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Preliminary Investigations of the Significance of the Ingestion Pathway Following Accidental Releases with Actinides

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Vorläufige Untersuchungen zur Bedeutung des Ingestionspfades bei unfallbedingten Freisetzungen mit Aktiniden

Kurzfassung

Im Rahmen des Vertrages mit der Europäischen Gemeinschaft "Methods for Assessing the Radiological Impact of Accidents" (CEC-MARIA) wurden mit dem Rechenprogramm UFOMOD vorläufige Unfallfolgenrechnungen durchgeführt, um die Bedeutung des Ingestionspfades bei einer unfallbedingten Freisetzung mit Aktiniden zu untersuchen. Dabei wurde die Freisetzungskategorie K1 der "Risikoorientierten Analyse zum SNR-300" zugrunde gelegt, bei der ein höherer Anteil an Aktiniden freigesetzt wird als bei der größten Freisetzungskategorie eines LWR. Die Untersuchung wurden mit dem bisher implementierten Nahrungskettentransportmodell WASH-1400/BSU und mit Daten des dynamischen Modells des Unfallfolgenmodells MARC ausgeführt. Um den Einfluß des Unfallzeitpunktes auf die ingestionspfadbezogenen Ergebnisse zu untersuchen, wurden anhand der MARC-Daten Freisetzungen im Januar und Juli betrachtet.

Dieser Bericht stellt die Unterschiede dar, die sich zwischen den beiden Nahrungskettentransportmodellen für Transurane sowie bei den potentiellen Ingestionsdosen, den von Verzehrverboten betroffenen Flächen und den Spätschäden durch die Verwendung beider Modelle und den Einfluß saisonaler Effekte ergeben.

Abstract

Within the frame of the contract with the European Community "Methods for Assessing the Radiological Impact of Accidents" (CEC-MARIA) preliminary accident consequence assessments have been performed with the computer code UFOMOD to study the significance of the ingestion pathway in accidental releases with actinides. The investigation was based on the release category K1 of the "Risk Oriented Analysis of the SNR 300", in which a higher fraction of actinides is released than in the worst release category for an LWR. The analysis was carried out using the currently implemented foodchain transport model WASH-1400/BSU and data from the dynamic model from the MARC methodology. To study the influence of the time of the accident on the foodchain-related results, releases in January and July were considered by means of the MARC data.

In this report the differences are presented between both foodchain transport models for transuranium elements and those which are observed in the potential individual doses due to ingestion, the areas affected by food-bans and the late health effects when using both models and taking the influence of the season into account.

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1. Introduction

In the accident consequence model UFOMOD /1/ of the GERMAN RISK STUDY /2/ the model currently in use to estimate the radiation exposure from the ingestion pathway is that of the U.S. Reactor Safety Study WASH-1400 /3/, in which only radioisotopes of iodine, strontium and caesium are considered. Within the modifications of the accident consequence model for the "Risk-oriented analysis of the German prototype fast breeder Reactor SNR-300" /4/ the ingestion pathway model has been extended by the BSU-model /5/ to include transuranium elements. Apart from this modification it remained the simple model type of the earlier analyses.

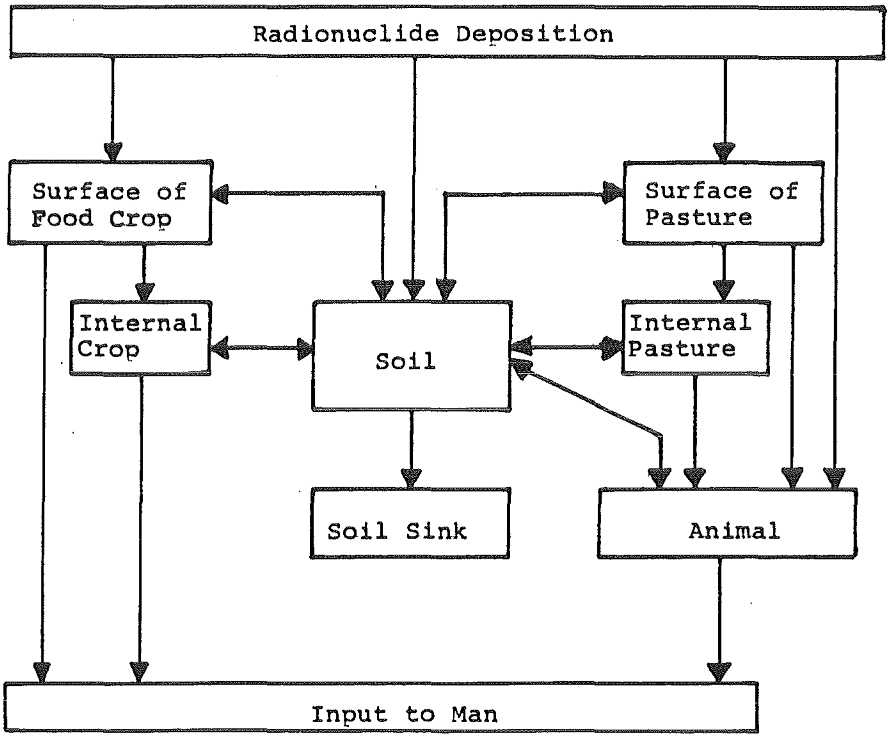
Several more sophisticated models have been developed after WASH-1400 to describe the transfer of radioactive material through terrestrial foodchains, for instance, the NRPB-model FOOD-MARC (UK) /6,7/ and the GSF-model ECOSYS (FRG) /8/. Both FOOD-MARC and ECOSYS represent the type of models which describe the transport of activity through the terrestrial environment to food by first order kinetics between interconnected compartments and can cover a wide range of radionuclides and foodstuffs. In comparison to the WASH-1400 model they have the principal advantage to allow for the possibility of accidental releases at different times of the year and an explicit treatment of the time dependence of the activity transport necessary for a detailed analysis of agricultural consequences.

A first analysis of possible differences in accident consequences assessed with UFOMOD when using data from equilibrium and dynamic foodchain transport models and taking seasonal effects into account has been described in an earlier study for accidental releases for LWRs /9/. These investigations have been continued for releases with considerable fractions of transuranium isotopes as they are described in probabilistic safety analyses of fast breeder reactors. The study is based on the release category K1 of the "Risk-oriented analysis of the SNR-300", which is characterized by an actinides release of 5% of the core inventory.

In the main text of this report, the differences in the foodchain-related results of assessments of the consequences following an assumed K1-release are discussed which are observed when using the WASH-1400/BSU-model and data derived from FOOD-MARC in the computer code UFOMOD (Version B04). The seasonal variations were studied with the MARC-data, however, the time dependent aspects of FOOD-MARC could not be included in the investigations due to presently existing limitations in UFOMOD in this respect. Summaries of the foodchain transport models for the transuranium elements, BSU and FOOD-MARC, and a comparison of the intakes of actinides predicted by the two models are given in the appendices.

2. Basic features of the foodchain transport models considered

The major processes by which radionuclides are transferred through the terrestrial foodchains to man are illustrated in the diagram below:



When material is deposited on the ground a fraction is intercepted by and initially retained on the foliage of plants. This surface deposit can be removed by a variety of processes which are generally referred to as weathering or field losses and which lead to material being transferred to the soil. Some of the material on the plant's surface may be absorbed in the plant's tissues and translocated from one part of a plant to another, for example, from the foliage to the fruit or grain. Activity from the soil can be transferred to the internal plant through absorption via the root system, and to the external plant by wind driven resuspension processes, splashing due to rain fall etc. Activity can be removed from the soil by migration down the soil column and out of the root zone, or made unavailable for root uptake by fixation to some component of the soil material.

Animals can incorporate activity by consumption of grass or other fodder crops or inadvertant intake of soil and by inhalation of resuspended material. Radioactive material can be returned to the soil by excretion processes. After the harvest of plants or the slaughter of animals a decrease of activity in the food product may occur during storage, processing or kitchen preparation. Finally, man acquires radioactive materials by the ingestion of various types of agricultural produce.

The general principles of the transfer processes involved and different model approaches are described, for instance, in /10/. In this assessment, three models "WASH-1400", "BSU" and "FOOD-MARC" have been applied. Apart from model type and capability they are different with respect to the radionuclides and foodstuffs considered and in the assumptions about the agricultural practices. The basic features of the three models are briefly summarized in the following sections. A summary of the models BSU and FOOD-MARC for the transuranium elements is given in Appendix A and B.

2.1 WASH-1400 model

The WASH-1400 foodchain transport model /3/ was developed as a part of the U.S. Reactor Safety Study for assessing the consequences of LWR accidents and is adopted to American agricultural practice and consumption habits. It is widely used and represents the type of equilibrium models called "multiplicative", which use a number of factors to relate levels of radioactivity in the various components of the foodchain to man.

The processes leading to a contamination of vegetation considered are direct deposition with subsequent weathering and root uptake, and only isotopes of iodine, strontium and caesium are taken into account. The transfer of these nuclides to man via the milk-pathway is modelled explicitely, and also the transfer of strontium via green vegetables by direct deposition. For iodine it is assumed that milk is the only possible source of exposure by ingestion. The transfer of isotopes of strontium and caesium to man via all other agricultural products is calculated by applying scaling factors to the milk values. These factors are derived from observations of the behaviour of nuclear weapons fallout and describe the relative contributions of milk and other products to the total intake of activity by man.

The output of the model is in the form of "Concentration Factors", which give the total activity incorporated by an individual consuming milk and other products contaminated by direct deposition and root uptake following unit deposition. Due to the modelling described above the results obtained represent some form of averaging of the intake that would occur for depositions at different times of the year.

2.2 BSU model

The BSU model was developed by G. Schwarz and H. Bastek /5/ from BRENK SYSTEMPLANUNG, Aachen, with the intention of extending the original foodchain transport model in UFOMOD (i.e. the WASH-1400-model) to isotopes of neptunium, plutonium, americium and curium for accident consequence assessments of the SNR-300.

The deposition is assumed to occur at the peak of the growth cycle of the vegetation, and the removal of activity initially deposited on the plant's surfaces by weathering processes is modelled. The soil is represented by a well-mixed compartment, from which activity is lost by migration out of the soil column and by removal from the soil-plant-system due to harvesting or grazing by animals. The transfer of activity from the soil to the plants by root uptake or resuspension processes and the transfer from pasture grass ingested by cows to milk and meat is described by means of equilibrium transfer-coefficients. Losses of activity by kitchen preparation or other processing of the food are not accounted for.

The food-products considered are milk, meat and plant products, and continuous production and consumption is assumed. In analogy to the WASH-1400 model, Concentration Factors are derived for an intake in the first year and the subsequent years after the deposition.

2.3 FOOD-MARC

The foodchain transport model from the NRPB accidence consequence methodology MARC /11/ was originally designed for continuous routine releases and was further developed for application to accidental releases occuring at any time of the year[1].

The model is a dynamic model of the compartment type, in which the physical processes of the transfer of radionuclides through terrestrial foodchains are described by first order kinetics between compartments representing the different parts of the foodchain, i.e. the transfer of material between compartments is linearly proportional to the inventories of the source compartments. The soil is represented by a well-mixed soil compartment for ploughed land and by several compartments representing layers of different depth for pasture land. For the contamination of plants, compartments for direct deposition and weathering, translocation, resuspension processes and root uptake are included. Preparation losses are accounted for. To account for the intake of activity by animals, consumption of hay and silage, soil consumption and inhalation of resuspended activity are considered. The transfer of the activity ingested by the animals to milk or meat is described by a relatively complex model of the animal's metabolism.

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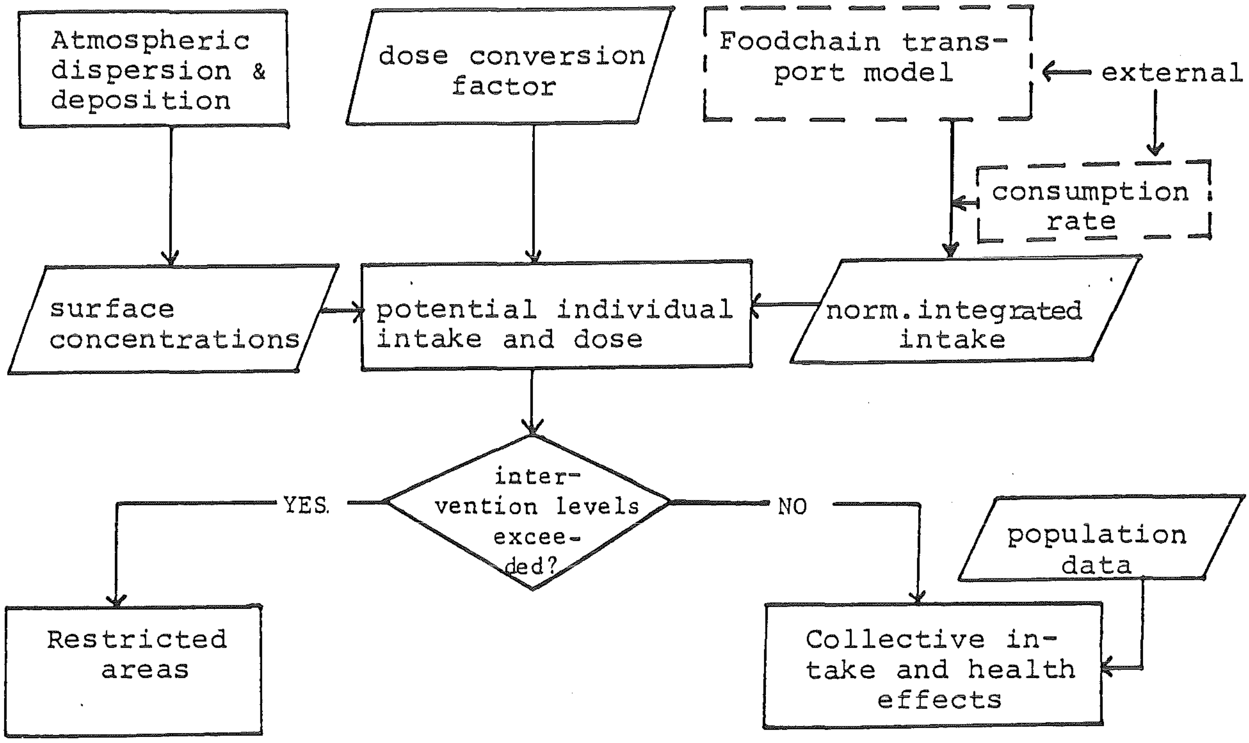
[1] A general description of the model is given in /6/. The model revisions to include seasonality effects are discussed in detail in /7/. A description of the (old) model for actinides can be found in /12/.

The output of the model is in the form of time-dependent concentrations and concentration integrals for various food products. The main foods considered in the model are green vegetables, grain products, milk and meat from cattle, and meat from sheep. Offals from cattle and sheep can also be included and a limited model exists for root crops. A large variety of nuclides can be included although the degree of detail in modelling is greatest for isotopes of caesium, strontium and iodine. The buildup of daughter-nuclides in food by radioactive decay chains can be taken into account.

