kih*(air+y0)
.END

SUBROUTINE UCYCL2

      If(mod(time,365).eq.1) then
      n=n+1
      m=m+1


      rewind 10
      rewind 20
      rewind 40


      endif

      If(time.gt.event+1) then

      domilk=df*milk*174/365 + domilk
      dobeef=df*beef*9/365 + dobeef
      doroot=df*broot*52/365 + doroot
      dopork=df*pork*35/365 + dopork
      doveg =df*veghar*47/365 + doveg
```

```
      dowbr =df*wbread*29/365 + dowbr
      dorbr =df*rbread*39/365 + dorbr
      dofru =df*fruit*56/365 + dofru

      dose=domilk+dobeef+dopork+doroot+doveg+dowbr+dorbr+dofru


      remilk = domilk/dose
      rebeef = dobeef/dose
      repork = dopork/dose
      reroot = doroot/dose
      reveg  = doveg/dose
      rewbr  = dowbr/dose
      rerbr  = dorbr/dose
      refru  = dofru/dose


      endif
.END

SUBROUTINE FINIS

      close(10)
      close(20)
      close(30)
      close(40)
      close(50)
      close(60)
.END

RATE EQUATIONS

   Subroutine "subny", time step 1 day

.SUBMODEL SUBNY, 500 ,STAT1,PARAM1,DT

      D:y2g=-(rf+k23+la)*y2g+k52*y5+sdep
      D:y2b=-(rf+k23+la)*y2b+whb*y20+sdep
      D:y2v=-(rf+k23+la)*y2v+whv*veg+sdep
      D:y3g=-(dbs*cr/(xr*ps)+k3+la)*y3g+k23*Y2g
      D:y3b=-(dbb*(crb+k0220)/(xr*ps)+k3+la)*y3b+k23*y2b
      D:y3v=-(dbv*crv/(xr*ps)+k3+la)*y3v+k23*y2v
      D:Y5=-(k52+fa*k52/(1-fa)+la)*y5+pdep
      D:y6=-la*y6+dbs*cr/(xr*ps)*y3g+fa*k52/(1-fa)*y5
      D:y20=-(whb+la)*y20+(dbb*k0220/(xr*ps))*y3b+bdep
      D:y21=-la*y21+(dbb*crb/(xr*ps))*y3b
      D:veg=-(la+whv)*veg+(crv*dbv/(xr*ps))*y3v+vdep
      D:blewin=-la*blewin
      D:browin=-la*browin
      D:sigra=-la*sigra
      D:cereal=-la*cereal
      D:rbread=-la*rbread
      D:pcer=-la*pcer
      D:wbread=-la*wbread
      D:veghar=-la*veghar
      D:fruit =-la*fruit
```

```
      D:grass=0
      D:grasen=0
      D:brosen=0
      D:wbrsen=0
      D:rbrsen=0
      D:vegsen=0
      D:bleave=0
      D:broot=0
.END
```

Subroutine "Sub2", time step 0.1 day

```
.SUBMODEL SUB2, 501 ,STAT2A,PRAM2A,DTC

      D:y10=-(k1011+tmc+la1)*y10+k1210*y12+fodder+ks*dtc*y2g
      D:y11=-(kex+k1113+tmc+la1)*y11+k1011*y10
      D:y12=-(k1210+k1213+tmc+la1)*y12+inh
      D:y13=-(k1314+k1315+k1316+kexb+tmc+la1)*y13+k1113*y11
       +k1213*y12+k1413*y14+k1513*y15
      D:y14=-(k1413+tmc+la1)*y14+k1314*y13
      D:y15=-(k1513+tmc+la1)*y15+k1315*y13
      D:y16=-(tmc+la1)*y16+k1316*y13-km*y16
      D:y17=-la1*y17+km*y16
      D:y18=-la1*y18+kex*y11
      D:y19=-la1*y19+kexb*y13
      D:fodder=0
      D:milk=0
      D:beef=0
      D:fodder=0
      D:y1p=-(klg+klc+tmp+la1)*y1p+inhp*air
      D:ygp=-(kgc+tmp+kge+la1)*ygp+klg*y1p+pfod
      D:ycp=-(ks1+ks2+tmp+kce+la1)*ycp+kst1*ys1+
       kst2*ys2+klc*y1p+kgc*ygp
      D:ys1=-(kst1+tmp+la1)*ys1+ks1*ycp
      D:ys2=-(kst2+tmp+la1)*ys2+ks2*ycp
      D:pork=0
      D:milsen=0
      D:befsen=0
      D:poksen=0
      D:frusen=0
      D:dose=0
      D:domilk=0
      D:dobeef=0
      D:dopork=0
      D:doroot=0
      D:doveg=0
      D:dowbr=0
      D:dorbr=0
      D:dofru=0
      D:remilk=0
      D:rebeef=0
      D:reroot=0
      D:repork=0
      D:reveg=0
      D:rewbr=0
      D:rerbr=0
```

