Assessing Internal Exposures and the Efficacy of Countermeasures from Whole Body Measurements

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ABSTRACT. Traditional procedures for modelling the ingestion dose pathway combine environmental transfer models with human metabolic models in order to assess the doses received. In general, these models have been developed for specific ecological and socio-economic circumstances, rather than for globally-averaged conditions. Experiences which occurred following the Chernobyl accident have demonstrated that in the event of a large scale radiation accident it will be virtually impossible to monitor adequately all the radiologically significant components of human diet which may have become contaminated with radionuclides.

This paper describes an internal dosimetry model based on the most widely available measurements following an accident: radiocaesium measurements in soil and milk, and whole body measurements in humans. One application of the model to estimate ingestion doses received by inhabitants of the northern region of the Rovno Oblast in Ukraine is also described. In addition, this model enables the effectiveness of food countermeasures to be estimated.

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INTRODUCTION

Following the accident at Chernobyl, a very wide area of territory in Russia, Belarus and Ukraine became contaminated with radionuclides. In order to estimate ingestion doses received by the inhabitants of these areas, a large database of measurements is required as input to the environmental and metabolic models utilised. These data must be representative of the wide range of ecological conditions in the contaminated areas and must also adequately reflect the habits of individuals in these regions, if dose assessments are to be realistic. The data commonly utilised are radionuclide concentrations in soil and food, and food consumption rates. It is also necessary to determine the proportion of diet which is obtained from local sources, since studies undertaken as part of Joint Study Programme 5 (JSP5) on pathway analysis and dose distributions, have shown that locally-produced foods contribute to the majority of the radiocaesium intake in the contaminated territories[1].

For post-accident management, it is necessary to be able to estimate the radiation doses received or being received as quickly as possible. It is therefore important to develop alternative approaches to dose estimation which do not place such emphasis on large measurement data sets.

Such approaches usually rely on a range of whole body measurements (WBM) to 'anchor' the dose model results, but otherwise they can be tailored to require as input data only those measurements which exist or can reasonably be provided, given the nature of the post-accident situation. Within Task 4 of JSP5[1] , a model for estimating average regional ingestion doses has been developed based on only the three most commonly recorded types of measurement: soil contamination, privately produced milk concentrations and WBM. This paper will outline the basis of the model, describe its structure and its mechanism for determining the effectiveness of countermeasures. One application of the model will then be described: the region under study being the area encompassing the northern part of the Rovno Oblast.

MODEL OVERVIEW

The schematic structure of the model is outlined in Figure 1. In summary, the model consists of two parts. The first part employs a simple phenomenological approach to estimate doses, but uses the concept of 'milk equivalent intake' to reduce the need for detailed data on consumption rates and radionuclide concentration levels for all foods. It is well established that the consumption of locally produced milk is the major contributor to the average regional dose, in the contaminated territories[2]. In the model the following two assumptions are made: that, in the absence of knowledge of the accident, dietary habits would remain unchanged; and that, for a given region, the time variation of food concentration has been similar in form for all foods. For the last to be true, measurement data should not be aggregated across areas with widely differing soil types, although it may be assumed that relative food concentrations are the same between different soil types. In addition, ideally, the region either should not have been subject to agricultural countermeasures, or such countermeasures should have been applied with equal effect to all the land from which food has been obtained. However, since the consumption of locally produced milk is the dominant exposure pathway, the selective implementation of agricultural countermeasures will only have a small influence on the validity of this assumption. Based on these assumptions, information on consumption rates prior to the accident, and knowledge of the radionuclide concentrations in all the foods of interest for a typical part of the region and a single representative time period, it is possible to determine the relative contribution of all parts of the average diet to the total dietary intake of caesium-137. From this, the equivalent consumption of locally produced milk can be determined that would exactly reproduce the calculated total intake of caesium-137. In the model, this is termed the 'absolute milk equivalent'. This absolute milk equivalent, together with information on the time variation of the concentration in locally produced milk, can then be used to estimate the intake of caesium-137 throughout the region and time period. This is termed the 'reference' intake.

The second part of the model uses WBM to estimate the actual or real intake of caesium-137. This 'real' intake can be compared with the reference intake and, provided the assumptions made in the calculation of the absolute milk equivalent were valid, the difference between the two is a measure of the influence of people's modified dietary behaviour in response to the accident.