3. Foodchain - consequence - model of UFOMOD

To evaluate the health effects resulting from ingestion of contaminated food, the actual intake of activity by individuals and in the population after an accidental release must be determined. How this is done in UFOMOD is illustrated by the following flowchart diagram:



In the atmospheric dispersion and deposition submodel the activity concentrations on the surface of the ground are calculated. These are input to the late health effects submodel, of which the foodchain pathway forms a part. In a first step the potential individual intake is calculated by multiplication of the surface concentration and the normalized integrated intake, that is, the activity incorporated by an individual consuming a particular food over a certain time following unit deposition. In estimating the individual intake, the assumption is made that all food consumed is produced locally. The radiation exposure is evaluated using dose factors which convert the ingested activity into organ doses[1].

In the current version of UFOMOD, the values for the normalized integrated intake are the "Concentration Factors" from the WASH-1400- and the BSU-model described in Chapter 2. For the comparative calculations, these Concentration Factors were replaced by integrated food concentrations from the foodchain transport model of MARC; apart from this modification everything remained the same (Chapter 4.2).

The collective intake is evaluated in UFOMOD on the basis of the individual intake by multiplying the spatial distribution of the individual intake with the spatial distribution of the population and integrating over all distances. This method has the advantage to provide information about the spatial distribution of the intake and with this on individual risk, but these values and the collective risk give only a rough estimate, because no agricultural production or food distribution patterns are taken into account. The evaluation of the health effects from the organ doses is described elsewhere /14/.

To keep the exposure of the population from ingestion within acceptable limits, intervention levels have been introduced at which interdictions will be placed on the consumption of contaminated food. In UFOMOD, these intervention levels refer to the potential doses accumulated in the total body, red bone marrow and the thyroid. The intervention levels currently implemented are:

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[1] The potential individual doses are calculated with dose factors taken from DOSE-MARC to account for an exposure accumulated over 50 years by an adult individual after a single intake of activity /13/.

Organ	Milk	Other Products
total body	$3.3 \cdot 10^{-2}$ Sv	$2.0 \cdot 10^{-2}$ Sv
red bone marrow	$3.3 \cdot 10^{-2}$ Sv	$2.0 \cdot 10^{-2}$ Sv
thyroid	$1.0 \cdot 10^{-1}$ Sv	-

The intervention levels are compared separately with the doses resulting from ingestion of milk and other products contaminated by direct deposition. If any one of the levels is exceeded, it is compared in addition with the doses resulting from intake of the corresponding food-category contaminated by root uptake. This is modelled within 540 km distance to the site, beyond this limit no restrictions are assumed to be imposed.

The modelling approach of UFOMOD described above is based on the U.S. Reactor Safety Study. Because the WASH-1400 Concentration Factors represent the total amount of activity transferred by direct deposition and root uptake, the countermeasure model is very crude and detailed information about the length of time the food-bans may need to be applied cannot be derived.

A more sophisticated model for the estimation of restricted areas and collective intake is implemented in the accident consequence code system MARC /15/. Although in MARC the countermeasure model is also based on the assumption of local production of the food consumed, the inherent time dependence of the foodchain transport models allows a detailed analysis of the duration of the required countermeasures. The collective intake is estimated using the actual spatial distribution of agricultural production and assuming that all contaminated food outside the restricted area is consumed by the whole population. This method gives a reasonable overall estimate of the collective intake, but the information about individual intake ranges is lost, unless food-distribution patterns are included.

4. Data used in the assessment

4.1 General data

The calculations were performed for the worst release category K1 determined for the German prototype fast breeder reactor SNR-300. This category was chosen because of the considerable fraction of actinides released, both in magnitude and in relation to other elements. The inventory of radionuclides and the release characteristics are shown in Tab. 1 and 2. The release category K1 represents a core destruction followed by over-pressurization and a failure of the outer containment. The initial fuel was assumed to originate from LWRs (~ 70%) and from Magnox reactors (~ 30%). This fuel contains ~150 times more Pu-238 than pure Magnox-plutonium.

Only one site was considered in this study, namely Kalkar, where the SNR-300 is situated. For the probabilistic investigations, 115 weather sequences were chosen from the synoptic data of 1977 measured at the meteorological station of the Jülich Nuclear Research Center. No consideration has been given to possible differences in the meteorological conditions when looking at accidental situations at different times of the year, and the weather sequences were selected uniformly by cyclic sampling from the recordings covering the complete year.

In Tab. 3 the foodchain related data used in this assessment are given for the three foodchain transport models.

The most important of the radionuclides taken into account are the isotopes of strontium, caesium and iodine and of plutonium, americium and curium. In principle also those radioactive decay products need to be considered, which lead to an increase of activity in the foodstuffs which is substantial in relation to the activity levels resulting from directly released isotopes. For the release considered here, this is the case only for the decay Pu-241 ($T^{1/2}$ = 14 a) → Am-241 ($T^{1/2}$ = 432 a). Since FOOD-MARC allows an explicit treatment of such a decay chain it was included in the analysis.

The seasonal variations were studied using data from FOOD-MARC for releases in January and July to represent agricultural conditions in winter and summer. In the WASH-1400 and the BSU model the releases are assumed to occur in summer at the peak of growth of the vegetation.

The food products were chosen according to German consumption habits /16/, where milk, beef, grain and green vegetables are among the most relevant foods. Pork and potatoes, which are also an important part of the average German diet, could not be considered, the former, because it is not modelled in MARC, and the latter because the model for root crops was under development. Although cow's liver gives only a very small contribution to the overall dietary intake, it was included because it may contribute a significant fraction of the actinides.

The agricultural practice adopted in the MARC model for each group of foods is based on practices common in the United Kingdom: Green vegetables are assumed to be produced and consumed continuously throughout the year, whereas grain is assumed to be planted in spring, harvested at the end of August and eaten uniformly throughout the following year. Beef and dairy cattle are assumed to graze pasture from mid-April to the end of October. For the rest of the year they are fed on locally grown hay or silage which was harvested between May and mid-September.

4.2 Normalized integrated intake

The results of the MARC foodchain transport model are given as time-dependent activity concentrations and concentration time-integrals for the different food products. For the comparison these had to be reduced to a form similar to the WASH-1400 Concentration Factors for milk and other products for "direct deposition" and "root uptake" required by the current countermeasure model of UFOMOD. Since direct deposition can affect only the first vegetation cycle after the accident and root uptake is a long term process, the Concentration Factors were approximated by intakes I in the first year and the subsequent years[1] calculated in the following way[2]:

$$I_m(t) = V_m \cdot C_m^{Int}(t)$$

$$I_{\substack{other\\prod.}}(t) = \sum_p V_p \cdot C_p^{Int}(t)$$

where m stands for milk, p for cow's meat and liver, grain and green vegetables, V are consumption rates (Tab. 3 (d)) and C^{Int} are the activity concentrations from FOOD-MARC integrated over the first year and the subsequent years, respectively, taking account of the agricultural practice for each product.

These intake values approximate the time dependence of the Concentration Factors suggested implicitely by the distinction of direct deposition and root uptake, but they do not necessarily correspond to the above transfer processes. For instance, for long-lived nuclides the first year's activity concentration in grain and the intake is only due to root uptake and resuspension processes for a deposition in January, while for a deposition in July the effects of direct deposition onto the grain partly show up in the second year's intake due to the consumption of the rest of the first year's harvest.

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[1] In this assessment, the maximum integration time was 200 years for the FOOD-MARC data and 250 years for the BSU data. The influence of this inconsistency on the results is negligible.

[2] This corresponds to the way in which the Concentration Factors are derived in the BSU-model.

In Tab. 4 the values of the integrated intake are given for the WASH-1400 model (Cs, Sr, I) and the BSU model (Np, Pu, Am, Cm), and in Tab. 5 and 6 for FOOD-MARC assumed depositions in July and January.

A comparison of the intakes of the non-actinides by both milk and "other products" shows, that in the first year the WASH-1400 data are in general somewhat lower than the MARC data for July, but higher than the MARC data for January. In the subsequent years the MARC data for both July and January are significantly higher for caesium, about equal for the long-lived Sr-90 and much lower for the short-lived Sr-89 than the WASH-1400 data.

For the actinides, the intake by milk is predicted to be negligible in comparison to the non-actinides in both models. For the group "other products", however, the intake of actinides becomes more significant than that of the non-actinides in the BSU-model, whereas in FOOD-MARC it is in general lower. The deviations between the individual intake data derived with both models may amount up to two orders of magnitude; the differences are discussed in detail in Appendix C.

The MARC-data are shown for all the different food products in Tab. 7 (intake in first year) and Tab. 8 (intake in the subsequent years); in these tables, the intakes of Am-241 resulting from the decay of Pu-241 are also included.

Besides for the green vegetables, which are assumed to be produced and consumed continuously throughout the year considerable seasonal variations are observed in the first year. The largest variations are seen for grain, where the intake in July is several orders of magnitude higher than in January. This is due to the fact that directly deposited radioactive material can only lead to a substantial contamination of the grain if the deposition occurs in the growth period of the plant. The variation with season is not so pronounced for long lived isotopes in milk and beef, because the effect of seasonality is somewhat diminished by feeding cattle in winter with hay or silage harvested during summer when the contamination level was still high. For nuclides with short half lives (e.g. I-131) the differences are bigger because of the radioactive decay during the storage time of the fodder. For caesium, the values for milk and meat are almost equal, whereas strontium in meat is about one order of magnitude lower than in milk, reflecting the fact that strontium is a bone seeking element. Green vegetables, which are assumed to be produced and consumed throughout the year, contribute significantly to the intake only for a deposition early in the year, when they become an important source of iodine, because the iodine levels in all other products are very low due to radioactive decay, and also of the transuranium elements. The contribution of the actinides to all other food products is predicted to be comparatively small in FOOD-MARC.

The intake in the subsequent years shows still some variation with the time of deposition, reflecting that the effects of direct deposition can influence also the intake in the second year after a release, due to the agricultural practice. For Sr-90 the intakes from the subsequent years generally exceed those from the first year, demonstrating the importance of root uptake for this isotope. In relation to the other elements, the actinides give a significant contribution only to cow's liver.

5. Results

The integrated intake values derived from the different foodchain transport models were implemented into UFOMOD to study the resulting differences in the accident consequences following a K1 release. The potential individual doses are discussed in Chapter 5.1 particularly with respect to the various food products available from FOOD-MARC and the contributions of the transuranium isotopes. The areas affected by agricultural countermeasures and the late health effects are discussed in Chapters 5.2 and 5.3, respectively.

5.1 Potential individual doses

In Tab. 9 and 10 the contributions of individual radionuclides to the expectation values of the potential individual organ doses due to ingestion in 100 km distance to the site are shown. For the release considered here, a considerable fraction of the doses of all organs besides the lung and the thyroid can arise from the ingestion of transuranium elements; for the lung the dominant contributor is Cs-137, and for the thyroid the dose results almost entirely from the isotope I-131.

In Tab. 11 the overall contribution of the actinides to the total body-, red bone marrow- and bone doses are summarized. As it is expected from the intake data (Chapter 4.2 and Appendix C), the relative importance of the actinides is very different between the two models. The W14/BSU[1] model predicts large contributions between ~50% and ~100%, whereas from FOOD-MARC much smaller contributions and also considerable seasonal differences are expected. The results of both models show that the actinides give rise to more than about 50% of the exposure of the bone surface. From the results obtained with FOOD-MARC in Tab. 11 it can also

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[1] The combined model from the WASH-1400 study and BSU is referred to as "W14/BSU"

be seen that a large fraction of the overall contribution from the transuranium isotopes in the subsequent years originates from 'indirect' Am-241 from the decay Pu-241 → Am-241; in the first year this process is unimportant because of the radioactive half-life of Pu-241 of 14 years.

Tab. 12 gives the contributions of the individual food products considered in the models to the organ doses. Besides for the thyroid, for which milk is most important, the collective group "other products" contributes the larger fraction. The results obtained with the FOOD-MARC data show that contributions from the actinides result mainly from green vegetables and cow's liver, the latter being especially of importance for the exposure of the bone in the subsequent years. Green vegetables give a significant contribution of both actinides and iodine mainly for a deposition in winter. This reflects the fact that they are assumed to be produced continuously throughout the year in FOOD-MARC. In summer, grain products are among the dominant contributors, but they give only a negligible fraction of the actinides.

The differences between the values of the potential organ doses calculated with the intake data from the individual foodchain transport models and the influences of seasonality are summarized in Tab. 13.

From the first section of results it can be seen that the lung- and thyroid doses are higher with FOOD-MARC than with the BSU-model. Since for these organs only the non-actinides are of relevance, this reflects differences between the WASH-1400 and MARC models only[1]. For the other organs the higher importance of the actinides in the BSU model shows up and the doses exceed those calculated with the MARC-data by factors between 1.6 and 17.

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[1] These differences are discussed in /9/.

The second section of Tab. 13 gives the seasonal variations predicted with FOOD-MARC. The observed differences reflect the agricultural practice assumed in the model. In the first year the seasonal differences are larger than the model differences mentioned before; for a release in July, when the cows graze on pasture and the grain crops are developing, the first year's doses are up to 17 times higher than for a deposition in January, when the cows are kept indoors and only green vegetables are growing. The doses in the following years show still some variation with the time of deposition, but these are mostly in the same order of magnitude as the intermodel differences.

The doses resulting from an intake of food in the first year are compared to the total doses in the last section of Tab. 13. For the thyroid, the short-lived I-131 is the main contributor to the dose so that virtually 100% of the exposure comes from food-intake in the first year. For the other organs longer-lived radionuclides are important, which can be transferred to the foodstuffs over a long time by root uptake or resuspension process. Therefore, the long-term intake becomes more relevant, especially for a deposition in January, when most of the foodstuffs are not contaminated by direct deposition.

5.2 Restricted areas

If the potential individual doses received in the thyroid, red bone marrow or the total body by ingestion of milk or "other products" exceed the intervention levels defined in Chapter 3, it is assumed that the corresponding food-product is made unavailable for human consumption. The complementary cumulative frequency distributions (CCFDs) of the areas affected by such food restrictions after a K1-release are shown in Fig. 1 (intake in first year) and Fig. 2 (intake in subsequent years) and Tab. 14-17 give characteristic quantities of these distributions.

In the first year the seasonal differences are more expressed than the differences between the W14/BSU and the MARC model, as would be expected from the behaviour of the potential individual doses discussed in the preceeding paragraph. For a release in summer almost all weather sequences considered lead to food restrictions and the affected areas can be large for both milk and "other products". Much smaller areas are predicted for a release in winter and in more than 50% of the weather situations no agricultural consequences are expected to occur. The variation with season is greatest for milk, because these restrictions result mainly from the exposure of the thyroid by the short-lived I-131, which is largely reduced for a release in winter due to the agricultural practice assumed in FOOD-MARC. The group "other products" contains the green vegetables which do not vary with the time of deposition, so that the influence of the time of deposition is somewhat diminished.

