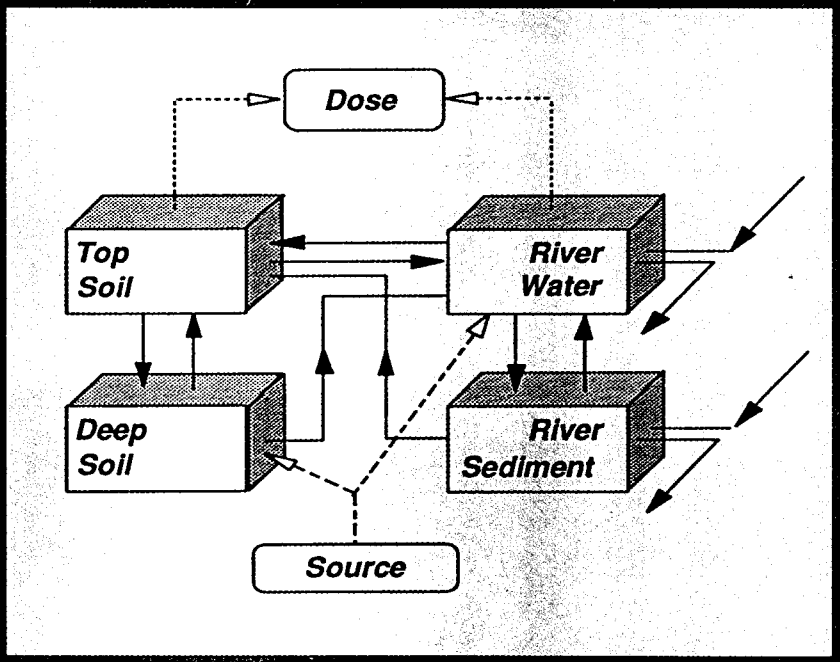
An International Code Intercomparison Exercise
on a Hypothetical Safety Assessment Case Study
for Radioactive Waste Disposal Systems

PSACOIN LEVEL 1B INTERCOMPARISON

Probabilistic System Assessment Group (PSAG)



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PSACOIN LEVEL 1B INTERCOMPARISON

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This report was prepared on behalf of the PSAG by

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium,Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971) and New Zealand (29th May 1973). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all European Member countries of OECD as well as Australia, Canada, Japan and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

PREFACE.

The NEA Radioactive Waste Management Committee (RWMC), established in 1975, is an international committee of senior governmental experts familiar with the scientific, policy and regulatory issues involved in radioactive waste management. A primary objective of the RWMC is to improve the general level of understanding of waste management issues and strategies, particularly with regard to waste disposal, and to disseminate relevant information. Current NEA programmes under the RWMC focus on methodologies for the long-term safety assessment of waste disposal, and on site evaluation and design of experiments for radioactive waste disposal.

The NEA Probabilistic Systems Assessment Group (PSAG) was established by the RWMC in January 1985 (as PSAC - the Probabilistic Systems Assessment Code User Group) to help coordinate the development of probabilistic safety assessment codes in Member countries. It meets twice a year to discuss topical issues and code intercomparisons and to exchange information. This is the fourth in a planned series of code intercomparisons undertaken by the Group and published by the OECD/NEA.

The NEA Data Bank undertakes the collection, validation, and dissemination of computer programmes and scientific data within the NEA's field of interest. Among its tasks is the provision of computing support for radioactive waste management activities, including code exchange and the analysis of code intercomparisons.

Contents

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EXECUTIVE SUMMARY.

The Probabilistic Systems Assessment Group (PSAG) was established by the Nuclear Energy Agency in 1985 to assist in the development of probabilistic safety assessment (PSA) codes by Member countries of the OECD. PSA codes are used in the preparation of environmental assessments to help quantify the variability and uncertainty associated with the calculations upon which assessments are largely based. In particular, PSA codes are of special interest in assessing concepts for the underground disposal of radioactive waste.

A major goal of PSAG is to enhance confidence in the capabilities of PSA and associated computer codes. Code intercomparisons can provide evidence that different codes developed and operated by different groups produce comprehensible results when applied to the same problem. Such evidence contributes to the verification of the codes involved.

This report documents the Group's fourth PSA code intercomparison (PSACOIN) exercise known as Level 1b. This exercise is part of a succession of exercises that began with the Level 0 study and has been continued with Level E and Level 1a. Level 0 involved a highly idealised disposal system model, and code verification focused on the executive and postprocessing functions. In Level E the existence of an exact analytical solution was particularly important because it allowed not only an intercomparison of the results between codes, but also a benchmark against which the results from all codes could be compared. The Level 1a intercomparison was based on a less idealised system model involving deep geological disposal concepts with a relatively complex structure for the repository vault.

In contrast to the previous PSACOIN exercises, Level 1b focuses on the biosphere modelling aspects of the assessment of the radiological impact of the disposal of radioactive waste in greater detail (and in doing so geosphere modelling is **not** included). In the earlier studies, the estimate of risk relied on the derivation of doses to individuals via their consumption of contaminated drinking water. In Level 1b seven exposure pathways are modelled (drinking water, freshwater fish, meat, milk and grain consumption as well as external γ-irradiation and contaminated dust inhalation). These doses are assumed to be received by an individual residing in an agricultural biosphere featuring surface soils (i.e. the rooting zone for crops and pasture) in which crops are grown, and on which cattle are grazed. The hypothetical exposed individual is assumed to obtain all dietary requirements from locally grown produce and to obtain drinking water from the river that flows in the region. This river is also used as an irrigation source and to provide drinking water for cattle. Airborne dust can also be inhaled by the individual and γ-irradiation from concentration of radionuclides in the soil also can lead to external doses. Annual exposures via these pathways assume that the hypothetical individual remains in the region on a yearly basis and doses via the inhalation pathway also take into account the possibility of enhanced airborne dust concentrations as a result of occupational activities such as ploughing for a limited fraction of the year. Variable parameters selected for the exposure pathway sub-model were chosen to focus on the exposure rates for these pathways.