In both parts of the model it is necessary to make an allowance for the contribution to average dose from foods obtained from outside the area. This contribution arises from several sources, including the wide official distribution of foods produced in contaminated regions across Ukraine, (to prevent their concentrated consumption by a few individuals), and foods illegally entering the market. This component can be estimated from the caesium body burdens of people living well away from the contaminated regions. This information can be combined with a knowledge of the fraction of diet obtained from 'imported' foods to provide an estimate of the intake of radiocaesium from this component of diet.

Detailed description of model

Among the inhabitants of a given settlement it is possible to single out some i subgroups (i = 1,...,n), which are distinguished by their type of diet. Typical subgroups include infants, children younger than seven years, children 7 - 15 years old, teenagers 15 - 18 years old, and several adult groups (*eg.* employed indoors, agricultural workers, pensioners). *The total diet* W_i, of the members of i-th group may be represented as:

$$W_i = \sum_j w_{ij} \tag{1}$$

where w_{ij} is the consumption rate (kg or L d^{-1}) of the j-th food-component in the diet of members of group i. Usually the diet consists of two parts: that which is locally produced and that which comes from other areas. With the locally produced fractions denoted by f_{ij}, eqn (1) may be rewritten as:

$$W_i = \sum_j f_{ij}\, j_{ij} w_{ij} + \sum_j (1 - f_{ij}) w_{ij} \tag{2}$$

In contaminated territories the first term, representing locally grown food, is more important.

If the ^{137}Cs concentration in the j-th component of locally-produced diet is c_j, then the intake of ^{137}Cs, q_i, in the total diet for members of the i-th group is:

$$q_i = \sum_j c_j f_{ij} w_{ij} \tag{3}$$

The value of c_j may be determined as the product of the parameters σ_{sj} and k_{sj} where σ_{sj} is the level of deposition on the s-th field or pasture where the j-th food or pasturage is produced, and k_{sj} is defined as the "*j-th transfer factor*", which is determined as:

$$k_{sj} = \frac{c_j}{\sigma_{sj}} \tag{4}$$

Since the value of k_{sj} (and, accordingly, the value of c_j) changes with time, the intake function q_i is also a function of time. Thus, combining eqns (3) and (4), the intake function for the i-th group is:

$$q_i(t) = \sum_j k_{sj}(t)\sigma_{sj} f_{ij} w_{ij} \tag{5}$$

Eqn (5) describes the time-dependent ^{137}Cs-intake function for the group of people living on the contaminated territory, if the style of life (diet and agricultural practices) has not changed after the accident. This function may be calculated, if detailed information on all parameters is available.

Reference parameters of the model

In actual situations it is practically impossible to obtain detailed, valid information about thousands of communities, or even to obtain detailed information for one community for the values of σ_{sj}, k_{sj} and f_{ij}. Thus, it is important to introduce a system of generalised, reference indexes of the radiation situation for a single settlement, and to consider the primary dosimetric variables relative to the reference values. The average (for the settlement and its environs) ^{137}Cs-deposition density, σ_0 is used as the primary reference index, where:

$$\sigma_0 = \frac{\sum_{sj} \sigma_{sj}}{n} \tag{6}$$

and n is number of measurements for σ_g for each settlement. For the parameter σ_g we will use the term *"reference ^{137}Cs-soil deposition"*. It is also useful to modify the previous definition [eqn (4)] of the transfer factor and to introduce the term *"reference transfer factor"* k_j^0 for the j-th locally produced food:

$$k_j^0(t) = \frac{c_j(t)}{\sigma_0} \tag{7}$$

Parameter $k_j^0(t)$ represents the main transfer between Compartments 1 and 2.
Now eqn (5) may be rewritten as:

$$q_i(t) = \sigma_0 \sum_j k_j^0(t) f_{ij} w_{ij} \tag{8}$$

The ^{137}Cs-intake function, $q_i(t)$, which results from the ingestion of contaminated foods in the case where no limitations and countermeasures had been taken ("people knew nothing about the accident") is noted as the "*reference-intake function*" q_i^0. Equations (4) and (8) determine the ^{137}Cs flow with the total diet. But in the actual situation of a large-scale accident, usually only one or a few diet components can be measured reliably over large territories. In practice, in Ukraine following the Chernobyl accident, only the ^{137}Cs concentration in milk was well characterised. If the average individual consumption rate of milk by persons in group i is $w_{i,m}$ litres per day (m is used here and below to denote milk), $f_{i,m}$ is the part of milk locally produced, and the ^{137}Cs contamination of locally produced milk is $c_m(t)$, the total intake of ^{137}Cs with milk is:

$$q_{i,m}(t) = c_m\,(t)_0\,f_{i,m}\;w_{i,m} \tag{9}$$

Further, the *relative milk equivalent*, $p_{i,m}(t)$ is defined as the ratio of ^{137}Cs intake with the whole diet to that consumed with locally produced milk alone:

$$P^0_{i,m}(t) = \frac{q^0_i(t)}{q_{i,m}(t)} \tag{10}$$

Then,

$$P^0_{i,m}(t) = \frac{\sum\limits_j c_j(t)f_{ij}\;w_{ij}}{c_m(t)f_{i,m}\;w_{i,m}} \tag{11}$$

The parameter $P^0_{i,m}(t)$ is non-dimensional and is greater or equal to one. Now, the term "*whole diet absolute milk equivalent*", defined in the model overview, $w^0_{i,m}(t)$ may be introduced as:

$$q^0_i(t) = c_m(t)w^0_{i,m}(t) \tag{12}$$

where

$$*w^{0}_{i,m}(t) = p^{0}_{i,m}(t)f_{i,m}\, w_{i,m} = \sum_{j} l_{j,m}(t)f_{ij}\, w_{ij} \qquad (13)$$

In Equation 13 the term $l_{j,m}(t) = \frac{c_j(t)}{c_m(t)}$ is the function of ratio of ^{137}Cs concentrations in the j-th component of diet to one in milk. Absolute milk equivalent $w^{0}_{i,m}(t)$ is equal to the amount of locally produced milk that could be consumed to provide the value of $q_i(t)$ with the whole diet.

In reality after the Chernobyl accident food production in the contaminated areas was not stopped. Instead, the produced foods (butter, sour cream, meat and others) were distributed to the other less contaminated territories. For this reason, some low level of food contamination existed throughout the whole country, and resulted in both the so-called "*imported ^{137}Cs-food contamination*" $c_{j,imp}$ and a permanent (background) level of ^{137}Cs body burden Q_{bac}. The imported ^{137}Cs-food contamination may be expressed as:

$$q_i(t) = q^{0}_{i}(t) + q_{i,imp}(t) \qquad (14)$$

where $q_{i,imp}(t) = \sum_{j} c_{j,imp}(t)(1 - f_{ij})w_{ij}$ represents the intake of ^{137}Cs resulting from the consumption of imported food, $c_{j,imp}(t)$ is the ^{137}Cs concentration in the imported fraction of the j-th component of diet. If $q^{0}_{i}(t)$ is known, the corresponding committed effective dose, $D^{0}_{T}(t)$ *("reference dose")* due to ^{137}Cs intake up to time T after the accident for members of group i is derived from $q^{0}_{i}(t)$ as:

$$D^{0}_{i,T} = K_i \int_{0}^{T} q^{0}_{i}(t)dt \qquad (15)$$

where K_i***(Sv Bq^{-1}*ingested)** is the effective dose-coefficient for group i.

Countermeasures

The main food countermeasures implemented in Ukraine were the partial or complete replacement of locally produced foods with ones produced in relatively clean areas. These countermeasures were initiated both by the government, which organised deliveries of "clean" foods, and by individuals, who modified their own diets. Food replacement is considered in the model by the introduction of the *food-replacement function,* $h_{ij}(t)$, which is equal to or less than one and which characterises the decreased consumption of locally produced food as a result of countermeasures. Let the function $q_i^0(t)$ modified by $h_{ij}(t)$ be denoted by $q_i^*(t)$ and termed the "*countermeasure intake function*". Thus,

$$q_i^*(t) = \sum_j c_j(t)\, h_{ij}\, (t)\, f_{ij}\, w_{ij} \tag{16}$$

As above, *the countermeasure whole diet absolute milk equivalent* $w_{i,m}^h(t)$ can be introduced as:

$$q_i^*(t) = c_m(t) h_{ij}(t) w_{i,m}^h(t) \tag{17}$$

where $w_{i,m}^h(t)$ is the daily consumption of locally produced milk that would equal the ^{137}Cs intake with whole diet when the countermeasures take place.