The CCFDs of the milk restrictions in the first year obtained with the W14/BSU- and the FOOD-MARC (July)-data do not reflect the large deviations between the two models which were observed in the potential individual doses. This is an effect of the cutoff of the countermeasures in UFOMOD at 540 km. For the relatively large release considered here, the dose levels due to ingestion of milk exceed the intervention levels at this distance in almost all of the weather sequences considered, so that larger deviations can be expected only beyond this limiting radius where the doses become sufficiently low.

In the subsequent years the areas affected by milk restrictions have largely decreased and in about 60% of the cases the intervention levels are never exceeded at all. The restrictions for "other products" are somewhat higher than for milk, and there are considerable differences between the predictions of the two foodchain transport models due to the higher importance of the actinides in the BSU-model.

Although it is not yet possible in UFOMOD to examine the individual contributions of the food products to the restrictions imposed collectively on "other products", the contributions of the foodstuffs to the potential individual doses derived with the FOOD-MARC data have shown, that the restrictions will mainly affect grain products for a release in summer and green vegetables for a release in winter; and, with less variation with the time of deposition, also cow's meat and liver.

Since the current modelling in UFOMOD of the intervention levels has originally been developed to limit the total transfer of activity to man via the foodchain, the time resolution of the duration of the restrictions is very limited, allowing only for an implicit gross distinction of "year one" and "all following years" after the accident for the two groups of food products considered. For a future utilization of the explicit time dependencies of the transfer of activity through various components of the foodchain offered by more advanced foodchain transport models, such as FOOD-MARC and ECOSYS, a more sophisticated system of intervention levels will be required.

5.3 Late health effects

Fig. 3 and Tab. 18 show the CCFDs and characteristic quantities of the overall number of late fatalities, which are estimated with UFOMOD for a K1 release taking the countermeasures into account. Since the contributions of the other exposure pathways are always the same, any deviation between the curves result from the ingestion pathway. Between 10% and ∼20% of all fatalities are calculated beyond 540 km distance to the site, where countermeasures are no longer modelled in UFOMOD.

The foodbans imposed after this relatively big release largely reduce the influence of the season and of the differences between the two foodchain transport models, and the three sets of results agree within ~20%. This insensitivity of the late health effects against the large model and seasonal differences is a consequence of the relative insignificance of the ingestion pathway compared to other exposure pathways, as can be seen numerically in Tab. 19a. Due to the high fraction of transuranium isotopes present in the K1-release, the overall number of late health effects is dominated by the inhalation of actinides from the passing radioactive plume, and, to a smaller extent, from resuspended activity. However, if no agricultural countermeasures were applied (Tab. 19b), the ingestion pathway would contribute ~ 40% to the late fatalities for an accidental release in summer. For January, when the areas affected by food restrictions are in general much smaller, the influence of food-bans on the late health effects ist negligible.

From Tab. 19c it can be seen that the current countermeasure model of UFOMOD does not give a reasonable estimate of the amount of food-bans actually required. If the intervention levels for the long term intake are omitted in the calculations, the contribution of the ingestion pathway and thus the total number of late health effects does not change significantly.

6. Summary

Results have been presented for the foodchain pathway in accident consequences following an assumed K1-release from the German prototype fast breeder reactor SNR-300. The assessment was performed with the computer code UFOMOD/B04 using data from the foodchain transport models WASH-1400/BSU and FOOD-MARC. The influence of the time of the accident was studied by means of the MARC data for July and January. An adoption of the FOOD-MARC data had been necessary to comply with the current UFOMOD code.

Big differences are observed in the data from the two foodchain transport models for actinides which lead to a much greater importance of the transuranium isotopes in the WASH-1400/BSU model. They are partly due to a different choice of parameters and partly reflect differences in the modelling of the transfer processes involved.

In the potential individual doses and the areas affected by agricultural countermeasures the differences from seasonal effects are more significant than the model differences and the doses and restricted areas are much larger for a release in summer than in winter. However, the intervention level model in UFOMOD needs further development to utilize the explicit time dependencies offered by a dynamic foodchain transport model in order to obtain a better time resolution of potential agricultural consequences.

The seasonal variation in the late health effects resulting from the consumption of contaminated food are largely reduced by the assumed agricultural countermeasures. Due to the presence of a high fraction of actinides in the release, the contribution of the ingestion pathway to the overall number of late health effects is rather small, ranging from 6% for a release in winter to ~15% for a release in summer.

Tab. 1

Inventory of radionuclides (SNR-300)

No.	Nuclide	Half-life (d)	Inventory (Ci)
1	CO- 58	7.098E+01	3.260E+06
2	CO- 60	1.923E+03	4.620E+03
3	KR- 85	3.913E+03	5.680E+04
4	KR- 85M	1.865E-01	3.270E+06
5	KR- 87	5.312E-02	5.140E+06
6	KR- 88	1.183E-01	7.190E+06
7	RB- 86	1.865E+01	2.230E+04
8	SR- 89	5.045E+01	9.040E+06
9	SR- 90	1.040E+04	3.450E+05
10	SR- 91	3.951E-01	1.340E+07
11	Y - 90	2.665E+00	3.520E+05
12	Y - 91	5.855E+01	1.190E+07
13	ZR- 95	6.417E+01	2.200E+07
14	ZR- 97	7.036E-01	2.750E+07
15	NB- 95	3.518E+01	1.970E+07
16	MO- 99	2.747E+00	3.120E+07
17	TC- 99M	2.507E-01	2.740E+07
18	RU-103	3.932E+01	3.300E+07
19	RU-105	1.848E-01	2.600E+07
20	RU-106	3.679E+02	1.230E+07
21	RH-105	1.472E+00	2.600E+07
22	TE-127	3.894E-01	2.660E+06
23	TE-127M	1.090E+02	3.030E+05
24	TE-129	4.832E-02	6.960E+06
25	TE-129M	3.356E+01	1.020E+06
26	TE-131M	1.249E+00	3.210E+06
27	TE-132	3.261E+00	2.710E+07
28	SB-127	3.856E+00	2.740E+06
29	SB-129	1.831E-01	7.070E+06
30	J -131	8.037E+00	2.070E+07
31	J -132	9.583E-02	2.770E+07
32	J -133	8.662E-01	3.480E+07
33	J -134	3.646E-02	3.670E+07
34	J -135	2.756E-01	3.390E+07
35	XE-133	5.242E+00	3.520E+07
36	XE-135	3.783E-01	3.840E+07
37	CS-134	7.496E+02	1.010E+05
38	CS-136	1.311E+01	1.100E+06
39	CS-137	1.100E+04	9.710E+05
40	BA-140	1.279E+01	2.810E+07
41	LA-140	1.674E+00	2.830E+07
42	CE-141	3.247E+01	2.800E+07
43	CE-143	1.376E+00	2.350E+07
44	CE-144	2.844E+02	1.180E+07
45	PR-143	1.355E+01	2.290E+07
46	ND-147	1.106E+01	1.110E+07
47	NP-239	2.338E+00	1.480E+08
48	PU-238	3.208E+04	2.780E+05
49	PU-239	8.902E+06	9.010E+04
50	PU-240	2.387E+06	1.400E+05
51	PU-241	5.242E+03	2.160E+07
52	AM-241	1.579E+05	9.510E+04
53	CM-242	1.630E+02	1.660E+06
54	CM-244	6.629E+03	3.090E+03

Tab. 2

Release characteristics and released fractions of inventory

Reactor type	Release Cat.	Description	Time of release (h)	Duration of release (h)	Release height (m)	released energy (KJ)	Frequency of release (1/a)
SNR-300	K1	core destruction, failure of containment	0	1	100	$5.3\cdot10^{8}$	$1\cdot10^{-8}$

Reactor type	Release Cat.	Released fraction of inventory						
		Xe-Kr	I-Br	Cs-Rb	Te-Sb	Ba-Sr	Ru 1)	La 2)
SNR-300	K1	1.0	$1.5\cdot10^{-1}$	$1.5\cdot10^{-1}$	$1.5\cdot10^{-1}$	$5.0\cdot10^{-2}$	$5.0\cdot10^{-2}$	$5.0\cdot10^{-2}$

1) including Ru, Rh, Co, Mo, Tc

2) including Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am, Cm

Tab. 3

Foodchain related data

(a) Nuclides

Sr-89	Sr-90	Cs-134	Cs-136^{+}	Cs-137	I-131	I-133	Ru-106*
Np-239^{+}	Pu-238	Pu-239	Pu-240	Pu-241	Am-241	Cm-242	Cm-144

Note: $^{+}$only in W14/BSU *only in MARC

(b) time of deposition

W14/BSU:	deposition "in summer"
MARC:	1st January and 1st July

Tab. 3 cont'd

Foodchain related data

(c) food-products and modelling of agricultural practice

WASH 1400	milk other products	cows outside all year No explicit agricultural practice
BSU	milk, meat	In any year, cows consume 50% fresh grass and 50% grass stored 90 days
	plant products	continuous harvest and consumption
MARC	milk cow's meat cow's liver	Cows outside 17th April to 30th Septemper. Hay/silage harvested 1st May to 15th September until end of first winter. Cows permanently outside after first winter.
	grain products	Growth from 1st May to 31st August for first two crops. Continuous harvesting for all following crops.
	green vegetables	Continous harvest and consumption

(d) consumption rates

WASH 1400	milk	$255 \ l \cdot a^{-1}$	small child
	other products	no explicit consumption rates	
BSU	milk	$220 \ l \cdot a^{-1}$	small child
	meat	$70 \ kg \cdot a^{-1}$	average adult
	plant products	$248 \ kg \cdot a^{-1}$	
MARC	milk	$300 \ l \cdot a^{-1}$	adult member of critical group
	cow's meat	$60 \ kg \cdot a^{-1}$	
	cow's liver	$10 \ kg \cdot a^{-1}$	
	grain	$130 \ kg \cdot a^{-1}$	
	green vegetables	$80 \ kg \cdot a^{-1}$	

Tab. 4

Normalized integrated intake (Bq/(Bq*m^{-2})) for milk and "other products" from WASH-1400 (non-actinides) and BSU (actinides)

	dir. dep. / 0-1 a		root upt. / 1-250 a		total / 0-250 a	
nuclide	milk	other products	milk	other products	milk	other products
Sr- 89	4.0E-01	4.0E-01	6.8E-03	1.4E-02	4.1E-01	4.1E-01
Sr- 90	5.9E-01	5.1E-01	6.7E-01	1.3E+00	1.3E-00	1.9E+00
I -131	6.9E-01	0.0	0.0	0.0	6.9E-01	0.0
I -133	4.2E-03	0.0	0.0	0.0	4.2E-03	0.0
Cs-134	4.2E+00	8.4E+00	5.5E-02	1.6E-01	4.3E+00	8.6E+00
Cs-136	1.4E+00	2.8E+00	0.0	0.0	1.4E+00	2.8E+00
Cs-137	4.2E+00	8.4E+00	8.4E-02	2.5E-01	4.3E+00	8.7E+00
Np-239	2.3E-04	6.7E-01	0.0	0.0	2.3E-04	6.7E-01
Pu-238	4.3E-04	1.2E+01	2.5E-05	5.3E+00	4.6E-04	1.7E+01
Pu-239	4.3E-04	1.2E+01	5.5E-05	1.2E+01	4.9E-04	2.4E+01
Pu-240	4.3E-04	1.2E+01	5.4E-05	1.2E+01	4.9E-04	2.4E+01
Pu-241	4.2E-04	1.2E+01	5.0E-05	1.1E+00	4.3E-04	1.3E+00
Am-241	8.6E-02	1.2E+01	1.1E-02	1.2E+01	9.7E-02	2.4E+01
Cm-242	4.7E-02	1.0E+01	1.1E-05	1.4E-02	4.7E-02	1.0E+01
Cm-244	8.5E-02	1.2E+01	2.4E-03	2.5E+00	8.8E-02	1.5E+01

Tab. 5

Normalized integrated intake (Bq/(Bq*m^{-2})) for milk and "other products" derived from FOOD-MARC for a deposition at 1st of July

nuclide	intake 0 - 1 year		intake 1-200 years		intake 0-200 years	
	milk	other products	milk	other products	milk	other products
Sr- 89	2.3E-01	2.5E-01	4.5E-04	4.7E-04	2.3E-01	2.5E-01
Sr- 90	7.8E-01	6.9E-01	9.3E-01	1.9E+00	1.7E+00	2.6E+00
Ru-106	3.8E-04	3.1E-01	1.7E-05	4.3E-02	4.0E-04	3.6E-01
I -131	1.2E+00	1.9E-01	0.0	0.0	1.2E+00	1.9E-01
I -133	9.4E-02	2.2E-02	0.0	0.0	9.4E-02	2.2E-02
Cs-134	4.9E+00	9.5E+00	1.6E-01	1.1E+00	5.0E+00	1.1E+01
Cs-137	5.5E+00	1.1E+01	3.8E-01	1.9E+00	5.9E+00	1.3E+01
Pu-238	3.2E-04	3.4E-01	9.4E-04	2.3E-01	1.3E-03	5.7E-01
Pu-239	3.2E-04	3.4E-01	9.4E-04	2.3E-01	1.3E-03	5.7E-01
Pu-240	3.2E-04	3.4E-01	9.4E-04	2.3E-01	1.3E-03	5.7E-01
Pu-241	3.1E-04	3.3E-01	7.6E-04	1.8E-01	1.1E-03	5.2E-01
Am-241	3.2E-04	3.4E-01	9.6E-04	2.5E-01	1.3E-03	5.9E-01
Am-241 *	2.0E-07	7.6E-05	6.2E-06	1.9E-03	6.4E-06	2.0E-03
Cm-242	1.4E-04	2.7E-01	4.3E-05	1.1E-02	1.9E-04	2.8E-01
Cm-244	3.1E-04	3.3E-01	8.1E-04	2.0E-01	1.1E-03	5.3E-01

* From the decay Pu-241 -> Am-241 normalized to a unit deposition of Pu-241

Tab. 6

Normalized integrated intake (Bq/(Bq*m^{-2})) for milk and "other products" derived from FOOD-MARC for a deposition at 1st of January

nuclide	intake 0 - 1 year		intake 1-200 years		intake 0-200 years	
	milk	other products	milk	other products	milk	other products
Sr- 89	9.4E-03	2.1E-01	3.3E-04	1.3E-04	9.7E-03	2.1E-01
Sr- 90	1.3E-01	3.1E-01	8.0E-01	1.8E+00	9.4E-01	2.1E+00
Ru-106	2.9E-05	2.4E-01	2.3E-05	2.5E-02	5.3E-05	2.7E-01
I -131	0.0	1.0E-01	0.0	0.0	0.0	1.0E-01
I -133	0.0	1.6E-02	0.0	0.0	0.0	1.6E-02
Cs-134	2.8E-01	5.0E-01	2.3E-01	2.3E-01	5.1E-01	7.4E-01
Cs-137	3.3E-01	5.5E-01	4.9E-01	6.5E-01	8.2E-01	1.2E+00
Pu-238	1.3E-05	2.5E-01	1.9E-04	4.8E-02	2.0E-04	2.9E-01
Pu-239	1.3E-05	2.5E-01	1.9E-04	4.8E-02	2.0E-04	2.9E-01
Pu-240	1.3E-05	2.5E-01	1.9E-04	4.8E-02	2.0E-04	2.9E-01
Pu-241	1.2E-05	2.5E-01	1.4E-04	3.3E-02	1.5E-04	2.8E-01
Am-241	1.3E-05	2.5E-01	2.2E-04	6.8E-02	2.3E-04	3.1E-01
Am-241 *	0.0	2.6E-05	2.1E-06	9.8E-04	2.1E-06	1.0E-03
Cm-242	4.9E-06	2.3E-01	4.1E-06	9.6E-04	8.9E-06	2.3E-01
Cm-244	1.2E-05	2.5E-01	1.6E-04	4.2E-02	1.7E-04	2.9E-01