```
    D:refru=0
.END
```

STATE VARIABLES AND PARAMETERS

(Listed in the order they were introduced in the model)

Name/Unit/Description/Initial value

\>DATA

TIME [d]
The initial value assigned to the simulated time, 1

Y2G [Bq/m**2]
State variable (STV), upper soil compartment for grass production, 0

Y2B [Bq/m**2]
STV, upper soil compartment for production of beets and root vegetables, 0

Y2V [Bq/m**2]
STV, upper soil compartment for production of leafy vegetables, 0

Y3G [Bq/m**2]
STV, root zone for production of grass, 0

Y3B [Bq/m**2]
STV, root zone for production of beets and root vegetables, 0

Y3V [Bq/m**2]
STV, root zone for production of leafy vegetables, 0

Y5 [Bq/m**2]
STV, external plant, grass, 0

Y6 [Bq/m**2]
STV, internal plant, grass, 0

Y20 [Bq/m**2]
STV, leaves above ground, beets, 0

Y21 [Bq/m**2]
STV, plant tubes, beets and potatoes, 0

VEG Local variable for intermediate results (LV), 0

BLEWIN LV, 0

BROWIN LV, 0

SIGRA [Bq/m**3, dry weight]
Radionuclide concentration in the grass at the time of harvest for silage production, 0

CEREAL [Bq/kg, fresh weight]
STV, radionuclide concentration in cereal, 0

RBREAD [Bq/kg]
STV, radionuclide concentration in rye bread, 0

WBREAD [Bq/kg]
STV, radionuclide concentration in white bread, 0

VEGHAR [Bq/kg, fresh weight]
STV,radionuclide concentration in leafy vegetables, 0

FRUIT [Bq/kg fresh weight]
STV, radionuclide concentration in fruit, 0

GRASS [Bq/kg, dry weight]
STV, radionuclide concentration in grass, 0

GRASEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, grass, 0

BROSEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, bread, 0

WBRSEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, white bread, 0

RBRSEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, rye bread, 0

VEGSEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, leafy vegetables, 0

BLEAVE [Bq/kg, fresh weight]
STV, radionuclide concentration in beet leaves, 0

BROOT [Bq/kg]
STV, radionuclide concentration in beets, 0

PCER [Bq/kg]
STV, radionuclide concentration in cereal, 0

Y10 [Bq]
STV,radionuclide concentration in the stomach, cow, 0

Y11 [Bq]
STV, radionuclide concentration in the intestines, cow, 0

Y12 [Bq]
STV, radionuclide concentration in the lungs, cow, 0

Y13 [Bq]
STV, radionuclide concentration in the circulating fluids, cow, 0

Y14 [Bq]
STV, radionuclide concentration in the soft tissue,long retention time, cow, 0

Y15 [Bq]
STV, radionuclide concentration in soft tissue, short retention time, cow, 0

Y16 [Bq]
STV, radionuclide concentration in the udder, 0

Y17 LV,

Y18 LV,

Y19 LV,

MILK [Bq/l]
STV, radionuclide concentration in milk, 0

BEEF [Bq/kg]
STV, radionuclide concentration in beef, 0

MILSEN [Bq y/l per Bq/m**2]
STV, radioecological sensitivity, milk, 0

BEFSEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, beef, 0

FRUSEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, fruit, 0

DOSE [Sv]
STV, individual dose to adults, 0

DOMILK [Sv]
STV, contribution from consumption of milk to the total dose, 0

DOBEEF [Sv]
STV, contribution from consumption of beef to the total dose, 0

DOROOT [Sv]
STV, contribution from consumption of root vegetables to the total dose, 0

DOVEG [Sv]
STV, contribution from consumption of leafy vegetables to the total dose, 0

DOWBR [Sv]
STV, contribution from consumption of white bread to the total dose, 0

DOFRU [Sv]
STV, contribution from consumption of fruit to the total dose, 0

REMILK STV, relative contribution to the total dose, milk, 0

REBEEF STV, relative contribution to the total dose, beef, 0

REROOT STV, relative contribution to the total dose, root vegetables, 0

REVEG STV, relative contribution to the total dose, leafy vegetables, 0

REWBR STV, relative contribution to the total dose, white bread, 0

REFRU STV, relative contribution to the total dose, fruit, 0

DORBR [Sv]
STV, contribution from consumption of rye bread to the total dose, 0

RERBR STV, relative contribution to the total dose, rye bread, 0

YLP [Bq]
STV, radionuclide concentration in the lungs, pig, 0

YGP [Bq]
STV, radionuclide concentration in the intestines, pig, 0