Radionuclides released in groundwaters in the region will accumulate in the upper soil (where they will be taken up by plants) and in the river water (used for drinking and irrigation purposes). In order to model the accumulation of radionuclides in these parts of the biosphere, transport mechanisms between other parts of the biosphere must be modelled. The Level 1b biosphere transport model takes into account a deeper soil layer which is not directly involved in root uptake processes, and a river sediment layer which may in the course of time become transferred to the associated farmland as a result of river ageing or dredging of the river. The variable parameters in the biosphere transport model included factors influenced by climate, the size of the river, the area of the biosphere affected by the release from the regional groundwaters and the mechanisms for the transport of radionuclides on solid material.

The biosphere system defined for the exercise is based on the type used in several Member countries to estimate the consequences of the release of radionuclides to inland terrestrial-aquatic biospheres. The transport and exposure pathway sub-models were precisely defined and, although the list of features, events and processes (FEPs) included in the Level 1b representation of the biosphere is not exhaustive, the model as used in the exercise is able to illustrate many generic features of the biosphere response to the release of radionuclides via groundwaters. The exercise itself should not be seen as a model of a particular site or of a certain type of disposal concept, rather, the Level 1b biosphere model should be seen as a test-bed for this type of biosphere representation in the context of PSA for radioactive waste disposal assessments.

The choice of the source term for Level 1b reflects this usage. The timescales for the release to the biosphere are representative of those which may be expected in assessments of the geologic disposal of radioactive waste. The start time of the release to the biosphere is chosen, for convenience, to be time zero. The radionuclides selected were chosen because they have been shown to be of interest in other studies and because of their physical, chemical and radiological properties. Thus a single, relatively short-lived, mobile radionuclide and a relatively long-lived, sorbing, decay-chain parent were selected, because of the different ways in which they would interact with the biosphere system. The release of the parent of the chain causes the daughters to grow in in the biosphere. Each of the decay-chain members has specific properties, so adding to the variety of the biosphere response. Doses for the chain were calculated by summing over the radionuclides, so that the end point gives the dose associated with the release of the parent to the biosphere.

The objectives of the Level 1b exercise can be summarised as follows:

1. to gain experience in the application of probabilistic systems assessment methodology to transport and radiological exposure sub-models for the biosphere and hence to methods of estimating the total risk to individuals, or groups of individuals;
2. to contribute to the verification of biosphere transport and exposure sub-models used by the participants;
3. to investigate the effects of parameter uncertainty in the biosphere transport and exposure sub-models on the estimate of mean dose to individuals exposed via several exposure pathways.

Corresponding to the second of these aims, a Questionnaire was designed to extract the basic information from the participants' results and so to enable the intercomparison of the models employed in the exercise. Participants were also encouraged to submit additional analyses of their results in support of the other objectives, and these results have been useful in demonstrating features of this kind of biosphere representation that are relevant to performance assessment applications.

Although the specification of the PSACOIN Level 1b model is only one representation of the biosphere, and it is not expected be universally applicable to all biosphere systems, the following conclusions can be drawn on the basis of the analysis of the participants' responses to this exercise. (The corresponding Level 1b objective is given in brackets.)

- The different codes and routines used by the participants to solve the compartment model transport equation performed equally well. This is true not only of the deterministic central case, but also extends to the ranges and combinations of parameters specified in the stochastic phase of the exercise. Some apparently systematic variation was seen in the stochastic results, but it is largely possible to account for this in terms of the scatter seen in the deterministic results. However the precise nature of this feature could not be fully understood with the data available and investigations should continue if similar features are seen in subsequent probabilistic intercomparisons (1, 2);
- The biosphere is a complex system potentially containing many feedback loops. One consequence of this is that no single parameter dominates the uncertainty in the biosphere as modelled here. Different parameters have a significant effect on the overall uncertainty in dose at different times. Thus the issue of timescales becomes important, as well as the influence of the repository release time and the transport time in the geosphere, both of which have **not** been addressed here (1, 3);
- It is not easy to account for the uncertainties in biosphere transport and accumulation processes with simpler models of the biosphere than the one specified in this exercise. However the successful application of the Level 1b model demonstrates that such relatively complex biosphere models can be implemented in PSA codes for waste disposal assessments. The use of such models is recommended since they demonstrate time-dependent features not available from simpler systems (1);
- In this exercise the peak mean dose calculated in the stochastic runs was around a factor of five greater than the peak dose in the deterministic central case (3).;
- The relative importance of the various exposure pathways can vary as a function of time. This feature can be important for decay chains and is particularly apparent when the properties of the daughter radionuclides governing transport and accumulation in the exposure pathways are different to those of the parent and in this case it was illustrated that doses via the consumption of contaminated drinking water may not in every case provide a reliable (or pessimistic) estimate of the radiological impact of the release of radionuclides to the biosphere (1, 3);
- The analyses here confirm that exposure pathways other than those associated with the transport of groundwater can lead to increased annual

doses. This is particularly noticeable when the dose via the inhalation mechanism is calculated (1, 3);

- The transport of sorbed contaminants on solid materials (for example as a result of erosion or bioturbation) is a potentially important process affecting the long-term transport and accumulation of radionuclides in the biosphere (1, 3);
- The nature of the interface between the geosphere and the biosphere requires careful consideration. The size of the recipient area is a significant factor affecting individual doses in the release region. Some of the modelling boundary conditions assumed in this exercise indicate that surface erosion could, in some circumstances, have a role regarding the input of radionuclides to the biosphere from the geosphere, at the interface between the models (1, 3).