If countermeasures were realised, the *countermeasure committed effective dose,* D_T^* , is calculated as follows:

$$D_{i,T}^* = K_i \int_0^T q_i^*(t) dt \tag{18}$$

Effectiveness of the countermeasures

There are two important considerations that must be discussed in order to define the effectiveness of countermeasures. First, it must be decided whether the degree of effectiveness is the achieved decrease in the contamination level of the food crops produced in the area under consideration, or whether it is the decrease in the internal dose received by the subpopulation of interest. Second, if reduced dose is the accepted criterion, it is necessary to determine exactly in which subpopulation the dose decreased, *ie.* the inhabitants of the settlement where these foods were produced or, if these foods were distributed via a system of governmental purchasing and redistribution, the inhabitants of the whole area or country. Here the reduction of dose is considered by the authors as the main criterion of the effectiveness of countermeasures. Moreover, the Chernobyl experience has shown that, from the point of view of dose, the exact consumption rates of the locally produced foods are critical; and the critical subpopulation is the inhabitants of the rural settlements where these foods are produced and consumed. So, the *dose effectiveness of countermeasures* for the members of group i up to time *T* after the accident may be characterised by a coefficient $H_{i,T}$, which is the ratio of the reference and countermeasure committed effective dose up to time *T*:

$$H_{i,T} = \frac{D^{0}_{i,T}}{D^{*}_{i,T}} \tag{19}$$

In addition, *the function of countermeasure effectiveness, $H_i(t)$,* which characterises the relative decrease with time of the intake of ^{137}Cs due to the countermeasures is defined as:

$$H_i(t) = \frac{q^{0}_{i}(t)}{q^{*}_{i}(t)} = \frac{\sum_j c_j(t) f_{ij} w_{ij}}{\sum_j c_j(t) h_{ij}(t) f_{ij} w_{ij}} = \frac{w^{0}_{i,m}(t)}{w^{h}_{i,m}(t)} \tag{20}$$

APPLICATION OF MODEL

This ingestion dose model has been applied to one region within Ukraine, to illustrate some of the information that can be derived from it. The region chosen is the area encompassing the northern parts of the Rovno oblast. This is a predominantly rural area of low economic status, in which fallout from Chernobyl was relatively low, but the soil-to-milk transfer coefficient is frequently high. All these factors combine to make the potential dose from ingestion higher than that from external exposure. For application of the model, the region has been divided into three sub-regions, according to the effective soil-milk transfer factor. The sub-regions were defined as follows: soil-milk transfer factors of 1-5 Bq/l per kBq/m^2, 5-10 Bq/l per kBq/m^2 and >10 Bq/l per kBq/m^2.

The absolute milk equivalent consumption rate and other consumption rate data appropriate to the region are available[3,4,5] as shown in Table 1. The dietary data are for a year before the Chernobyl accident, and therefore, before people's dietary behaviour was modified in response to the accident. By combining all these data, it can be shown that the predominant ingestion dose pathway for average dose is privately produced milk. This is indicated in the final column of Table 1. No other single foods make a major contribution; the remaining intake is spread over a wide range of foods. Therefore, for the estimation of average potential dose in this region, it is reasonable to assume that normal variations in the relative concentrations foods and in relative consumption rates can be neglected, so long as the concentration and consumption rate of privately produced milk is well-characterised. As indicated in the final column of Table 1, assuming the statistics on locally produced milk consumption are reliable, the average potential intake of caesium-137 from total diet can be assumed to be equivalent to 1.6 l/day of locally produced milk.