* From the decay Pu-241 -> Am-241 normalized to a unit deposition of Pu-241

Tab. 7

Normalized intake in the years 0- 1 $(\mathrm{Bq}/(\mathrm{Bq}{*}\mathrm{m}^{-2}))$ derived from FOOD-MARC

food nuclide	milk	cow's meat	cow's liver	grain products	green vegetables
			deposition 1st July		
Sr- 89	2.3E-01	9.2E-03	1.5E-03	3.8E-02	2.1E-01
Sr- 90	7.8E-01	3.3E-02	5.5E-03	3.6E-01	2.9E-01
Ru-106	3.8E-04	4.8E-02	7.9E-03	2.3E-02	2.3E-01
I -131	1.2E+00	7.4E-02	1.2E-02	1.4E-03	1.0E-01
I -133	9.4E-02	5.1E-03	8.5E-04	0.0	1.6E-02
Cs-134	4.9E+00	3.4E+00	5.6E-01	5.3E+00	3.0E-01
Cs-137	5.5E+00	3.9E+00	6.4E-01	6.3E+00	3.0E-01
Pu-238	3.2E-04	3.5E-03	7.0E-02	1.9E-02	2.4E-01
Pu-239	3.2E-04	3.5E-03	7.0E-02	1.9E-02	2.4E-01
Pu-240	3.2E-04	3.5E-03	7.0E-02	1.9E-02	2.4E-01
Pu-241	3.1E-04	3.4E-03	6.8E-02	1.9E-02	2.4E-01
Am-241	3.2E-04	3.5E-03	7.0E-02	1.9E-02	2.4E-01
Am-241 *	2.0E-07	2.2E-06	4.6E-05	5.0E-06	2.3E-05
Cm-242	1.4E-04	1.6E-03	3.1E-02	8.3E-03	2.2E-01
Cm-244	3.1E-04	3.4E-03	6.9E-02	1.9E-02	2.4E-01
			deposition 1st January		
Sr- 89	9.4E-03	3.8E-04	6.3E-05	1.4E-04	2.1E-01
Sr- 90	1.3E-01	5.6E-03	9.4E-04	7.7E-03	2.9E-01
Ru-106	2.9E-05	2.7E-03	4.5E-04	3.4E-03	2.3E-01
I -131	0.0	0.0	0.0	0.0	1.0E-01
I -133	0.0	0.0	0.0	0.0	1.6E-02
Cs-134	2.8E-01	1.8E-01	2.9E-02	7.5E-04	3.0E-01
Cs-137	3.3E-01	2.1E-01	3.5E-02	9.7E-04	3.0E-01
Pu-238	1.3E-05	1.4E-04	2.7E-03	1.1E-06	2.4E-01
Pu-239	1.3E-05	1.4E-04	2.7E-03	1.1E-06	2.4E-01
Pu-240	1.3E-05	1.4E-04	2.7E-03	1.1E-06	2.4E-01
Pu-241	1.2E-05	1.3E-04	2.7E-03	1.0E-06	2.4E-01
Am-241	1.3E-05	1.4E-04	2.8E-03	2.0E-06	2.4E-01
Am-241 *	0.0	1.4E-07	2.9E-06	0.0	2.3E-05
Cm-242	4.9E-06	5.3E-05	1.0E-03	5.5E-07	2.2E-01
Cm-244	1.2E-05	1.4E-04	2.7E-03	1.9E-06	2.4E-01

* From the decay Pu-241 -> Am-241 normalized to a unit deposition of Pu-241

Tab. 8

Normalized intake in the years 1-200 (Bq/(Bq*m^{-2})) derived from FOOD-MARC

food nuclide	milk	cow's meat	cow's liver	grain products	green vegetables
	deposition 1st july				
Sr- 89	4.5E-04	1.9E-05	4.0E-06	3.6E-04	4.5E-05
Sr- 90	9.3E-01	4.0E-02	6.7E-03	7.9E-01	1.1E+00
Ru-106	1.7E-05	2.3E-02	3.8E-03	1.6E-02	4.8E-04
I -131	0.0	0.0	0.0	0.0	0.0
I -133	0.0	0.0	0.0	0.0	0.0
Cs-134	1.6E-01	1.9E-01	3.2E-02	9.0E-01	7.2E-03
Cs-137	3.8E-01	3.8E-01	6.4E-02	1.4E+00	1.1E-01
Pu-238	9.4E-04	1.0E-02	2.1E-01	4.2E-03	2.2E-03
Pu-239	9.4E-04	1.0E-02	2.1E-01	4.2E-03	2.2E-03
Pu-240	9.4E-04	1.0E-02	2.1E-01	4.2E-03	2.2E-03
Pu-241	7.6E-04	8.4E-03	1.7E-01	3.6E-03	0.0
Am-241	9.6E-04	1.1E-02	2.2E-01	4.4E-03	1.7E-02
Am-241 *	6.2E-06	6.7E-05	1.4E-03	1.6E-05	4.7E-04
Cm-242	4.3E-05	4.7E-04	9.8E-03	7.3E-04	0.0
Cm-244	8.1E-04	8.9E-03	1.8E-01	3.9E-03	3.7E-03
	deposition 1st January				
Sr- 89	3.3E-04	1.4E-05	2.3E-06	3.1E-05	4.5E-05
Sr- 90	8.0E-01	3.5E-02	5.8E-03	7.3E-01	1.1E+00
Ru-106	2.3E-05	6.5E-03	1.1E-03	1.7E-02	4.8E-04
J -131	0.0	0.0	0.0	0.0	0.0
J -133	0.0	0.0	0.0	0.0	0.0
Cs-134	2.3E-01	1.9E-01	3.1E-02	7.5E-03	7.2E-03
Cs-137	4.9E-01	3.8E-01	6.4E-02	9.6E-02	1.1E-01
Pu-238	1.9E-04	2.1E-03	4.3E-02	3.4E-04	2.2E-03
Pu-239	1.9E-04	2.1E-03	4.3E-02	3.4E-04	2.2E-03
Pu-240	1.9E-04	2.1E-03	4.3E-02	3.4E-04	2.2E-03
Pu-241	1.4E-04	1.5E-03	3.1E-02	5.7E-05	0.0
Am-241	2.2E-04	2.4E-03	4.9E-02	5.5E-04	1.7E-02
Am-241 *	2.1E-06	2.3E-05	4.8E-04	1.5E-05	4.7E-04
Cm-242	4.1E-06	4.4E-05	9.1E-04	1.0E-06	0.0
Cm-244	1.6E-04	1.8E-03	3.6E-02	1.3E-04	3.7E-03

* From the decay Pu-241 -> Am-241 normalized to a unit deposition of Pu-241

Tab. 9

Contribution of nuclides to the potential individual doses due to ingestion in the first year (release category K1, distance 100 km, under centerline of plume)

nuclides	total body	red bone marrow	lung	bone	thyroid	model
Sr- 89	0.3%	0.8%	0.3%	0.1%	0.0%	W14/BSU
Sr- 90	0.3%	2.2%	0.1%	0.5%	0.0%	
Ru-106	0.0%	0.0%	0.0%	0.0%	0.0%	
I -131	2.9%	0.3%	1.7%	0.0%	98.6%	
I -133	0.0%	0.0%	0.0%	0.0%	0.2%	
Cs-134	5.3%	2.4%	11.0%	0.2%	0.1%	
Cs-136	3.0%	1.4%	6.1%	0.1%	0.1%	
Cs-137	38.3%	15.8%	80.8%	1.6%	1.0%	
Np-239	0.4%	0.2%	0.0%	0.0%	0.0%	
Pu-238	8.8%	16.7%	0.0%	21.3%	0.0%	
Pu-239	3.1%	6.1%	0.0%	7.4%	0.0%	
Pu-240	4.9%	9.5%	0.0%	11.5%	0.0%	
Pu-241	8.9%	0.0%	0.0%	0.1%	0.0%	
Am-241	16.9%	33.3%	0.0%	42.6%	0.0%	
Cm-242	6.7%	10.7%	0.0%	13.9%	0.0%	
Cm-244	0.3%	0.6%	0.0%	0.7%	0.0%	
Sr- 89	0.3%	1.5%	0.1%	1.1%	0.0%	MARC July
Sr- 90	0.6%	10.0%	0.1%	11.1%	0.0%	
Ru-106	0.5%	0.6%	0.7%	0.3%	0.0%	
I -131	8.9%	1.9%	2.7%	0.9%	97.1%	
I -133	0.3%	0.1%	0.2%	0.1%	2.1%	
Cs-134	9.3%	9.2%	10.1%	4.3%	0.1%	
Cs-136	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-137	78.0%	69.5%	86.1%	36.1%	0.7%	
Np-239	0.0%	0.0%	0.0%	0.0%	0.0%	
Pu-238	0.4%	1.5%	0.0%	10.0%	0.0%	
Pu-239	0.1%	0.6%	0.0%	3.5%	0.0%	
Pu-240	0.2%	0.9%	0.0%	5.4%	0.0%	
Pu-241	0.4%	0.0%	0.0%	0.0%	0.0%	
Am-241	0.7%	3.2%	0.0%	20.9%	0.0%	
Cm-242	0.3%	0.9%	0.0%	6.1%	0.0%	
Cm-244	0.0%	0.1%	0.0%	0.3%	0.0%	
Sr- 89	1.5%	4.9%	1.1%	1.2%	0.0%	MARC Jan.
Sr- 90	2.5%	21.8%	0.4%	8.2%	0.0%	
Ru-106	5.5%	3.6%	9.4%	0.6%	0.1%	
I -131	8.6%	1.0%	3.2%	0.2%	95.5%	
I -133	0.5%	0.1%	0.3%	0.0%	3.9%	
Cs-134	6.6%	3.6%	9.2%	0.6%	0.1%	
Cs-136	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-137	54.4%	26.8%	76.3%	4.8%	0.5%	
Np-239	0.0%	0.0%	0.0%	0.0%	0.0%	
Pu-238	3.6%	8.1%	0.0%	18.1%	0.0%	
Pu-239	1.3%	3.0%	0.0%	6.3%	0.0%	
Pu-240	2.0%	4.6%	0.0%	9.8%	0.0%	
Pu-241	3.7%	0.0%	0.0%	0.0%	0.0%	
Am-241	7.0%	16.5%	0.0%	36.9%	0.0%	
Cm-242	2.9%	5.6%	0.0%	12.7%	0.0%	
Cm-244	0.1%	0.3%	0.0%	0.6%	0.0%	

Tab. 10

Contribution of nuclides to the potential individual doses due to ingestion in the subsequent years
(release category K1, distance 100 km, under centerline of plume)

nuclides	total body	red bone marrow	lung	bone	thyroid	model
Sr- 89	0.0%	0.0%	0.3%	0.0%	0.3%	W14/BSU
Sr- 90	1.8%	6.9%	6.1%	1.3%	6.1%	
Ru-106	0.0%	0.0%	0.0%	0.0%	0.0%	
I -131	0.0%	0.0%	0.0%	0.0%	0.0%	
I -133	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-134	0.3%	0.1%	7.6%	0.0%	8.1%	
Cs-136	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-137	3.3%	0.7%	85.9%	0.1%	85.5%	
Np-239	0.0%	0.0%	0.0%	0.0%	0.0%	
Pu-238	12.6%	12.2%	0.0%	13.2%	0.0%	
Pu-239	10.1%	10.1%	0.0%	10.4%	0.0%	
Pu-240	15.5%	15.6%	0.0%	16.0%	0.0%	
Pu-241	2.5%	0.0%	0.0%	0.0%	0.0%	
Am-241	53.6%	54.1%	0.0%	58.8%	0.0%	
Cm-242	0.0%	0.0%	0.0%	0.0%	0.0%	
Cm-244	0.2%	0.2%	0.0%	0.2%	0.0%	
Sr- 89	0.0%	0.0%	0.0%	0.0%	0.0%	MARC July
Sr- 90	8.0%	50.6%	1.3%	26.3%	1.3%	
Ru-106	0.5%	0.2%	0.8%	0.1%	0.8%	
I -131	0.0%	0.0%	0.0%	0.0%	0.0%	
I -133	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-134	5.5%	2.1%	7.0%	0.5%	7.3%	
Cs-136	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-137	71.6%	25.2%	91.0%	6.2%	90.6%	
Np-239	0.0%	0.0%	0.0%	0.0%	0.0%	
Pu-238	1.7%	2.8%	0.0%	8.5%	0.0%	
Pu-239	0.6%	1.0%	0.0%	3.0%	0.0%	
Pu-240	0.9%	1.6%	0.0%	4.6%	0.0%	
Pu-241	1.4%	0.0%	0.0%	0.0%	0.0%	
Am-241	9.7%	16.3%	0.0%	50.4%	0.0%	
Cm-242	0.1%	0.1%	0.0%	0.3%	0.0%	
Cm-244	0.1%	0.1%	0.0%	0.2%	0.0%	
Sr- 89	0.0%	0.0%	0.0%	0.0%	0.0%	MARC Jan.
Sr- 90	14.8%	68.8%	2.5%	46.7%	2.5%	
Ru-106	0.6%	0.2%	0.9%	0.1%	0.9%	
I -131	0.0%	0.0%	0.0%	0.0%	0.0%	
I -133	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-134	3.9%	1.1%	5.1%	0.3%	5.3%	
Cs-136	0.0%	0.0%	0.0%	0.0%	0.0%	
Cs-137	70.7%	18.2%	91.6%	5.8%	91.3%	
Np-239	0.0%	0.0%	0.0%	0.0%	0.0%	
Pu-238	0.7%	0.8%	0.0%	3.3%	0.0%	
Pu-239	0.2%	0.3%	0.0%	1.2%	0.0%	
Pu-240	0.4%	0.5%	0.0%	1.8%	0.0%	
Pu-241	0.5%	0.0%	0.0%	0.0%	0.0%	
Am-241	8.2%	10.1%	0.0%	40.6%	0.0%	
Cm-242	0.0%	0.0%	0.0%	0.1%	0.0%	
Cm-244	0.0%	0.0%	0.0%	0.1%	0.0%	