1. GENERAL INTRODUCTION

1.1 Background

The Probabilistic Systems Assessment Group (PSAG) was established in 1985 by the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD). The principal purpose of this Group is to further the development, in OECD Member countries, of computer codes for the probabilistic safety assessment (PSA) of radioactive waste disposal systems. Activities of the group comprise information exchange, peer review, joint code development, discussion of topical issues and code comparisons. This last activity is particularly important as formal code intercomparisons help to verify that codes developed for safety assessments function as intended. PSA codes consist of *executive* functions, such as a sampling algorithm to select input parameter values, and a set of *mathematical submodels* that represent the system to be analysed. Statistical *postprocessing* codes are used in close conjunction with PSA codes. Code verification is viewed as a necessary step in building confidence in the ability of PSA codes to provide meaningful information for safety assessments.

This report summarises the results and recommendations arising from the fourth of the Group's code intercomparison (PSACOIN) exercises, known as Level 1b, and follows the earlier Level 0[1.1] Level E[1.2] and Level 1a[1.3] exercises. Level 0 involved a relatively simple disposal system model and code verification focused on the executive and postprocessing functions. In Level E, the existence of an *exact* numerical solution was particularly important because it allowed not only intercomparison of the results between codes, but also a benchmark against which results from all the participating codes could be compared. The Level 1a case was a step towards an intercomparison based on a more realistic system model, involving a deep geological disposal concept with a relatively complex structure for the repository vault.

The Level 1b intercomparison is concerned with the question of parameter uncertainty in *biosphere models* and the influence this has on the calculation of individual doses arising from exposures to radionuclides via multiple, parallel pathways. In the previous PSACOIN exercises the exposure of humankind to the radionuclides released from the vault and geosphere has been assumed to take place via consumption of contaminated water - either from a stream or from a well. In this exercise the biosphere is represented by a network of four compartments - a top soil layer, representing the rooting zone of crops and pasture for livestock, a deeper soil layer, a surface water compartment (representing a river), which is used for drinking water and as an irrigation source, and a river sediment compartment. It is not suggested that these biosphere compartments are all that may ever need to be included in an assessment, they do however represents commonly considered components of biosphere models for solid waste disposal.

A further PSACOIN exercise in progress is Level S, an intercomparison exercise of different techniques for sensitivity analysis. There is also the Level 2 exercise, which represents a further increase in model realism. A summary of the work of PSAG was published in 1990[1.4] giving further background information about the group and discussing the results of the completed exercises.