Food	Concentration relative to milk	Consumption rate (kg/day)	Local fraction	Component of caesium-137 intake (kg/day)
Milk	1	0.9	1	0.9
Milk products	0.4	0.2	0.6	0.092
Beef	3.5	0.01	0.01	0.0035
Pork	0.9	0.016	1	0.144
Wild game	9	0.002	1	0.018
Poultry	1.5	0.01	1	0.015
Potatoes	0.08	0.35	1	0.08
Leafy vegetables	0.5	0.09	1	0.045
Grain (bread)	0.001	0.4	0.01	-
Mushrooms	10	0.02	1	0.2
Fish	2	0.038	1	0.076
Milk equivalent				1.6

Table 1 Dietary components of adult caesium-137 intake for rural areas of Rovno oblast

The model also includes the possibility of a correction to the reference intake to allow for contamination in imported foods. Table 2 gives whole body measurements made on individuals in Kiev (ie individuals not obtaining their diet from locally produced foods) over a period of several years. From these whole body measurements total intakes of caesium-137 from imported foods can be inferred. From Table 1 it is clear that less than 20% of the average diet in Rovno oblast came from outside of the local area in the years preceding the Chernobyl accident. Therefore, the total potential intake of caesium-137 can be obtained (conservatively) as the sum of the reference intake determined from the absolute milk equivalent and the intake determined for individuals living in Kiev.

Year	Number of measurements	Geometric mean (Bq)	Geometric standard deviation
1986	220	850	6.3
1987	62	740	5.1
1988	752	560	1.6
1980	726	480	1.6

Table 2 Body burdens of caesium-137 in Kiev residents

The real intake of caesium-137 by adults, as a function of time, can be inferred from whole body measurements. This real intake function is compared with the reference intake function in Fig. 2 for the three sub-regions of the Rovno region studied. It can be seen that at all times the reference intake exceeds the real intake. If all the model assumptions are valid, it follows that the only reason for this difference is the modification of people's dietary habits in response to the accident (in particular, the substitution of locally produced milk with imported milk).

In order to explore this further, the ratio of the reference intake function to the real intake function, $H_{adult,real}(t)$, was computed. This function was fitted by the following formula:

$$H_{adult,real}(t) = L\,e^{\lambda_h t} \tag{21}$$

where L and λ_h are constants, and t is the time after the accident. These parameters characterise both the level and the change with time of the countermeasures. In addition, the effective half-time (in years) of countermeasure introduction, T_h, can be defined:

$$T_h = \ln 2 / (365\lambda_h) \tag{22}$$

In Table 3 the values of these parameters are given for each sub-region. It can be seen that, at early times after the accident, measures to modify dietary habits were most successful in areas with an intermediate soil-milk transfer factor (highest value of L). This is most likely to be related to practical aspects, for example, the quality of roads etc for transporting substitute milk supplies to the settlements. However, in those areas where initial measures were less effective, the half-times of countermeasure introduction are relatively shorter. This can be interpreted as rapidly increasing effort being applied to making the countermeasure effective in those areas where initially it was not effective. This is something that warrants further investigation.

Milk-soil factor (Bq/l per kBq/m^2)	L	λ_h (days^{-1})	T_h (years)
1-5	1.9 ± 0.7	$(10.2 \pm 3.7)\ 10^{-4}$	1.9
5-10	6.9 ± 6.1	$(2.6 \pm 5.9)\ 10^{-4}$	7.3
>10	3.1 ± 1.6	$(4.4 \pm 3.9)\ 10^{-4}$	4.3

Table 3 Effectiveness of countermeasures: parameter values from the model

By comparing the reference and real intake functions, it is possible to calculate the average individual ingestion doses that have been averted by changes in dietary behaviours. These are shown in Table 4 for the three defined areas and integrated to various times after the accident. The effectiveness of such countermeasures, particularly in the areas with an intermediate value of soil-milk transfer factor and within the first year of the accident is clear.

Soil-milk transfer factor	Integration Time Relative to Time of Accidents, y		
(Bq/1 per kBq/m^2)	0-1	0-4	0-6
1-5	2.4	3.6	4.2
5-10	7.2	8.1	8.5
>10	3.4	4.1	4.5

Table 4 Estimated average individual ingestion doses averted by changes in diet in northern regions of Rovno oblast, mSv

Conclusions

In conclusion, ingestion is potentially a very significant exposure pathway for caesium-137 following an accident. Owing to the rural structure and lifestyle in much of the contaminated territories, the consumption of local produce forms a major part of the diet. The uneven pattern of contamination and the varying availability of some local foods (eg forest produce) means that it is difficult to predict the doses that will be received in settlements based on consumption rates and food concentrations, without detailed knowledge of each settlement. However, regional average consumption rates are presented to enable the order of the doses to be predicted.