Tab. 11

Contribution of the actinides to the potential individual doses due to ingestion
(release category K1, distance 100 km, under centerline of plume)

intake time	model	total body	red bone marrow	bone
years 0- 1	W14/BSU	50%	77%	97%
	MARC July	2%	7%	46%
	MARC Jan.	21%	38%	85%
years 1-200	W14/BSU	95%	92%	99%
	MARC July (1)	25%	22%	67%
	MARC Jan. (1)	10%	13%	47%
	MARC July (2)	9%	13%	52%
	MARC Jan. (2)	4%	4%	23%

note:
including (1) / excluding (2) the decay chain Pu-241->Am-241

Tab. 12

Contribution of food-products to the potential individual doses due to ingestion (release category K1, distance 100 km, under centerline of plume)

intake in years 0- 1

food	total body	red bone marrow	lung	bone	thyroid	
milk	18.9%	8.7%	34.5%	1.4%	99.2%	W14/BSU
oth. prod. *	81.1%	91.3%	65.5%	98.7%	0.8%	---------
milk	37.3%	33.8%	34.4%	20.6%	85.7%	MARC July
cow's meat	20.9%	18.9%	22.7%	10.2%	5.5%	---------
cow's liver *	3.9%	4.6%	3.8%	11.2%	0.9%	
grain prod.	33.4%	32.8%	36.5%	20.6%	0.4%	
green veg. *	4.5%	10.0%	2.6%	37.5%	7.5%	
milk	23.6%	18.3%	32.2%	4.6%	0.2%	MARC Jan.
cow's meat	14.6%	7.6%	20.4%	1.4%	0.1%	---------
cow's liver	2.7%	1.7%	3.4%	1.2%	0.0%	
grain prod.	0.2%	0.5%	0.2%	0.2%	0.0%	
green veg. *	59.0%	72.0%	43.8%	92.7%	99.7%	

intake in years 1-200

food	total body	red bone marrow	lung	bone	thyroid	
milk	1.6%	2.6%	25.5%	0.5%	25.5%	W14/BSU
oth. prod. *	98.4%	97.4%	74.5%	99.5%	74.5%	---------
milk	15.2%	21.2%	16.4%	10.0%	16.3%	MARC July
cow's meat	13.6%	6.2%	16.5%	4.1%	16.5%	---------
cow's liver *	14.1%	18.5%	2.8%	54.4%	2.8%	
grain prod.	48.9%	31.0%	59.4%	12.3%	59.5%	
green veg. *	8.2%	23.1%	4.9%	19.2%	4.9%	
milk	36.8%	29.5%	42.5%	17.1%	42.5%	MARC Jan.
cow's meat	25.9%	7.8%	32.9%	4.1%	33.0%	---------
cow's liver *	10.3%	8.1%	5.5%	28.1%	5.5%	
grain prod.	10.6%	20.9%	9.1%	14.1%	9.1%	
green veg. *	16.4%	33.7%	10.0%	36.7%	10.0%	

* these products contribute a significant fraction of actinides

Tab. 13

Ratios of potential doses due to ingestion
(release category K1, distance 100 km, under centerline of plume)

ratio	intake time or model	total body	red bone marrow	lung	bone	thyroid
W14/BSU --------- MARC July	yrs 0- 1	1.6	3.3	0.81	17.	0.51
	yrs 1-200	3.1	5.3	0.15	15.	0.15
MARC July --------- MARC Jan.	yrs 0- 1	13.	7.2	17.	17.	13.
	yrs 1-200	2.0	1.4	2.0	1.9	2.0
yrs 0- 1 --------- yrs 0-200	W14/BSU	0.76	0.65	0.98	0.58	1.0
yrs 0- 1 --------- yrs 0-200	MARC July	0.87	0.72	0.88	0.52	1.0
yrs 0- 1 --------- yrs 0-200	MARC Jan.	0.49	0.35	0.48	0.48	0.99

Tab. 14

Characteristic values of the CCFDs of the restricted areas for milk in the first year from UFOMOD with different foodchain models

foodchain transport model	area restricted by countermeasures, A					
	expectation value, E	value at P^{th} percentile			% probability	
		P = 50	P = 95	P = 99	p(A=0)	p(A>E)
W14/BSU	3.0 E+4	3.0 E+4	3.9 E+4	4.2 E+4	0	62
FOOD-MARC						
- July	3.5 E+4	3.6 E+4	4.5 E+4	4.6 E+4	0	54
- January	8.4 E+0	0.0	6.8 E+1	1.4 E+2	64	12

Tab. 15

Characteristic values of the CCFDs of the restricted areas for other products in the first year from UFOMOD with different foodchain models

foodchain transport model	area restricted by countermeasures, A					
	expectation value, E	value at P^{th} percentile			% probability	
		P = 50	P = 95	P = 99	p(A=0)	p(A>E)
W14/BSU	8.7 E+3	5.6 E+3	2.8 E+4	3.2 E+4	0	39
FOOD-MARC						
- July	2.2 E+3	1.9 E+2	1.1 E+4	1.7 E+4	3	30
- January	2.2 E+2	0.0	1.7 E+3	1.7 E+3	55	19

Tab. 16

Characteristic values of the CCFDs of the restricted areas for milk in the subsequent years from UFOMOD with different foodchain models

area restricted by countermeasures, A						
foodchain transport model	expectation value, E	value at P^{th} percentile			% probability	
		P = 50	P = 95	P = 99	p(A=0)	p(A>E)
W14/BSU	3.0 E+1	0.0	2.0 E+2	3.9 E+2	63	16
FOOD-MARC						
- July	5.3 E+1	0.0	5.1 E+2	7.0 E+2	61	15
- January	8.4 E+0	0.0	6.8 E+1	1.4 E+2	64	12

Tab. 17

Characteristic values of the CCFDs of the restricted areas for other products in the subsequent years from UFOMOD with different foodchain models

area restricted by countermeasures, A						
foodchain transport model	expectation value, E	value at P^{th} percentile			% probability	
		P = 50	P = 95	P = 99	p(A=0)	p(A>E)
W14/BSU	6.0 E+3	2.6 E+3	2.2 E+4	2.6 E+4	0	36
FOOD-MARC						
- July	9.5 E+2	2.6 E+1	5.6 E+3	8.0 E+3	11	24
- January	2.2 E+2	0.0	1.7 E+3	1.7 E+3	55	19

Tab. 18

Characteristic values of the CCFDs of the total number of late health-effects from UFOMOD with different foodchain models

foodchain transport model	expectation value, E	value at P^{th} percentile P = 50	P = 95	P = 99	% probability p(N=0)	p(N>E)
W14/BSU	8.7 E+3	7.9 E+3	1.7 E+4	2.4 E+4	0	43
FOOD-MARC						
- July	8.5 E+3	7.6 E+3	1.8 E+4	2.4 E+4	0	43
- January	7.6 E+3	6.6 E+3	1.7 E+4	2.3 E+4	0	43

(number of late health effects, N)

Tab. 19

Average contribution of the ingestion pathway to the total number of late health effects

foodchain transport model	(a) with foodbans	(b) without foodbans	(c) reduced * foodbans
W14/BSU	17%	42%	22%
FOOD-MARC			
- July	15%	42%	16%
- January	6%	7%	6%

* no intervention levels for longterm intake

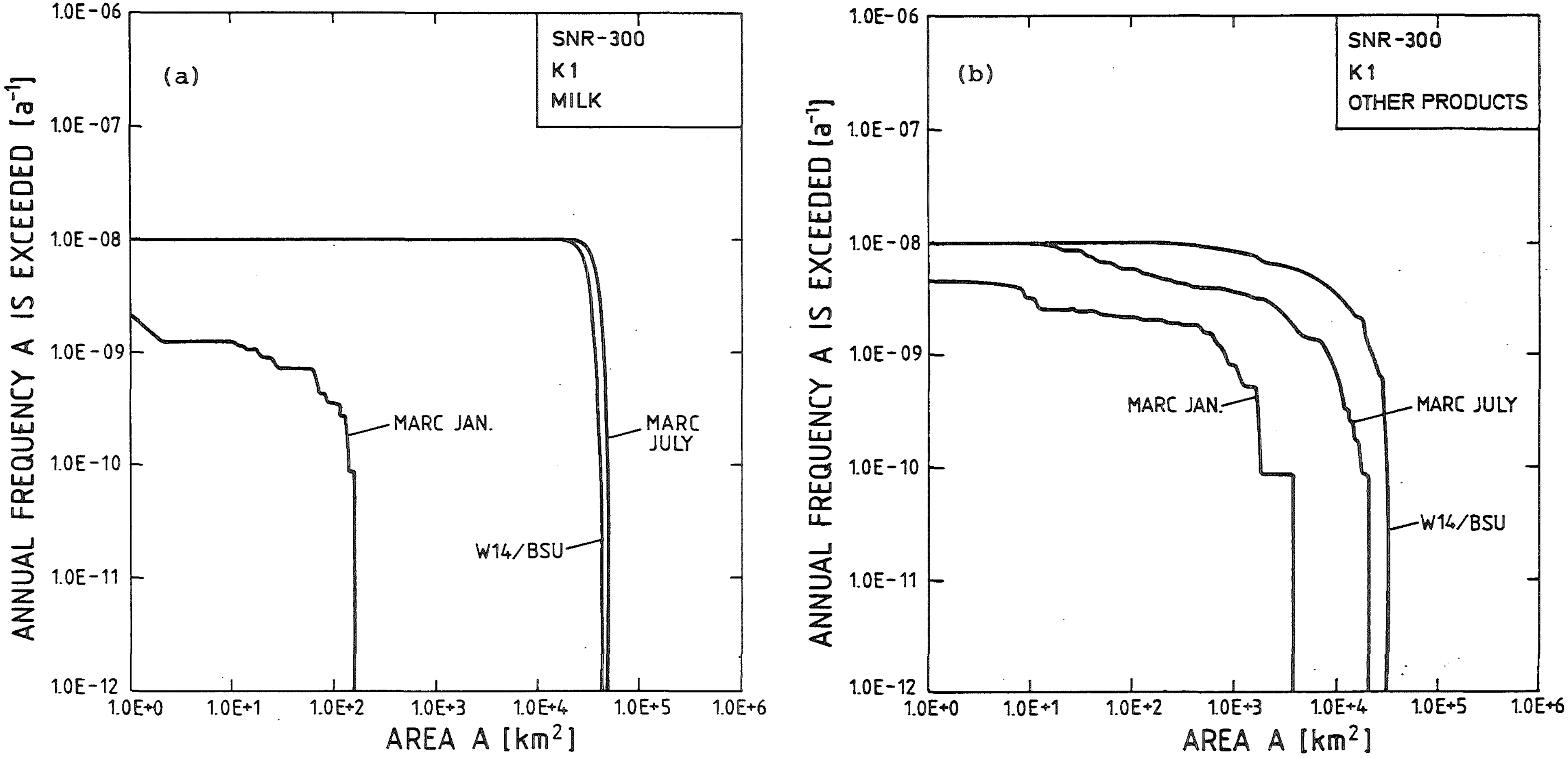

Fig. 1

<u>CCFDs of areas affected by food restrictions in the first year from UFOMOD with different foodchain transport models</u>

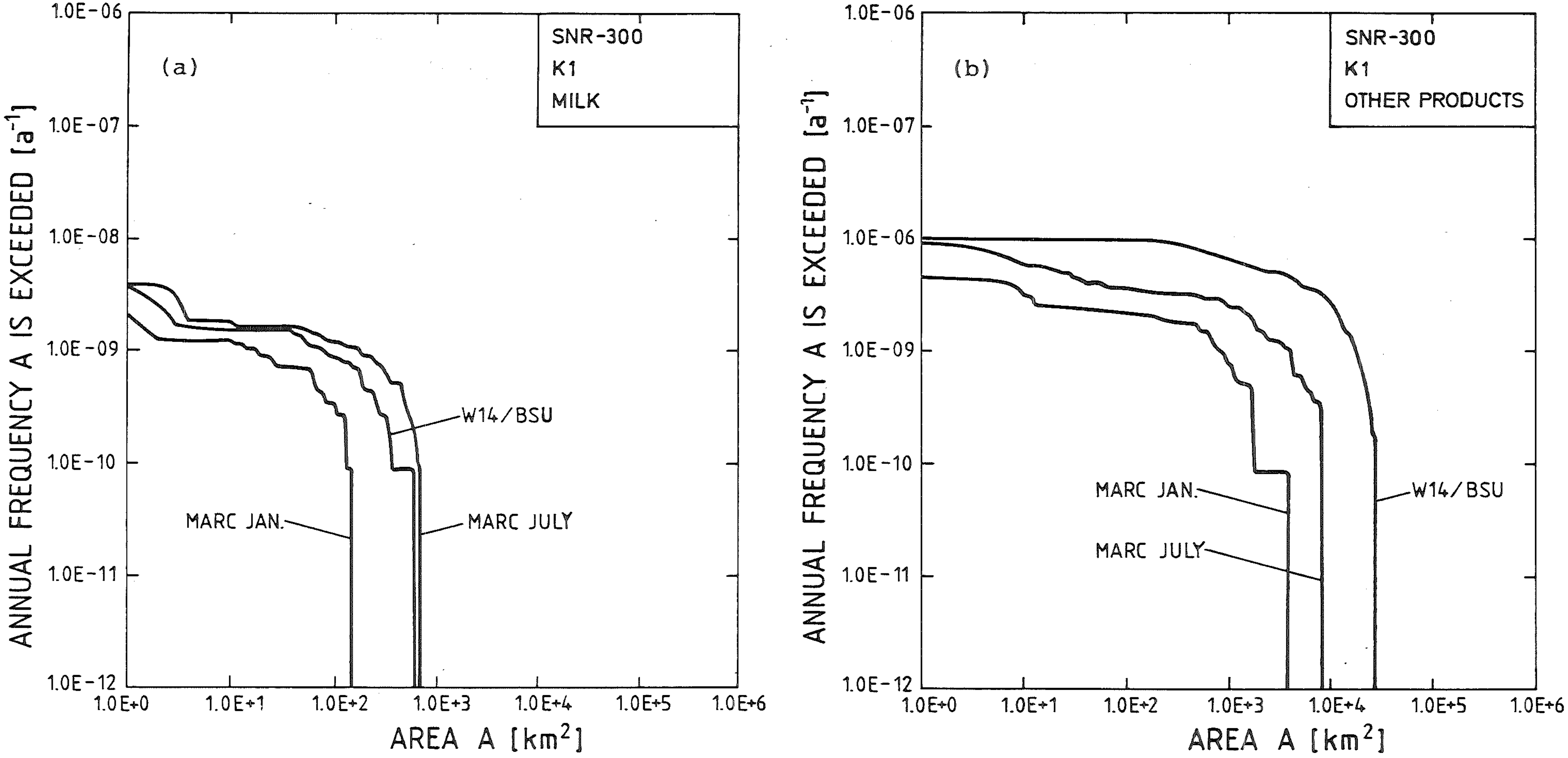

Fig. 2

CCFDs of areas affected by food restrictions in the subsequent years from UFOMOD with different foodchain transport models