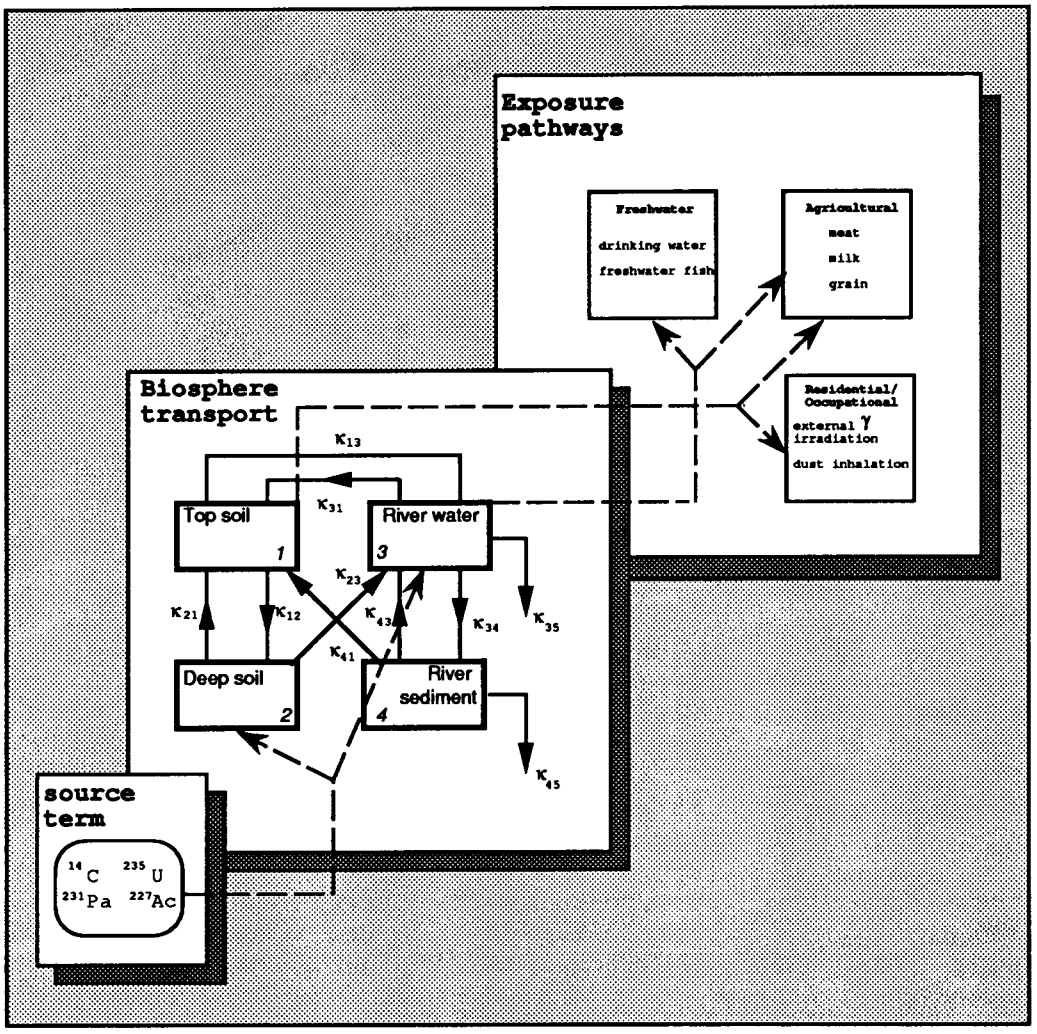


Figure 1.1
The PSACOIN Level 1b Intercomparison System Model

Illustration of the three submodels of the PSACOIN Level 1b system model. Release of radionuclides to the biosphere occurs simultaneously to the deep soil and river water compartments. Transport within the biosphere leads to the build up of radionuclides in all compartments, with activity being lost downstream from the river water and river sediment compartments. Dose to individuals arises by exposure to the radionuclides in the Top soil and River water boxes.

1.2 **Purpose of the Level 1b exercise.**

The principal aims of the Level 1b exercise were:

- to gain experience in the application of probabilistic systems assessment methodology to transport and radiological exposure submodels for the biosphere and hence to methods of estimating the total risk to individuals, or groups of individuals;
- to contribute to the verification of biosphere transport and exposure submodels used by the participants;
- to investigate the effects of parameter uncertainty in the biosphere transport and exposure submodels on the estimate of mean dose[1] to individuals exposed via several exposure pathways.

In addition to these aims, participants in the exercise were encouraged to investigate any other performance assessment related aspects of the case which might prove to be of interest.

1.3 **Problem Specification**

The PSACOIN Level 1b case specification (given in full in Annex A) describes three submodels - a source of radionuclides to the biosphere, a compartment model for biosphere transport and an exposure pathway submodel - which together form a complete assessment model for evaluating the consequences of the release of radionuclides to the biosphere. The relationship of the Level 1b submodels is shown in Figure 1.1.

Starting from an initial radionuclide inventory a simple constant fractional leach rate is assumed for the source term which, together with radioactive decay and ingrowth, defines the release rate of radionuclides into the biosphere. This release submodel was chosen to give a timescale of release which is representative of those which may be expected in assessments of the geologic disposal of radioactive waste. The selection of radionuclides for the case study is discussed in Section 1.5 below. The release of radionuclides occurs to a section of the biosphere represented by the four compartments: **Top soil**, **Deep soil**, **River water** and **River sediment**, representing an inland river section. The source term is partitioned between river water and soil according to the relative areas of the river and agricultural land. The characteristics of the biosphere were chosen to represent an area of land from which a small farming community could obtain all its basic food requirements.

Activity entering each compartment is assumed to be instantaneously well mixed throughout the bulk of the box and the transfer of activity between the

[1] In this text the word *dose* is taken to mean the *effective dose equivalent*, and is the sum of weighted *committed dose equivalents* in specific organs from the intake of radionuclides into the body in one year, plus the sum of weighted *dose equivalents* from external irradiation in one year. This definition is consistent with the concept of *dose* given in ICRP-26[1.5].

compartments is described in terms of the mean annual transfer coefficients (or rate constants), κ_{ij}, between boxes i and j of the model. This leads to a set of coupled first order linear differential equations, which give the time variation (t) of the contents N_i of box i as

$$\frac{dN_i}{dt} = \sum_{j \neq i} \kappa_{ji} N_j + \lambda_M M_i + S_i(t) - \sum_{j \neq i} \kappa_{ij} N_i - \lambda_N N_i \qquad (1.1)$$

The first three terms on the right hand side (see Annex A for a full definition of the terms) represent transfers into box i from transport, ingrowth from the parent radionuclide M (with decay constant λ_M), in box i, and the source term, respectively. The remaining two terms represent losses from box i via transport and radioactive decay (at rate λ_N) respectively. The solution to this set of equations gives the radionuclide inventories in the compartments as a function of time. These are then used in the exposure pathway submodel to calculate the doses to individuals via the seven exposure pathways: **drinking water** and **freshwater fish** consumption, **meat** and **milk** consumption, **grain** consumption, **external γ-irradiation** and **dust inhalation.**

The mechanisms involved in translating the top soil and river water activity concentrations into annual individual doses are represented here by conversion factors so that, in general terms, the total annual individual dose from radionuclides N, via exposure pathways p in the i boxes of the model can be written as

$$D_{tot} = \sum_{n,i,p,exp} E_p \, P_{p,n,i} \, N_{i,n} \, D_{exp,n}. \qquad (1.2)$$

where E_p is the exposure rate for pathway p, $P_{p,n,i}$ is a processing factor for converting the inventory of radionuclide n in compartment i, $N_{i,n}$, into a concentration for the exposure pathway p at which the exposure takes place. $D_{exp,n}$ converts the intake of radioactivity (Bq y^{-1}) into an annual individual dose (Sv y^{-1}) for the intake mechanism *exp* (ingestion or inhalation).