Once whole body measurements have been made, it is possible to develop models which estimate doses already received with much improved accuracy. The model described sucessfully compares the 'real' intake function derived from whole body measurements with that predicted from consumption rates appropriate to the years prior to the accident and food concentrations (the reference intake function) to provide good estimates of the internal doses received by a population. This modelling and comparison procedure enables an analysis, among other things, of the effectiveness of countermeasures. It is clear that the substitution of local milk with clean milk imported from uncontaminated areas has resulted in a very substantial reduction in the exposure resulting from ingestion.

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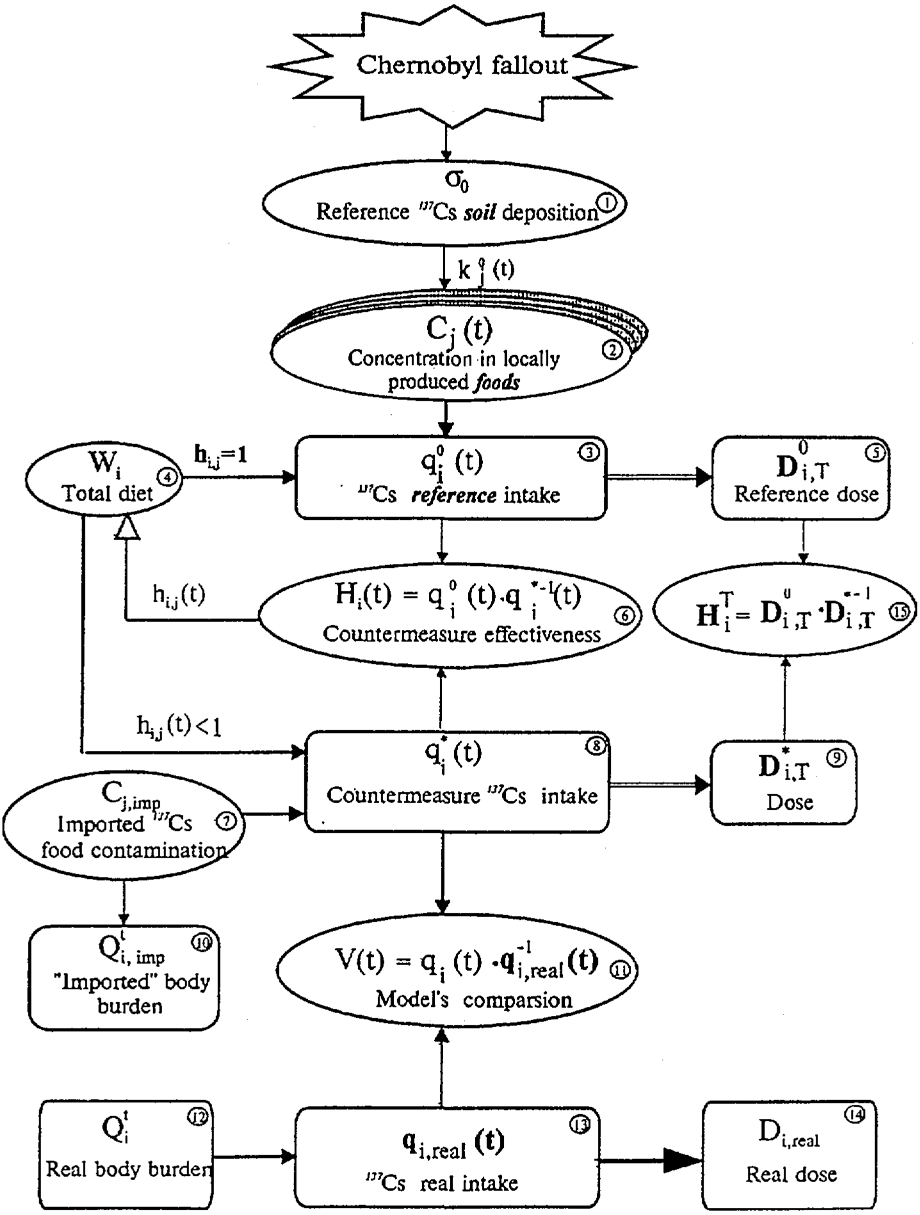