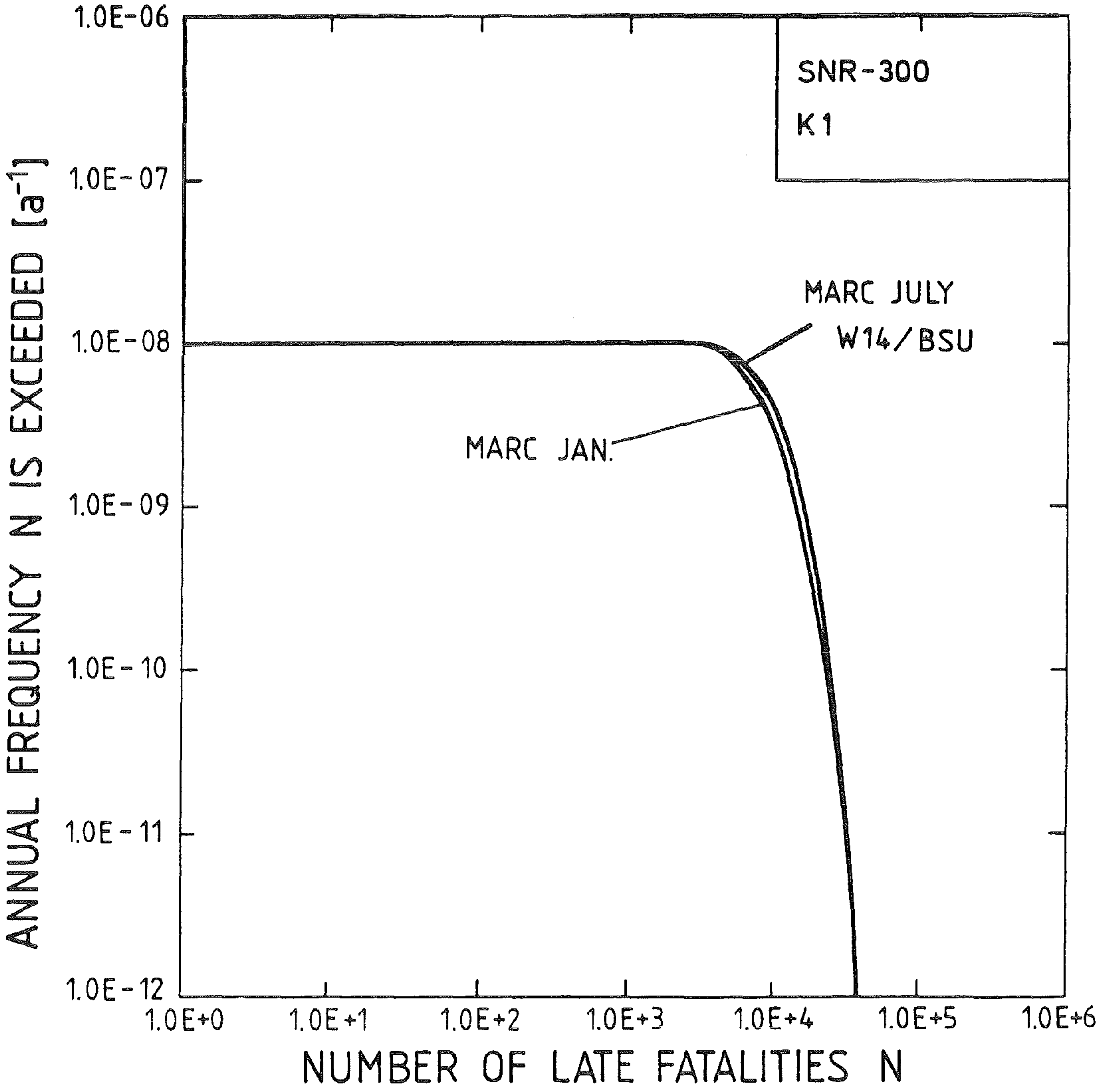

Fig. 3

CCFDs of the number of late fatalities from UFOMOD with different foodchain transport models

Appendix A: Summary of the BSU foodchain transport model for transuranium isotopes

The terrestrial foodchain transport model for transuranium elements implemented in UFOMOD/B04 has been developed by G. Schwarz and H. Bastek from BRENK SYSTEMPLANUNG ('BSU-model') with the intention to estimate the normalized integrated intake of transuranium isotopes resulting from the foodchain pathway. These intakes are given for the first and the subsequent years after a hypothetical accident under the assumption, that the release occurs at the peak of the plants growth. In this appendix the calculation of the intake of activity by ingestion of edible plants and cow's milk and meat are briefly described. Details of the model and the choice of the parameters are given in /5/.

A1. Intake of activity by ingestion of plant products

For edible plants, continuous harvesting is modelled with a rate equivalent to one crop per year. The specific activity C, normalized to an initial deposition[1] of 1 Bq/m^2, is calculated for all plants by:

$$C(t) = \frac{1}{Y} \exp-(\lambda_r+\lambda_w)\cdot t + \frac{CF_r+CF_s}{\rho\cdot D} \exp-(\lambda_r+\lambda_l+\lambda_h)\cdot t \quad (\frac{Bq}{kg} / \frac{Bq}{m^2})$$

where Y is the crop yield, ϱ the soil density, D the depth of the root zone, and CF_r and CF_s are Concentration Factors explained later.

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[1] The activity is assumed to be initially deposited on the surface of the plants, i.e. the interception factor is 1. This can be considered to be realistic, if deposition velocities specific for each depositing substance and vegetative surface are used /17/. In connection with the deposition velocities used in UFOMOD, which represent average values with respect to different surfaces, this assumption is conservative.

The first term of above equation refers to the specific activity on the external parts of the plant which results from direct deposition of activity onto the plant, allowing for removal of the initial activity by radioactive decay (λ_r) and weathering processes (λ_w).

The second term relates the specific activity in soil to the specific activity of the plant by means of Concentration Factors[1]. CF_r describes the transfer of activity from the soil to the plant's interior by root uptake, whereas CF_s describes the contamination of the external parts of the plant by resuspension processes.

The soil is modelled as a single compartment with depth D and is assumed to be well-mixed, i.e. the activity distribution over the root zone is uniform. The exponential factor accounts for activity losses from the soil by radioactive decay (λ_r), leaching to deeper soil layers (λ_l), and the periodic removal out of the soil-plant-system by harvesting of contaminated vegetation (λ_h). The rate constant λ_h depends on the cropping frequency ν, the harvest yield Y, and the activity extracted from the soil by the plant:

$$\lambda_h = \nu \cdot Y \cdot \frac{CF_r + CF_s}{\rho \cdot D} \qquad (d^{-1})$$

The rate constant for leaching λ_e is calculated by

$$\lambda_e = \frac{V}{D \cdot (1 + \rho/\theta \cdot K_d)} \qquad (d^{-1})$$

where V is the leaching velocity of water in the upper soil, D the depth of the soil compartment, ρ the soil density, θ the water content of the soil, and K_d the sorption coefficient.

---

[1] The equilibrium Concentration Factors are defined by

$$CF = \frac{\text{Activity/wet weight plant}}{\text{Activity/dry weight soil}}$$

The transfer of activity from external parts of the plant to the interior (translocation) is considered to be an unimportant pathway for actinides and is thus not taken into account.

The parameters used are collected in Tab. A1 and A2 on pages 46 and 47. The normalized integrated intakes due to the consumption of plant products are calculated by multiplication of the consumption rates (Tab. 3d on page 26) and the integrals over the specific activity for the corresponding span of time (first year or subsequent years). Allowance is made for radioactive decay during an average delay of 1 day between production and consumption of the products, but no account is taken of any removal of activity by washing or other processing of the fresh food (i.e. freezing, canning, drying).

The integrated intakes are given for "leafy vegetables" and "other plant products", but this difference is only generated by the consumption rates and not by different parameters for the activity transport to the plants.

A.2 Intake of activity by ingestion of milk and beef

To approximate German agricultural practice, where cows either graze on pasture only for a fraction of the year or are totally kept indoors for all of the year, it is assumed that the total amount of feed of the cows is composed of 50% fresh pasture grass and 50% hay stored on the average for 90 days, allowing for radioactive decay during storage. In the first year, hay is assumed to be harvested immediately after the deposition so it is not affected by weathering processes.

The transfer of activity to grass by direct deposition, root uptake and soil contamination is described in the same way as for the edible plant products. An empirical factor F relates the daily intake I_c of activity by the cow to the specific activity found in milk and beef. The normalized integrated intake I by man due to the consumption of these foods is calculated by:

$$I_{m,b}(t) = \dot{V}_{m,b} \cdot f_{del} \cdot F_{m,b} \cdot I_c \cdot$$

$$\sum_{n=1}^{2} \left[0.5 \cdot f_n \cdot \frac{1}{y} \cdot \frac{1}{\lambda_{eff,n}} \cdot (1-\exp-\lambda_{eff,n} \cdot t_n) \right.$$

$$+ 0.5 \cdot f_n \cdot \frac{CF_r + CF_s}{\rho \cdot D}$$

$$\left. \cdot \frac{1}{\lambda_r + \lambda_l + \lambda_w} \cdot (1-\exp-(\lambda_r+\lambda_l+\lambda_w) \cdot t) \right]$$

where

t	denotes the integration time
m,b	stands for milk and beef
V	is the consumption rate (see Tab. 3d on page 26)
f_{del}	accounts for radioactive decay for an average delay of 1 day between the production and consumption of milk and beef
n	stands for fresh grass (n = 1) or hay (n = 2), leading to the following set of parameters:

$f_1 = 1$ $\qquad$ $f_2 = \exp-\lambda_r \cdot 90\ d$

$\lambda_{eff,1} = \lambda_r + \lambda_w$ $\qquad$ $\lambda_{eff,2} = \lambda_r$

$t_1 = t$ $\qquad$ $t_2 = 180\ d$

Tab. A1

Parameters for the soil

ρ	density of dry soil		1.60	g/cm^3
Θ	water content		0.22	ml/cm^3
V	water velocity		31	cm/a
D	depth of root zone		15	cm
K_d	sorption coefficient 1)	Np	1.0 E+2	ml/g
		Pu	1.0 E+4	ml/g
		Am	1.5 E+4	ml/g
		Cm	2.0 E+4	ml/g

Note:

1. $$K_d = \frac{\text{sorbed activity} \;/\; \text{g dry soil}}{\text{dissolved activity} \;/\; \text{ml solution}}$$

Tab. A2

Parameters for edible plant products

ν	cropping frequency		1	1/a
Y	harvest yield (wet weight)		2.4	kg/m^2
T_w	weathering half life		30	d
CF_r	Concentration Factor 1) for root uptake	Np	5.0 E-2	
		Pu	1.0 E-3	
		Am	1.0 E-2	
		Cm	5.0 E-2	
CF_s	Concentration Factor 2) for contamination by soil		5.0 E-2	

Notes:

1. $$CF_r = \frac{\text{Bq / kg wet weight plant}}{\text{Bq / kg dry weight soil}} \quad \text{(root uptake)}$$

2. CF_s is defined as above but is for soil contamination of the external plant by resuspension processes

Tab. A3

Parameters for the pasture - milk/meat pathway

	pasture			
ν	cropping frequency		6	1/a
Y	harvest yield (wet weight)		0.85	kg/m^2
T_w	weathering half life		30	d
CF_r	Concentration Factor 1) for root uptake	Np	5.0 E-2	
		Pu	1.0 E-3	
		Am	1.0 E-2	
		Cm	5.0 E-2	
CF_s	Concentration Factor 2) for contamination by soil		5.0 E-2	
	cow			
I_c	grass consumption (wet wgt.)		55	kg/d
T_h	cows feed on stored hay		180	d
T_s	storage duration		90	d
F_m	fraction of the daily intake of activity by the cow found in milk	Np	5.0 E-6	d/l
		Pu	1.0 E-7	d/l
		Am	2.0 E-5	d/l
		Cm	2.0 E-5	d/l
F_b	fraction of the daily intake of activity by the cow found in meat	Np	2.0 E-6	d/kg
		Pu	1.0 E-6	d/kg
		Am	4.0 E-6	d/kg
		Cm	2.0 E-6	d/kg

Notes:

1. $$CF_r = \frac{\text{Bq / kg wet weight plant}}{\text{Bq / kg dry weight soil}} \quad \text{(root uptake)}$$

2. CF_s is defined as above but is for soil contamination of the external plant by resuspension processes

Appendix B: Summary of the MARC foodchain transport model for transuranium isotopes

At the NRPB methods have been developed to evaluate the transfer of transuranium elements through the foodchains with the general compartment model FOOD-MARC. The compartmental structure of the different components of the foodchain are the same as for the non-actinides elements, only translocation of contamination from plant surfaces to internal tissues is not accounted for, because this is generally not considered to be an important transfer mechanism for transuranium elements. However, in comparison to the non-actinides, the uncertainties for many parameters and transfer processes involved are considerably larger.

In this appendix, the compartments and parameters used to produce the results discussed in this report are briefly summarized; more details of the model and the calculations of the specific activities in the foodstuffs can be found in /7/.

B.1 Basic element-independent parameters

Basic element-independent parameters used in the model are given in Tab. B1, they represent average values appropriate for the Uk.