The Level 1b case study there are 115 input parameters, 52 in the source and transport submodels and 63 in the dose model. Of these parameters, uncertainty is taken into account in the case of 26 (19 in the transport model and 7 in the dose model). The radionuclides chosen for the study were ^{14}C and the ^{235}U chain (with daughters ^{231}Pa and ^{227}Ac). In the context of the principal aims of the intercomparison the influence of the choice of parameter values on the results of the model are discussed in Section 1.4 below and the reasons for the selection of the radionuclides are outlined in Section 1.5 below.

The Level 1b questionnaire requests details of the time evolution of the quantities described in the Equations (1.1) and (1.2) above. The questionnaires used to obtain results in a standard form for the intercomparison are shown in Annex B.

All the input parameters values and functional relationships are stated in the case specification. Although this leaves little scope for additional interpretation of the case by participants, it does contribute to the verification of the methods and coding used to solve the transport equation (Equation 1.1) which plays a central rôle in many of the computer codes used in biosphere modelling for the performance assessment of radioactive waste repositories. The case therefore provides a useful benchmark against which the other codes can be compared. Furthermore, additional work carried out by the participants in the exercise, and discussed in Chapter 3 of this report, contributes to the understanding of biosphere models for performance assessments and in particular illustrates that such models have a useful part to play in PSA.

1.4 Parameterisation of the Level 1b Models

The transport of radionuclides in the PSACOIN Level 1b biosphere is governed by the intercompartment transfer coefficients. κ_{ij}. There are ten of these coefficients in the PSACOIN Level 1b model and, in principle, it would be feasible for a given site to measure these transfer rates directly although the complexities inherent in such a system and the long measurement times required to fully characterise all the relevant timescales make this practically impossible for all but the most simple features, events and processes. It can, however, be argued that it is preferable to model the mechanisms which influence the transfer rates. This allows a clearer definition of the features, events and processes (FEPs) at work in the model. Furthermore the physical, chemical and biological properties of the system can be more easily determined under field conditions than can the transfer rates themselves, and these then become the fundamental input parameters of the overall transport model. This approach is taken in this exercise.

For example, the transfer rate of radionuclides from the top soil compartment (box 1) to the deep soil (box 2) is given as

$$\kappa_{12} = \frac{d_{rain} + d_{irri}}{R\ \varepsilon\ l_{ss}} + \frac{(R - 1)B + D}{R\ l_{ss}\ \min(l_{ss},l_{ds})} \tag{1.3}$$

where the advective processes of rainfall and irrigation (rates $d_{rain} + d_{irri}$ m y^{-1}), the diffusion process (coefficient D), and the bioturbation process (coefficient B) are all included. R is the retention coefficient for radionuclides in soil and it is in turn parameterised as

$$R = 1 + \frac{\rho}{\varepsilon} k_d \tag{1.4}$$

in terms of the element dependent soil-groundwater distribution coefficient k_d, the bulk density of soil, ρ, and the porosity of soil, ε.

The advantages of mechanistic parameterisation include:

- the same model can be applied to different sites, differences in site performance can then be identified with differences in site parameters which in turn are derived from measurable site characteristics;
- parameters important in determining the transport of radionuclides in the environment can be identified;
- estimation of parameter uncertainty, and consequent uncertainty in the overall system performance, can be done on a rational, systematic basis.

This final point is particularly important for probabilistic studies such as the Level 1b exercise. It would be extremely difficult to assign ranges of uncertainty to the κ_{ij} values directly. Moreover, since some of the mechanistic parameters enter more than one way into the κ_{ij}, correlations between the κ_{ij} are generated in a realistic and self consistent way.

It is recognised that the particular parameterisation adopted for the Level 1b exercise is by no means universally applicable. However, it should be adequate for the purposes of the exercise, to demonstrate the principles of the probabilistic uncertainty analysis, and to indicate the kinds of conclusions about parameter sensitivity that can be drawn. The model used is based on the *MiniBIOS* model[1.6], which has previously been used in the BIOMOVS B7 exercise[1.7] and the CEC's *PACOMA* project[1.8]. An example of the further development of the parameterisation of biosphere compartment models can be found in the *Terrestrial - Aquatic Model of the Environment (TAME)*[1.9] which has recently been developed in Switzerland. In Level 1b, uncertainty has not been attributed to every parameter - the parameters that were assigned a distribution were those that had previously been shown to be significant in other studies[1.7,1.8,1.10].

In the dose model, parameters such as root uptake factors for radionuclides in crops could be highly site dependent and subject to many uncertainties. In the present study, no attempt has been made to quantify the uncertainties in this class of parameter. Attention has instead been focused on uncertainties in the exposure rates as determined by an individual's dietary preferences and total food energy intake.

1.5 **Choice of Radionuclides**

^{14}C and the ^{235}U chain (including ^{231}Pa and ^{227}Ac), were selected because of the wide range of differing properties. ^{14}C is very mobile in the biosphere and has a relatively short half-life (5.7 10^3 years). The uranium chain members show a range of mobilities in the biosphere with protactinium and actinium both being highly sorbed. ^{235}U has a 7.0 10^8 year half life, ^{231}Pa, 3.3 10^4 years, and ^{227}Ac, 22 years. Another important feature is that the dose per unit intake values for the chain members differ according to the type of intake. As is typical for the α-emitting actinides the inhalation dose per unit intake can be much higher than

via the ingestion pathway - in the case of ^{227}Pa the ratio is 450. This feature can have a significant influence on the exposure pathways contributing most to the total annual individual dose.