Figure 1: Schematic structure of the model

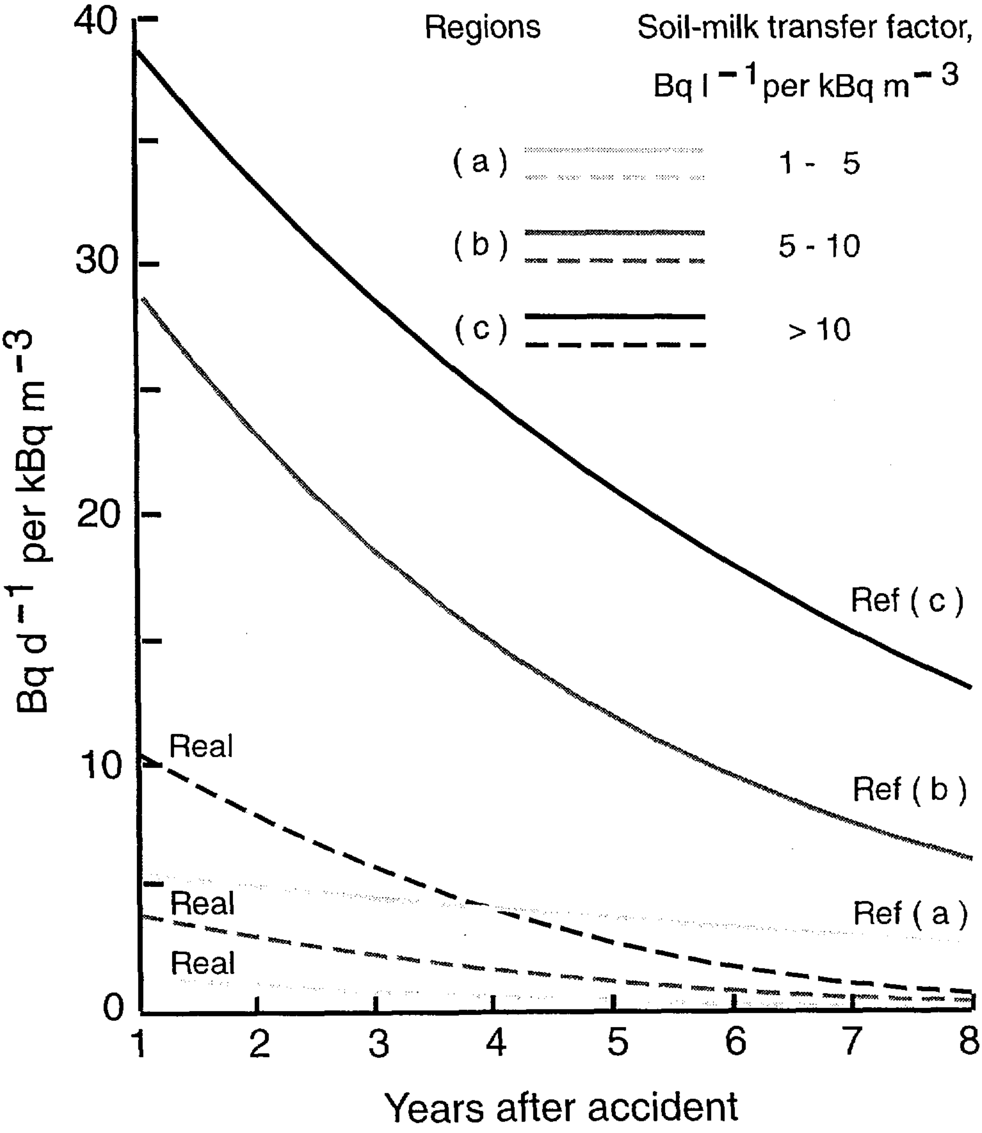

Figure 2: Real and reference intake functions