YCP [Bq]
STV, radionuclide concentration in the circulation fluids, pig, 0

YS2 [Bq]
STV, radionuclide concentration in soft tissue, short retention time, pig, 0

YS1 [Bq]
STV, radionuclide concentration in soft tissue, long retention time, pig, 0

PORK [Bq/kg]
STV, radionuclide concentration in pork, 0

POKSEN [Bq y/kg per Bq/m**2]
STV, radioecological sensitivity, pork, 0

DOPORK [Sv]
STV, contribution from consumption of port to the total dose, 0

REPORK STV, relative contribution to the total dose, pork, 0

FODDER [Bq/kg]
STV, radionuclide concentration in the total fodder for the cow, 0

TEND [d]
Time at which a simulation will end, 1400

DTPL is the time step on which simulated values are stored for plotting or printing, 10

DT [d]
Length of time step for the first block of differential equations, 1

DTC [d]
Length of time step for the second block of differential equations, .1

DAY LV, 0

BDILU LV, 0

EXCR LV, 0

URIN LV, 0

AIN [FU]
Total number of fodder units in the cows diet, 16

GRASAC LV, 0

MILKAC LV, 0

BEEFAC LV, 0

SDEP [Bq/m**2]
Radionuclides deposited fraction to soil, 0

PDEP [Bq/m**2]
Radionuclide deposited fraction to grass, 0

BDEP [Bq/m**2]
Radionuclides deposited fraction to beet leaves, 0

AIR [Bq/m**3]
Contribution to radionuclide concentration in the air from resuspension, 0

DEP LV, 0

INH [Bq/0.1day]
Inhalated radionuclides, cow, 0

HARVST Harvest time for cereals, 0

CRC [Bq/kg plant per Bq/kg soil]
Concentration ratio, cereals, .02

FVV Interception factor, leafy vegetables, .25

VEGDEN [kg/m**2, fresh weight]
Density of leafy vegetables, 1.5

VEGCUT Harvest time for leafy vegetables, 0

VEGCON LV, 0

DBV [Kg/day]
Growth rate for leafy vegetables, 0

VDILUS LV, 0

VDILU LV, 0

VEGEM Time when the leafy vegetables emerge, 0

BROTAC LV, 0

RBRTAC LV, 0

WBRTAC LV, 0

VEGAC LV, 0

FRUHAR Harvest time for fruit, 0

Y3 LV, 0

YST1 LV, 0

YST2 LV, 0

PFOD [Bq/(0.1day)]
Total radionuclide concentration in pigs fodder, 0

CERQ [kg]
Daily amount of cereals in pigs fodder (one tenth), .1

WHEY [l]
Daily amount of skimmed milk in pigs fodder

TMC [1/day]
Transfer coefficient (TC) for periodic slaughter, cow, .000047

PIMILK LV, 0

I LV, 0

J LV, 0

M LV, 0

M LV, 0

DBS [Kg/day]
Growth rate for grass, 0

CR [Bq/kg plant per Bq/kg soil, dry weight]
Concentration ratio for grass, .3

DBB [Kg/day]
Growth rate for beet leaves, 0

CRB [Bq/kg plant per Bq/kg soil]
Concentration ratio for beets, .3

K0220 [Bq/kg plant per Bq/kg soil]
Concentration ratio for beet leaves, 1.17

XR [m]
Depth of root zone, .25

PS [Kg/m**3]
Soil bulk density, 1400

K3 [1/day]
TC, fixation in the root zone, .001

K23 [1/day]
TC from upper soil layer to root zone, .00063

K52 LV, 0

FA Fraction of surficial deposit absorbed into plant, .05

LA [1/day]
Physical decay constant, .000063

FV Interception factor, grass, .3

V [m/day]
Dry deposition velocity, 172.8

W Washout ratio, 1000000

REGN [m/day]
Daily amount of rainfall, 0

WHB [1/day]
Weathering constant, beet leaves, .08

FVB Interception factor, beet leaves, .25

RF [1/m]
Final resuspension factor, 1E-09

FS Fraction deposited on the soil, .7

CETCON LV, 0

WHV [1/day]
Weathering constant, vegetables, .08

VDEP [Bq/m**2]
Radionuclide deposited fraction to vegetables, LV

CRV [Bq/kg plant per Bq/kg soil]
Concentration ratio, leafy vegetables, .5

CEREA1 LV, 0

YO LV, 0

PORKAC LV, 0

K1011 [1/(0.1day)]
TC from stomach to intestines, cow, .07

LA1 [1/(0.1day)]
Physical decay constant, .0000063

K1210 [1/(0.1day)]
TC from lungs to stomach, cow, .246

KS [1/(0.1day)]
TC for soil consumption, cow, .03

KEX [1/(0.1day)]
TC for excretion from intestines, .5

K1113 [1/(0.1day)]
TC from intestines to circulating fluids, cow, 1.48

K1213 [1/(0.1day)]
TC from lungs to circulating fluids, cow, .154

KIH [m**3/(0.1day)]
Inhalated amount of air, cow, 13

K1314 [1/(0.1day)]
TC from soft circulating fluids to soft tissue, .0035

K1315 [1/(0.1day)]
TC from circulating fluids to soft tissue, .011

K1316 [1/(0.1day)]
TC from circulating fluids to udder, .018

KEXB [1/(0.1day)]