It is recognised that the approach taken here for the behaviour of ^{14}C in the environment might not be the most appropriate and that a *specific activity model*[1.10] in particular might be more suitable and indeed simpler in terms of the dose calculations derived from the presence of the radionuclide in the food chain.

Letter	Code	Establishment	Country	Stochastic case Sampling Method⊕ and sample number
A	*MiniBIOS/ACTIVI*†/ *SYVAC 3.05*	Paul Scherrer Institute◊	Switzerland	MC 1000
B	*MASCOT-3B*	AEA Technology◊	UK	MC 1000
C	*IMA Methodology 1B.2*‡	IMA/CIEMAT◊	Spain	LHS 1000
D	*BIOPATH/PRISM**	Studsvik◊	Sweden	LHS 200
E	*CIRCLE*	JAERI◊	Japan	MC 1000
F	*SYVAC-3.08*	AECL	Canada	MC 1000
G	*ESP-MiniBIOS*	NRPB	UK	LHS 1000

Notes:

⊕ MC ⇒ Monte Carlo Sampling, LHS ⇒ Latin Hypercube Sampling.

† Solution of the transport equation performed by the *BIOPATH* equation solver *ACTIVI*.

‡ Solution of the transport equation performed by the *BIOPATH* equation solver *LINDIF*.

* Solution of the transport equation performed by the *BIOPATH* equation solver *LINDIF*. In the deterministic calculations two methods were used, in the following Chapter these are distinguished by D1 and D2:

D1 *LINDIF*
D2 *IMPEX*

In the subsequent stochastic calculations the *LINDIF* solution method was used.

◊ Participants contributing additional sensitivity analyses.

Table 1.1: List of Participants in the PSACOIN Level 1b exercise.

1.(**Participants**

The specified Questionnaire results were received from seven organisations, and five of these organisations contributed further results in the form of additional sensitivity analysis. Table 1.1 identifies the participants and

codes used and provides a unique letter for each contribution to identify it in the tables provided in Chapters 2 and 3 of this report. Brief code and methodology descriptions, provided by the contributing organisations, are given in Annex C.

2. QUESTIONNAIRE RESULTS.

2.1 Overview of the Questionnaire.

2.1.1 Introduction.

The performance assessment quantities used in the PSACOIN exercises are related to the overall radiological impact of the disposal concept under study. This means that the end points of the exercises are doses or risks to individuals and groups, although there may be a wide variety of intermediate quantities that might be calculated in the course of the modelling work. This is also the case in the Level 1b exercise, where the biosphere transport and dose submodels are quite distinct. The main stochastic results from the exercise therefore concentrate on the time evolution of the doses to individuals and the rankings of the various exposure pathways. In addition, a code verification step was required, in order to confirm the correct workings of the transport and dose submodels. The Questionnaire therefore comprises two stages - deterministic and stochastic. Only when agreement had been reached in the deterministic case was it possible to proceed to the stochastic case. The deterministic Questionnaire relates to the second objective (verification) whereas the stochastic results address the third of the aims (uncertainty analysis), with the first of the aims (gaining experience) being covered by the exercise as a whole, and by the request to participants to carry out any additional analyses that they felt were appropriate. This chapter deals with the results of the Questionnaire and the additional work carried out is discussed in the next chapter.

2.1.2 The Deterministic Results Questionnaire.

The correct functioning of the codes used in the case was demonstrated by the comparison of the results from a deterministic central case, in which the central values (medians) of the distributed parameters were used. Two tables of deterministic results were requested: one to test the correct operation of the transport submodel and one to test the dose submodel.

The first Questionnaire table (Table B.1 of Annex B) is designed to ensure that the transfer coefficients used in the case are calculated correctly and hence that the codes used to solve the transport equation (Equation 1.1) perform correctly. This is achieved by calculating the four compartment inventories of each of the four radionuclides at specified times. The times chosen (1, 10^3 and 10^5 years) provide a severe test of the numerical accuracy of the solver codes, since they specify the first year after the commencement of the release, when the daughters of the ^{235}U chain have had only a short time for ingrowth so that the inventories are very small. Similarly the inventories of the ^{14}C at the third time (10^5 years) are also very small, because of radioactive decay.

The coding of the dose model (Equation 1.2) is tested by the second Questionnaire table (Table B.2 in Annex 2). In this table the seven individual exposure pathway doses are requested, for each of the four radionuclides, at each of the three times specified in Table B.1.

2.1.3 The Stochastic Results Questionnaire.

The two end points of the Level 1b calculations were chosen to be the total annual individual dose for ^{14}C, summed over all exposure pathways and the total dose for the ^{235}U chain, summed over all the decay chain members and pathways. Table B.3 of Annex B requests the mean and standard deviation of these two quantities, together with a confidence bound for each mean value. The Case Specification does not specify the method to be used in arriving at the confidence bounds and, in their responses to the Questionnaire, the participants placed differing interpretations on this requirement. In this report the confidence bounds used are chosen to be those based on Chebyshev's Theorem and the responses from the participants have been amended accordingly. For an estimated mean quantity, μ, and a standard deviation, σ, the Chebyshev 95% confidence interval is $\mu \pm T_{95}$, where

$$T_{95} = \sqrt{\frac{1}{0.05N}}\,\sigma \qquad (2.1)$$

where N is the number of samples. This formula is based on the standard Monte Carlo sampling method and can also be used with Latin Hypercube sampling. It would, however, need modifying if Importance Sampling were used[2.1], but since this was not the case for any contribution to the present study, the formula, as given, could be used to convert the supplied means and standard deviations to the confidence bound as necessary.