Tab. B1

Element-independent parameters

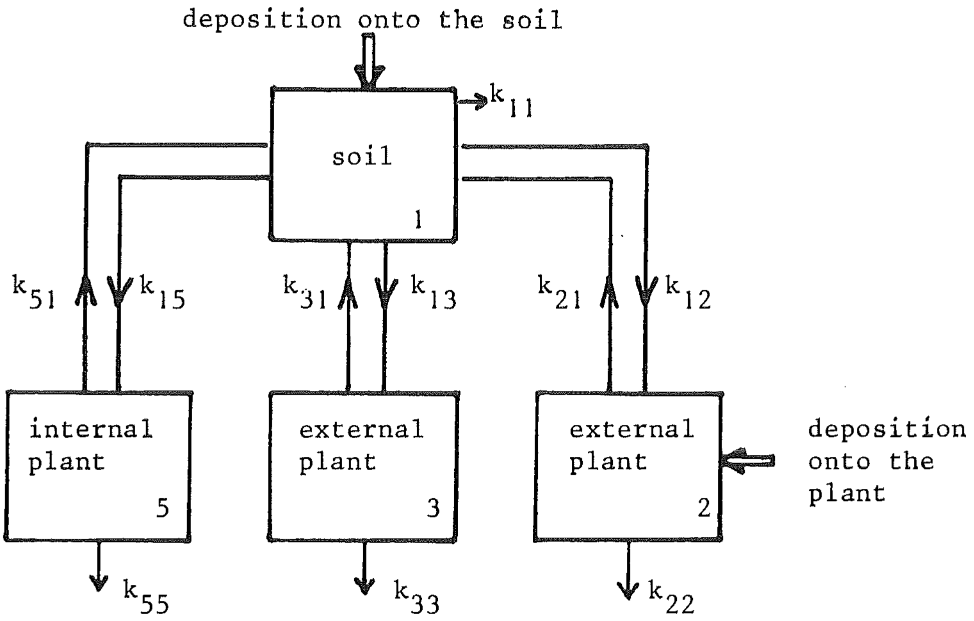
Parameter	Value			
	Grain	Green Vegetables	Pasture	
			grazed	hay/silage
Yield, fresh weight, $kg \cdot m^{-2}$	0.4 1)	1.0	0.5	1.0
water content of plant %	0 1)	90	80	80
Interception factor	0.3/0.012 2)	0.3	0.25	0.45
Soil on plant surface % of dry plant weight	0.01 3)	0.1 4)	-	4
Half-life on plant surface, d	14/14.4 2)	14	14	14
soil density $g.cm^{-3}$(dry)	1.5	1.5	1.5	1.5
Depth of soil, cm	30	30	15 6)	15 6)
half life in 30 cm soil, a	100	100	50 6)	50 6)
activity retained after preparation, %	10 5)	20 5)	-	-

notes:

1. grain seed
2. first value for whole cereal plant, second value for grain **ears** only
3. before processing and removal of husks
4. before kitchen preparation
5. applies to surface contamination only
6. soil is structured into several layers each with different half lives

B.2 Green vegetables

Green vegetables are assumed to be produced continuously throughout the year at a rate equivalent to two crops per year, and to be consumed immediately after harvesting. The structure of the model is illustrated below:



notes:

k_{11} represents leaching from the soil
k_{22}, k_{33}, k_{55} represent periodic cropping
k_{31}, k_{51} are derived from k_{13}, k_{15} for rapid equilibrium

Fig. B1:

Structure of the model for green vegetables

The soil (box 1) is assumed to be well mixed. Weathering of intercepted activity and initial resuspension is represented by box 2. Box 3 stands for the contamination of the external plant at harvest time from activity resuspended from the soil. Compartment 5 represents root uptake from the soil. The transfer coefficients are given in Tab. B2 and B3.

Tab. B2

Parameters for root uptake for edible plants

Element	green vegetables CF	green vegetables transfer coefficient (1/d)	grain CF	grain transfer coefficient (1/d)
plutonium	1.0 E-4	1.92 E-2	1.0 E-6	7.68 E-5
americium	1.0 E-3	1.92 E-1	1.0 E-5	7.68 E-4
curium	1.0 E-3	1.92 E-1	1.0 E-5	7.68 E-4

Note:

1. $$CF = \frac{\text{Bq / kg wet weight plant}}{\text{Bq / kg dry weight soil}}$$

Tab. B3

Parameters for contamination of the external plants

plant type	initial resuspension transfer coefficient (1/d)	soil contamination at harvest transfer coefficient (1/d)	soil contamination at harvest CF
green vegetables	1.56 E-5	1.92 E-2	0.01
grain	5.44 E-5	7.68 E-3	0.01

Note:

1. $$CF = \frac{\text{Bq / kg wet weight plant}}{\text{Bq / kg dry weight soil}}$$

B.-3 Grain

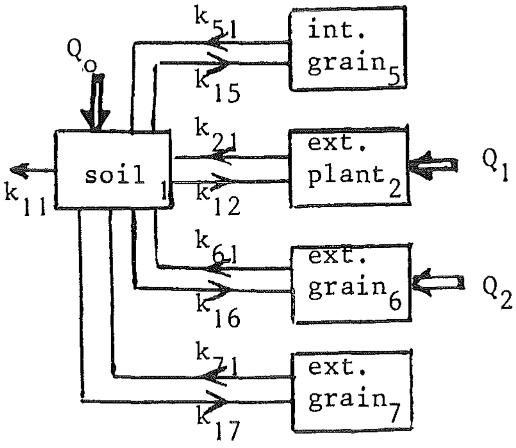
In the first two years, grain is assumed to grow for 123 d from 1st of May to 31st of August, followed by a fallow period of 242 d. In the subsequent years continuous harvesting is assumed with a rate equivalent to 1 crop per year. Taking the day of the assumed deposition as time zero, growth and fallow occur over the following times in the first two years **after** the accident:

day of deposition	fallow before deposition	growth before 1st harvest	fallow after first harvest	growth before 2nd harvest	fallow after 2nd harvest
	(all times in days)				
1st Jan	0 - 120	120 - 240	240 - 485	485 - 605	605 - 730
1st July	-	0 - 60	60 - 305	305 - 425	425 - 730

The grain harvested at 1st of September is assumed to be consumed until next harvest, taking into account the radioactive decay over this time. In calculating the intake of activity in the first year after the deposition, the time between 1st harvest and the end of year one after deposition must be determined:

day of deposition	1st Jan.	1st July
time of consumption of 1st crop in 1st year after deposition (d)	125	305

The structure of the model is illustrated on p. B6; the parameters are given in Tab. B2 and B3 on page 51.



(a) first growth

notes:

Q_o : deposition onto the soil

Q_1, Q_2 : deposition onto plant and grain

k_{11} : leakage from the soil

k_{55}, k_{77}: continuous cropping

k_{12} : initial resuspension } whole plant

k_{21} +): weathering losses } whole plant

k_{16} : initial resuspension } grain

k_{61} : weathering losses } grain

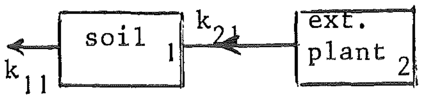
k_{15} : root uptake from soil

k_{51} : derived from k_{15} for rapid equilibrium

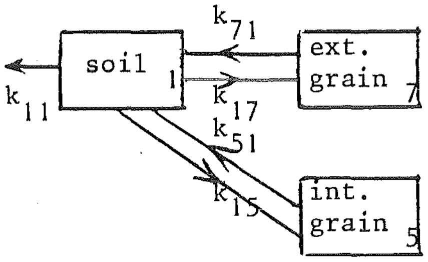
k_{17} : soil contamination at harvest

k_{71} : derived from k_{17} for rapid equilibrium

+) k_{21} : in case (b) represents transfer to soil from straw left on field and ploughed under (8.64 E+4 d^{-1})



(b) first fallow

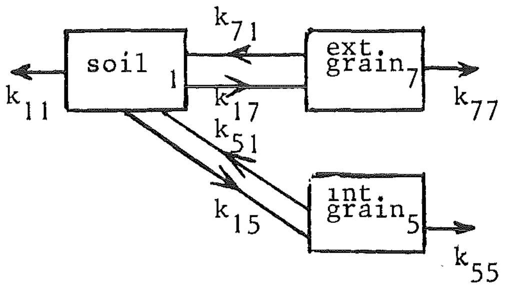


(c) second growth

(d) second fallow

Fig. B2

Structure of the model for grain



(e) continuous cropping

B.4 Pasture-milk/beef

Cows are assumed to graze on pasture from 17th April to 30th October (198 d) and stay indoors from 1st November to 16th April (167 d). During this time they are fed hay or silage. The hay or silage is assumed to have the same concentration of radionuclides, on a dry weight basis, as the grass from which it is obtained. Harvesting is assumed to be continuous between 1st of May to 15th of September (138 days) at a rate equivalent to three complete cuts during this time. Hay/silage is then stored until 1st November (46 d), allowing for radioactive decay, and fed to the animals until the next 16th April (167 d). From the time when the cows return to pasture after the first winter after the accident, when the effect of the direct deposition on the pasture is no longer felt, they are assumed to graze outside permanently. The time schedules relative to the date of deposition are given below:

Time schedule for hay/silage model (all times in days)

day of deposition	pasture without harvesting	harvesting	storage	fed to animals (total)	fed to animals in 1st year after deposition
1st Jan.	0 - 120	120 - 258	258 - 304	304 - 471	61
1st July	-	0 - 77	77 - 123	123 - 290	total=167

Time schedule for cow model (all times in days)

day of deposition	cows inside (fodder not yet contaminated)	cows outside	cows inside (fed contaminated fodder)	cows outside permanently
1st Jan.	0 - 106	106 - 304	304 - 471	≥ 471
1st July	-	0 - 123	123 - 290	≥ 290

The following table gives the basic parameters of the cow-model:

Tab. B4

Basic parameters of the cow-model

depth of soil for root uptake	15 cm
half-life in 30 cm soil	50 a
yield of edible pasture	$5 \cdot 10^5$ $kg \cdot km^{-2}$ (wet weight)
soil contamination on plant	4%
grass consumption (dry weight)	12/15 $kg \cdot d^{-1}$ for pasture/hay
number of animals per km^2	250
resuspension coefficient	10^{-6} m^{-1}
deposition velocity	$3 \cdot 10^{-3}$ $m \cdot s^{-1}$
inhalation rate	$1{,}5 \cdot 10^{-3}$ $m^3 \cdot s^{-1}$
lung class	W
gut transfer fraction	$5 \cdot 10^{-4}$
mean life for slaughter	6 a
milk production rate	10 $l \cdot d^{-1}$
carcass/lean meat per animal	360/150 kg
weight of liver per animal	6 kg

The basic model for the undisturbed pasture is illustrated in Fig. B3, the parameters are given in Tab. B5. The model for the behaviour of the transuranium elements in the cows and the transfer coefficients are shown in Fig. B4 and Tab. B6, (page 59).

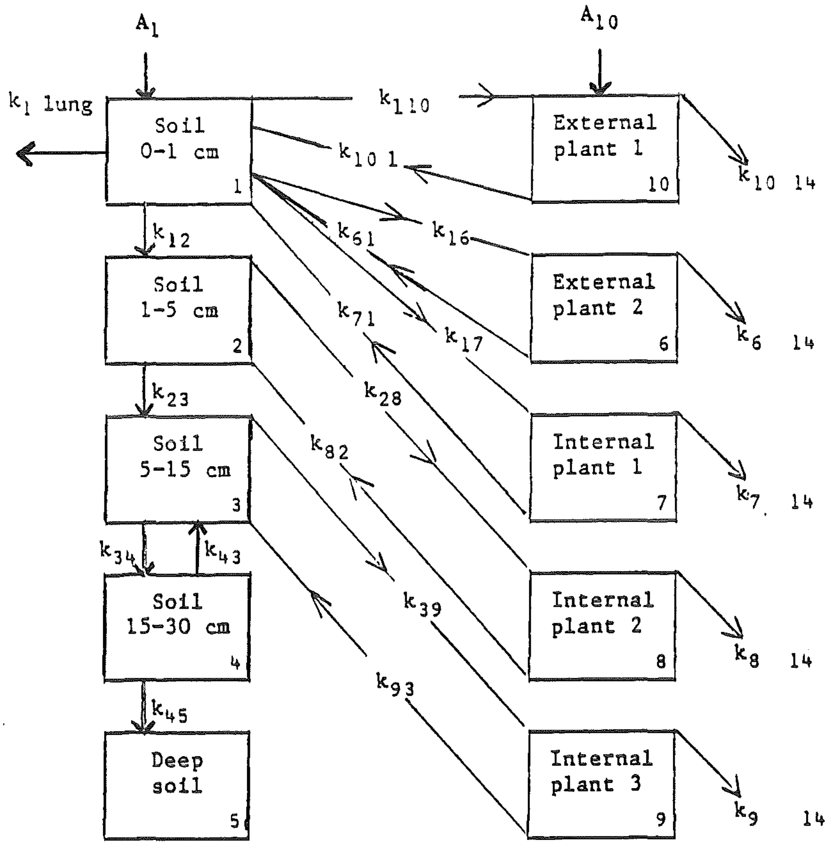


Fig. B3

Undisturbed pasture and hay/silage model

notes:

1. External plant (1) is for direct deposition and initial resuspension.
2. External plant (2) is for surface soil contamination of the plant, and represents all soil consumed by an animal on the pasture.
3. The internal plant compartments represent root uptake from the different layers of soil.
4. $k_{1\,10}$ represents resuspension onto the plant surface, and $k_{10\,1}$, the losses due to weathering processes.
5. $k_{6\,14}$, $k_{7\,14}$, $k_{8\,14}$, $k_{9\,14}$ and $k_{10\,14}$ represent losses from the pasture due to its consumption by animals.
6. $k_{1\,\text{lung}}$ represents inhalation by the animal of resuspended material from the soil.

The model for hay/silage is essentially the same as that for undisturbed pasture. The differences are:-

1. Compartment 5 represents hay both during cropping, and while it is being stored for silage.
2. External plant (2) is for contamination of the plant by soil.
3. The loss from compartment 4 to deep soil is now represented by k_{44}.
4. The hay crop is grown from 1st May until the 15th September and during this time it is assumed that there are 3 harvests. From 15th September to 31st October the hay is stored as silage before consumption by cattle during the winter months. During the storage period there is no input to compartment 5.