TC, excretion from circulating fluids, urin, cow, .07

K1413 [1/(0.1day)]
TC from soft tissue to circulating fluids, .003

K1513 [1/(0.1day)]
TC from soft tissue to circulating fluids, .04

KM [1/(0.1day)]
TC from udder to milk production, .4

DILU [Kg/day]
Growth dilution for grass, 0

WH1 [1/day]
First weathering constant, grass, .099

WH2 [1/day]
Second weathering constant, grass, .023

BEETEM Time when the beets emerge, 0

BEETUP Harvest time for beets, 0

ANSWER LV, 0

BDILUS LV, 0

SIDAY Harvest time for grass used for silage production, 0

MILKPR [1/day]
Milk production per day, 18

BEEFPR [kg/day]
Beef production per cow, 270

TIMBEG First day of restrictions when cows are stabled during a pastu-
ring season, 0

TIMEND Last day of restrictions when cows are stabled during pasturing season, 0

TPAST The first day cows are on pasture, 0

TSTABL The last day cows are on pasture, 0

SILAR Silage rate during winter, 0

BEETR Beet rate during winter, 0

MASHR Rate of mash or concentrate during winter, 0

FBEET First day cows get fresh beets at the end of pasturing season, 0

SILAC LV, 0

BEETC LV, 0

MASHC LV, 0

FVG [FU/kg dry weight]
Fodder unit in pasture grass, 1.2

ADFOD Rate of concentrate in the fodder for cows, 0

ADFODC [Bq/FU]
Estimated radionuclide concentration in concentrate, 0

EVENT Time of a single event, 0

GROCOR LV, 0

ZERO LV, 0

FRUAC LV, 0

DF [Sv/Bq]
Dose factor, 1.4E-08

KLG [1/(0.1day)]
TC from lungs to intestines, pig, .246

KLC [1/(0.1day)]
TC from lungs to circulating fluids, pig, .154

TMP [1/(0.1day)]
TC for periodic slaughtering,pig, .00067

INHP [m**3/(0.1day)]
Inhalated amount of air, pig, .864

KGC [1/(0.1day)]
TC from intestines to circulating fluids, pig, 1.48

KS1 [1/(0.1day)]
TC from circulating fluids to soft tissue, pig, .4

KS2 [1/(0.1day)]
TC from circulating fluids to soft tissue, pig, .0035

KST1 [1/(0.1day)]
TC from soft tissue to circulating fluids, pig, .04

KST2 [1/(0.1day)]
TC from soft tissue to circulating fluids, pig, .003

KGE [1/(0.1day)]
Excretion from intestines, pig, .2

KCE [1/(0.1day)]
Excretion from circulating fluids, pig, .07

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Abstract (Max. 2000 char.)

The transfer of radionuclides in the terrestrial environment have been investigated. The thesis is divided into two parts. Part I; Dynamic model for the transfer of radionuclides in the terrestrial environment. The study comprises the development of a compartment model, that simulates the dynamic transport of radioactive pollution in the terrestrial environment. The dynamic processes include, dry and wet deposition, soil resuspension, plant growth, root uptake, foliar interception, animal metabolism, agricultural practice, and production of bread. The ingested amount of radioactivity, by man, is multiplied by a dose conversion factor to yield a dose estimate. The dynamic properties and the predictive accuracy of the model have been tested. The results support the dynamics very well and predictions within a factor of three, of a hypothetical accident, are likely. Part II; Influence of plant variety on the root transfer of radiocaesium. Studies of genetic differences, in plant uptake of radiocaesium, were concluded with a pot experiment. Four varieties of spring barley and three varieties of rye-grass have been tested in two types of soil. The results for barley showed a significant difference between the four varieties. Analyses of variance confirmed a high root uptake of radiocaesium in the variety Sila and a significantly lower root uptake in the variety Apex in each type of soil. The pattern between the varieties was identical in 1988, 1989 and 1990. Similarly for the grass varieties, one variety, the Italian rye grass, was identified as having the relatively highest uptake of radiocaesium.

Descriptors – INIS

BARLEY; CESIUM 134; CESIUM 137; DOMESTIC ANIMALS; FOOD CHAINS; MATHEMATICAL MODELS; RADIOECOLOGY; RADIONUCLIDE MIGRATION; ROOT ABSORPTION; SEASONAL VARIATIONS; SIMULATION; SOILS; STRONTIUM 90; TERRESTRIAL ECOSYSTEMS

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