The final Questionnaire table (Table B.4 of Annex B) deals with the rankings of the individual exposure pathways as a function of time.

2.2 The Deterministic Results.

The agreement achieved between the contributions in response to the strict case specification was excellent. The discussion of the deterministic results can therefore concentrate on general trends and features of biosphere modelling for performance assessment in the context of the Level 1b case. The individual results received from the participants are presented in Annex D.

2.2.1 The Source Term.

The time variation of the Level 1b source term is given in Figure 2.1. This illustrates the output from the source before it is partitioned between the biosphere compartments receiving the radionuclide flux (the deep soil and the river water) according to the area of the compartments. These plots of release vs time for the four radionuclides provide a useful reference when comparing accumulation of the radionuclides in the biosphere. The first features to note are the plateaux and decay characteristics of the constant fractional release rate source terms for ^{14}C and the chain parent, ^{235}U, and the ingrowth and decay of the chain daughters. Second, the ^{14}C source term is limited by radioactive decay (with a half-life of 5.7 10^3 years), whereas the chain source terms are limited by the depletion of the source, with the constant fractional release rate of 10^{-5} y^{-1}.

2.2.2 **Biosphere Transport.**

The deterministic central case results for the compartment inventories of each of the radionuclides are shown in Figure 2.2. The plotted curves illustrate the time evolution of the inventories provided by participant A. The Questionnaire results for all the participants are also superimposed on this plot. However, the level of agreement between the participants is so good that it is not easy to distinguish the individual entries so the results for the Table B.1 are given here in Table 2.1, normalised (to one decimal place) to the mean values for all participants.

In general there is good agreement between the participants but the few discrepancies which do occur require some comment.

The results for ^{235}U are in almost perfect agreement and, similarly, the results for ^{14}C at 1 year and 10^3 years are also in exact agreement. There is however a small discrepancy for ^{14}C at 10^5 years, when the inventories of the ^{14}C become very small due to the radioactive decay of the nuclide and the rate of decrease is very steep. At the times where the compartment concentrations are radiologically most significant, all the results are within ±10% of one another.

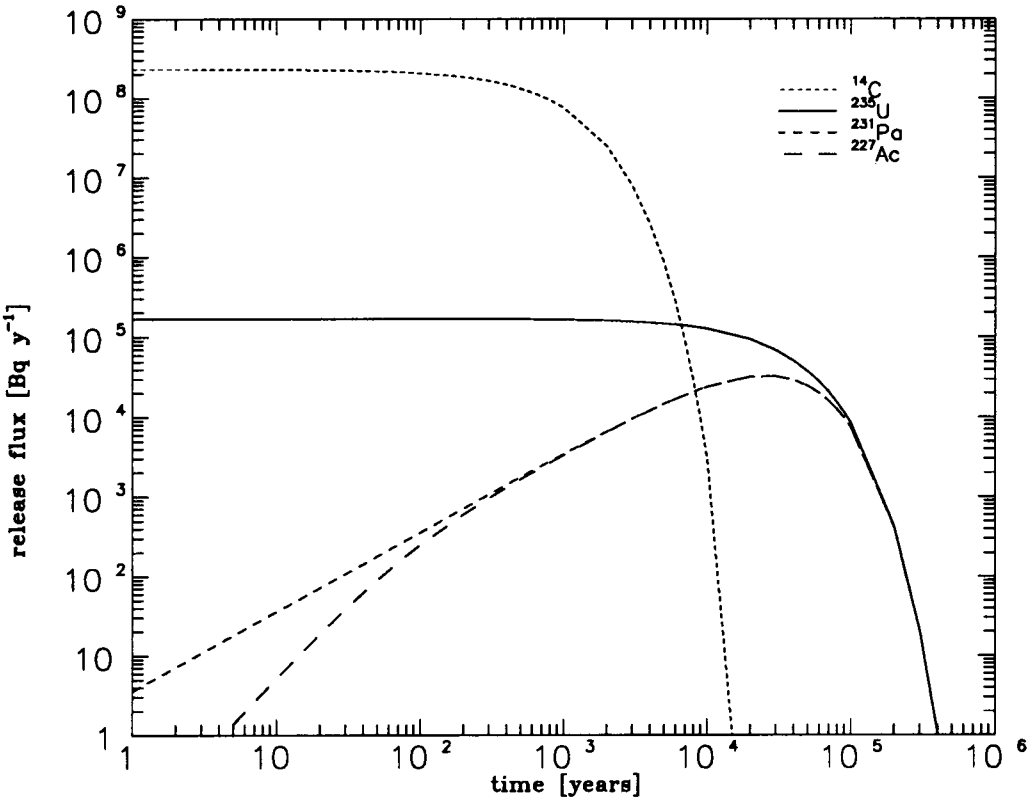
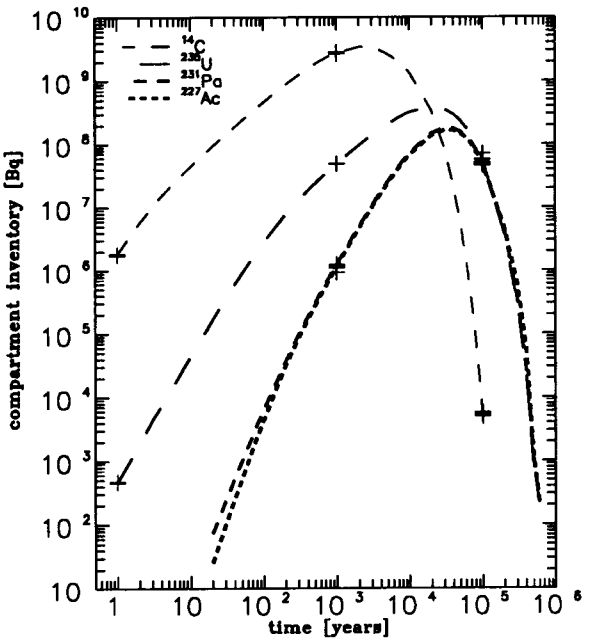


Figure 2.1 – The PSACOIN Level 1b source term.
Constant fractional release rates applied to ^{14}C and the members of the ^{236}U decay chain (allowing for ingrowth of the daughters).