Tab. B5

Transfer coefficients for the pasture and hay/silage models

(a) Element-independent transfer coefficients

Transfer coefficicient	Value d^{-1}	
	Pasture	Hay/silage
k_{12}	$6.65\ 10^{-4}$	$6.65\ 10^{-4}$
k_{23}	$1.72\ 10^{-4}$	$1.72\ 10^{-4}$
k_{34}	$1.07\ 10^{-4}$	$1.07\ 10^{-4}$
k_{43}	$4.03\ 10^{-6}$	$4.03\ 10^{-6}$
k_{45}	$3.80\ 10^{-5}$	-
k_{44}	-	$3.80\ 10^{-5}$
$k_{1\ 10}$	$6.48\ 10^{-6}$	$1.18\ 10^{-5}$
$k_{10\ 1}$	$4.95\ 10^{-2}$	$4.95\ 10^{-2}$
k_{16}	$2.31\ 10^{1}$	$4.98\ 10^{1}$
k_{61}	$8.64\ 10^{4}$	$8.64\ 10^{4}$
k_{71}	$8.64\ 10^{4}$	$8.64\ 10^{4}$
k_{82}	$8.64\ 10^{4}$	$8.64\ 10^{4}$
k_{93}	$8.64\ 10^{4}$	$8.64\ 10^{4}$
$k_{65}, k_{75}, k_{85}, k_{95}, k_{10\ 5}$	-	$2.17\ 10^{-2}$

(b) Animal dependent transfer coefficients

Transfer coefficients for cows	value (d^{-1})
$k_{6\ 14}$, $k_{7\ 14}$, $k_{8\ 14}$, $k_{9\ 14}$, $k_{10\ 14}$	$3.00 \cdot 10^{-2}$
$k_{1\ 21}$	$2.04 \cdot 10^{-9}$ (1)

note:

1) for transuranium elements

Tab. B5 cont'd

Transfer coefficients for the pasture and hay/silage models

(c) element-dependent transfer coefficients

element	model	value (d^{-1}) $k_{1\ 7}$	 $k_{2\ 8}$	 $k_{3\ 9}$	Concentration Factor [1]
plutonium	pasture hay/silage	2.88 E-1 6.22 E-1	7.20 E-2 1.55 E-1	2.88 E-2 6.22 E-2	1.0 E-4
americium	pasture hay/silage	2.88 E+0 6.22 E+0	7.20 E-1 1.55 E+0	2.88 E-1 6.22 E-1	1.0 E-3
curium	pasture hay/silage	2.88 E+0 6.22 E+0	7.20 E-1 1.55 E+0	2.88 E-1 6.22 E-1	1.0 E-3

note:

1. $$CF = \frac{\text{activity / unit wet weight plant}}{\text{activity / unit dry weight soil}}$$

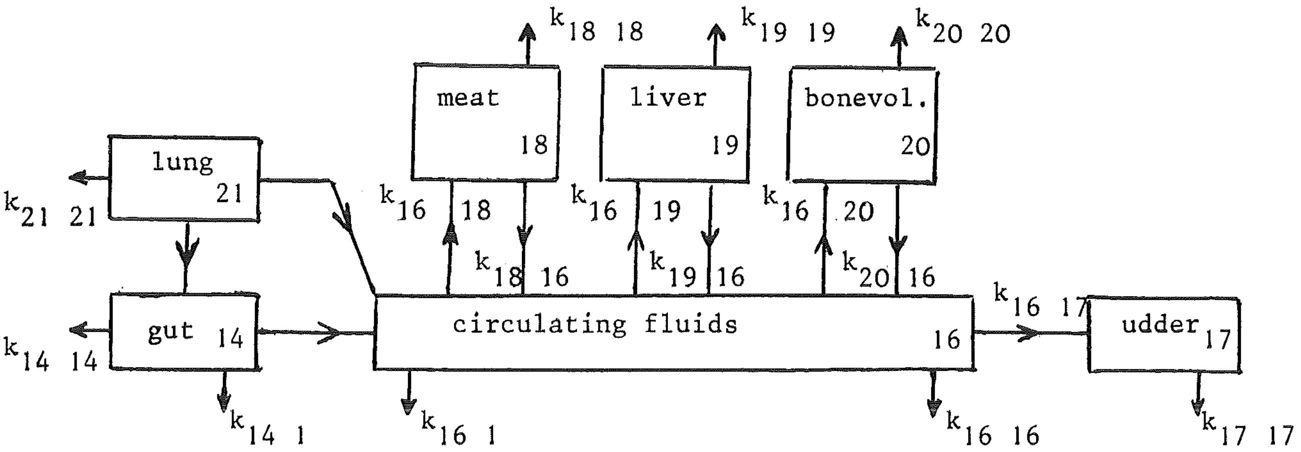


Fig. B4

Metabolism of the cows

notes:

1. $k_{14\ 1}$ **and** $k_{16\ 1}$ represent return to the soil (compartment 1) due to excretion processes
2. $k_{14\ 14} \ldots k_{21\ 21}$ represent the periodic slaughter of the cows
3. $k_{17\ 17}$ represents loss due to milking

Tab. B6

Transfer coefficients for cow model[1)]

$k_{\text{from to}}$	value (d^{-1})
$k_{14\ 14} \ldots k_{21\ 21}$	4.57 E-4
$k_{17\ 17}$	3.02 E+0
$k_{14\ 1}$	1.11 E+0
$k_{16\ 1}$	1.00 E-2
$k_{21\ 14}$	1.04 E-1
$k_{21\ 16}$	2.07 E-2
$k_{14\ 16}$	5.53 E-4
$k_{16\ 17}$	1.00 E-2
$k_{16\ 18}$ $k_{16\ 19}$ $k_{16\ 20}$	2.00 E+0
$k_{18\ 16}$	4.76 E-1
$k_{19\ 16}$	1.48 E-1
$k_{20\ 16}$	2.46 E-2

note:

1. for transuranium elements

Appendix C: Comparison of the intake values for actinides from FOOD-MARC and BSU

To study the differences between the foodchain transport models for actinides, BSU and FOOD-MARC, values of the normalized integrated intake for edible plant products, milk and cow's meat have been compared. Unit consumption rates (1 $kg \cdot a^{-1}$ or 1 $l \cdot a^{-1}$) were used in the calculations of the intake values to avoid any bias from the consumption rates assumed in both models. To represent the spectrum of radioactive half-lives and environmental behaviour, the radionuclides Pu-239 ($T^{1/2}$ = 24 000 a), Am-241 ($T^{1/2}$ = 432 a), Cm-244 ($T^{1/2}$ = 18 a) and Cm-242 ($T^{1/2}$ = 0.45 a) were considered. The FOOD-MARC data from July were used in the comparison which correspond approximately to the "deposition in summer" assumed in the BSU-model.

The values for an intake in the first year after an assumed accident and in the subsequent two hundred years are given in Tab. C1 and C2, respectively. The development of the intake with the integration time is shown exemplarily for Am-241 in Tab. C3 (FOOD-MARC) and Tab. C4 (BSU). The results obtained for the individual foodstuffs are discussed in the following sections.

C.1 Green vegetables

In the BSU-model the transfer of activity to edible plants is considered for one plant type only. The plants are assumed to be produced and consumed continuously and correspond to the green vegetables in FOOD-MARC.

The intake values from the BSU-model systematically exceed those from FOOD-MARC by a factor of about 15 in the first year and by two orders of magnitude or more in the following 200 years (Tab. C1 and C2). In FOOD-MARC, ~90% of the total intake in all years comes from the first year, compared to only 30% in the BSU-model (Tab. C3 and C4).

Tab. C1

Comparison of the intake in the first year from FOOD-MARC and BSU (unit consumption rates)

foodstuff	foodchain transport model	Pu-239	Am-241	Cm-244	Cm-242
green vegetables	BSU	5.0E-2	5.0E-2	5.0E-2	4.2E-2
	FOOD-MARC (July)	3.0E-3	3.0E-3	3.0E-3	2.8E-3
grain products	FOOD-MARC (July)	1.5E-4	1.5E-4	1.4E-4	6.4E-5
	BSU MODIFIED *	1.7E-4	1.7E-4	1.7E-4	1.5E-4
milk	BSU	2.0E-6	4.0E-4	3.9E-4	2.2E-4
	FOOD-MARC (July)	1.1E-6	1.1E-6	1.0E-6	4.8E-7
cow's meat	BSU	2.0E-5	7.9E-5	3.9E-5	2.2E-5
	FOOD-MARC (July)	5.8E-5	5.8E-5	5.7E-5	2.6E-5

* for details see text

Tab. C2

Comparison of the intake in the years 1-200 from FOOD-MARC and BSU (unit consumption rates)

foodstuff	foodchain transport model	Pu-239	Am-241	Cm-244	Cm-242
green vegetables	BSU	4.0E-2	4.0E-2	1.0E-2	5.7E-5
	FOOD-MARC (July)	2.7E-5	2.1E-4	4.6E-5	0.0
grain products	FOOD-MARC (July)	3.3E-5	3.4E-5	3.0E-5	5.6E-6
	BSU MODIFIED *	2.6E-6	4.2E-6	9.4E-7	6.0E-9
milk	BSU	2.1E-7	4.1E-5	1.1E-5	5.2E-8
	FOOD-MARC (July)	3.1E-6	3.2E-6	2.7E-6	1.4E-7
cow's meat	BSU	2.1E-6	8.3E-6	1.0E-6	5.2E-9
	FOOD-MARC (July)	1.7E-4	1.8E-4	1.5E-4	7.9E-6

* for details see text

Tab. C3

Contribution in % of the intake of Am-241 in different time-intervals to the total intake derived from FOOD-MARC

	intake time									
	0 - 1 a		0 - 2 a		0 - 5 a		0 - 50 a		0 - 100 a	
	time of deposition									
foodstuff	Jan.	July	Jan.	July	Jan.	July	Jan.	July	Jan.	July
green vegetables	92	92	92	92	93	93	95	95	97	97
grain products	0.3	81	1	97	4	97	35	98	57	99
milk; cow's meat, liver	6	25	20	51	44	72	98	99	100	100

Tab. C4

Contribution in % of the intake of Am-241 in different time-intervals to the total intake derived from BSU

	intake time				
foodstuff	0 - 1 a	0 - 2 a	0 - 5 a	0 - 50 a	0 - 100 a
edible plants	30	31	31	38	45
milk / meat	81	81	81	84	86

If the parameters in the BSU-model are replaced by the corresponding parameters from FOOD-MARC, the intake values calculated with this modified BSU-model agree with those from FOOD-MARC within 10%, showing that the differences between the model predictions are due to the choice of the input data rather than to the modelling of the transfer processes involved.

C.2 Grain products

In FOOD-MARC, grain is assumed to be harvested at the end of August and to be consumed over the following year[1], whereas in BSU all edible plants are assumed to be produced and consumed continuously. To study the influence of the different agricultural practice on the intake, values were calculated with the BSU-model using the parameters for grain from the MARC model.

From Tab. C1 and C2 it can be seen, that for the long-lived isotopes the first year's intake derived with the modified BSU-model and FOOD-MARC show only small deviations, whereas in the subsequent years the FOOD-MARC values are higher by a factor of $\sim$10.

In the BSU-model, the time after the accident is synchronous to the harvest- and consumption time scale, so that the important effect of direct deposition of activity onto the grain is only felt in the first year. In FOOD-MARC, however, a part of the first year's harvest may be consumed in the second year after the release. Although for an assumed accident at the 1st of July this affects only two months of the second year (July and August), the contribution to the long-term intake is considerable because of the much higher concentration level in the first years crop. For Cm-242, which has a radioactive half-life of $\sim$0.5 a, the influence of the agricultural practice is more expressed because of the radioactive decay during the delay time between production and consumption.

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[1] This is modelled for the first two years after the accident. In all following years, continuous production and consumption is assumed.

C.3 Cow's milk and meat

For the intake of milk, higher values are predicted with the BSU-model for most of the isotopes considered (Tab. C1 and C2). For meat, the first year's intakes agree within a factor of ~2, whereas in the following years the FOOD-MARC values are higher by one or two powers of 10. The contribution of the intake in the first year to the total intake and the time development is also very different between the two models (Tab. C3 and C4).

In contrast to the edible plant products, the differences cannot be attributed to the input data or the agricultural practices alone. Although this may eventually explain some of the gross features, for instance the higher intake of milk in the BSU-model, the overall behaviour of the results reflect the very different model assumptions about the transport of the activity ingested by the cow to milk and meat and the distribution of the radioactive material in the soil.

C.4 Conclusions

Large discrepancies have been found between the intakes of transuranium isotopes predicted by the BSU-model and FOOD-MARC. Part of the discrepancies can be explained completely by differences in the input data and in the assumptions about the agricultural practice (edible plants), part by a combination of both together with differences in the modelling of the transfer processes involved (cow's milk and meat).

Some of the differences in the parameter values are due to different model assumptions, e.g. about the interception of depositing activity 1) and the activity losses during food preparation. Although the BSU-model is not intended to be con-

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1) see also footnote on p. 42

servative in general, it is so with respect to these two aspects, whereas FOOD-MARC is not.

Another reason for the parameter differences lies in the considerable variation and uncertainty in many of the parameters for actinides (e.g. transfer coefficients, half-life in soil etc.). The variation of the values used in both models reflect the problem of "expert judgement" that has to be excercised in the choice of representative input data. However, there are also considerable differences in some other basic parameters, like for instance the harvest yield, effective depth of soil for root uptake etc..

Although the differences between the foodchain transport models for actinides may not show up in all results of an accident consequence assessment, as it was for instance the case in the overall number of late health effects discussed in Chapt. 4.3, a careful uncertainty analysis is necessary for applications where the ingestion of actinides may be important.

Acknowledgement

The author is kindly indebted to Joanne Burgess, NRPB, for providing the data from FOOD-MARC.

References

/1/ M. Schückler, S. Vogt
UFOMOD - Programm zur Berechnung der radiologischen Folgen von Reaktorunfällen im Rahmen von Risikostudien
Report KfK-3090 (1981)

/2/ A. Bayer, K. Burkart, J. Ehrhardt et al.
The German Risk Study: Accident Consequence Model and Results of the Study
Nucl. Technol., 59, 20 (1982)

/3/ Reactor Safety Study - An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants.
WASH-1400 (NUREG-75/914), NUREG (1975)

/4/ A. Bayer and J. Ehrhardt
Risk-Oriented Analysis of the German Prototype Fast Breeder Reactor SNR-300: Offsite Accident Consequence Model and Results of the Study
Nuclear Technology, Vol. 65, May 1984, p. 232

/5/ G. Schwarz, H. Bastek
Untersuchungen zum Transport und zur Verteilung von Transuranen in terrestrischen Nahrungsketten
BSU-report 8109/1, April 1982

/6/ J.R. Simmonds, G.S. Linsley, J.A. Jones
A general model for the transfer of radioactive materials in terrestrial food chains.
Chilton, NRPB-R89 (1979)

/7/ J.R. Simmonds
The Influence of Season of the Year on the Transfer of Radionuclides to Terrestrial Foods Following an Accidental Release to Atmosphere
Chilton, NRPB-M121 (1985)

/8/ M. Matthies, et al.
Simulation des Transfers von Radionukliden in Landwirtschaftlichen Nahrungsketten.
GSF-Bericht S-882 (1982)

/9/ C. Steinhauer
Comparison of the Foodchain Transport Models of WASH-1400 and MARC Using the Accident Consequence Model UFOMOD.
Report KfK 3907 (1985)

/10/ P.J. Coughtrey and M.C. Thorne
Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems (Vol. 1), EUR-8115 I (1983), Balkema, Rotterdam

/11/ R.H. Clarke, G.N. Kelly
MARC - the NRPB Methodology for Assessing Radiological Consequences of Accidental Releases of Activity.
Chilton, NRPB-R17 (1981) (London, HMSO)

/12/ G.S. Linsley, J.R. Simmonds and G.N. Kelly
An Evaluation of the Food Chain Pathway for Transuranium Elements Dispersed in Soils
Chilton, NRPB-R81 (1978)

/13/ D. Charles, et al.
DOSE-MARC: The Dosimetric Module in the Methodology for Assessing in Radiological Consequences of Accidental Release
Chilton, NRPB-M74 (1982)

/14/ J. Ehrhardt
Dokumentation der Datensätze im Dosis- und Schadensmodell des Rechenprogramms UFOMOD/B3.
Report KfK-3390 (1982)

/15/ J.R. Simmonds
The Influence of the Season of the Year on the Predicted Agricultural Consequences of Accidental Releases.
Chilton, NRPB-R178 (1985)

/16/ Statistisches Jahrbuch 1983 für die Bundesrepublik Deutschland.
Statistisches Bundesamt, Wiesbaden (1983)

/17/ C.W. Miller
Validation of a Model to Predict Aerosol Interception by Vegetation.
In: Biological Implications of Radionuclides Released from the Nuclear Industry, pp 351-361, IAEA, ST1/PUB/522 (1979)