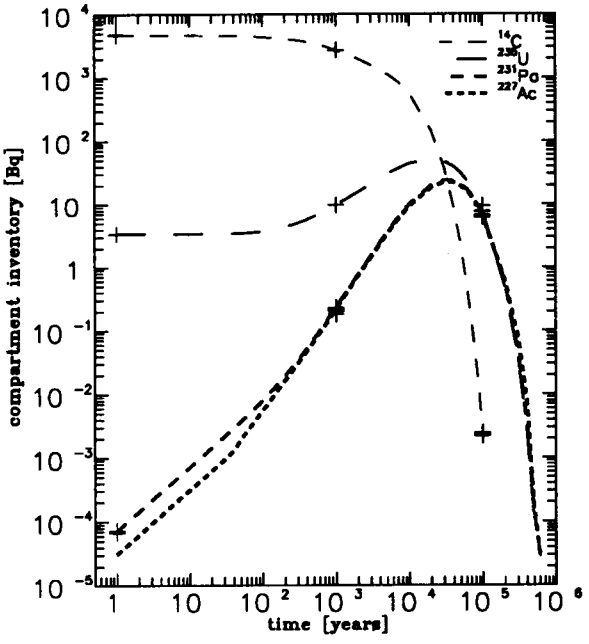
The contributed results for the calculations for the chain daughters do not show the same close agreement, especially at the earlier times. The discrepancies between the results from participants A, C and D (using versions of the same compartment model solving code - *ACTIVI*[2.2] from the *BIOPATH*[2.3] code package) have subsequently been traced to the choice of inital time steps leading in some cases the initial inventories of the the chain daughters at year 1, to calculated to be zero (indicated in Table 2.1 by '*'). However, using a revised time-stepping regime for the early phase of the calculation, Participant D (using both the *IMPEX*[2.4] and *LINDIF*[2.5] integration methods) has been able to reproduce the results of Participant C. These revised results have **not** been included here.

id	time, y	^{14}C W	S	T	D	^{235}U W	S	T	D	^{231}Pa W	S	T	D	^{227}Ac W	S	T	D
A	1	1	1	1	1	1	1	1	1	1	1.2	1.5	1.3	1.2	1.6	2.0	1.7
	10^3	1	1	1	1	1	1	1	1	1	1	1	1.1	1	1	1	1
	10^5	1	1	1.1	1.1	1	1	1	1	1	1	1	1	1	1	1	0.9
B	1	1	1	1	1	1	1	1	1	1	1.2	1.1	1.2	1	1	0.8	1
	10^3	1	1	1	1	1	1	1	1	1	1	1	0.6	1	1	1	1
	10^5	1	1	1	1	1	1	1	1	1	0.9	1	1	0.9	0.5	0.9	0.9
C	1	1	1	1	1	1	1	1	1	*	*	*	0.6	*	*	*	*
	10^3	1	1	1	1	1	1	1	1	0.9	1.1	1	1.1	1	1	1	1
	10^5	*	*	1	1	1	1	1	1	1	1	1	1	1	1	1	1
D1	1	1	1	1	1	1	1	1	1	1	0.5	0.4	0.6	*	*	*	*
	10^3	1	1	1	1	1	1	1	1	1	1	1	1	0.9	0.9	0.8	0.9
	10^5	1	1	1	1	1	1	1	1	1.1	1.1	1.1	1.1	1.4	1.4	1.4	1.4
D2	1	1	1	1	1	1	1	1	1	1	1.2	1.1	1.2	1	1	0.8	1
	10^3	1	1	1	1	1	1	1	1	1	1	1	1.1	1	1	1	1
	10^5	1	1	1	1	1	1	1	1	1	0.9	1	1	0.9	0.5	0.9	0.9
E	1	1	1	1	1	1	1	1	1	0.9	1.1	1.1	1.1	1	1.1	1.1	1.1
	10^3	1	1	1	1	1	1	1	1	1	0.9	1	1.1	1	1	1	1
	10^5	1.1	1.1	1.1	1.1	1	1	1	1	1	1.2	0.9	0.9	0.9	0.9	0.9	0.9
F	1	1	1	1	1	1	1	1	1	1	1.1	1.2	1.1	1	1	0.8	1
	10^3	1	1	1	1	1	1	1	1	1	1	1	1.1	1	1	1	1
	10^5	1	1	1	1	1	1	1	1	1	1	1	0.9	0.9	1	0.9	0.9
G	1	1	1	1	1	1	1	1	1	1	0.7	0.7	0.6	0.8	0.4	0.4	0.3
	10^3	1	1	1	1	1	1	1	1	1	1	1	1.1	1	1	1	1
	10^5	1	1	1	1	1	1	1	1	0.9	1	1	1	0.9	0.9	0.9	0.9

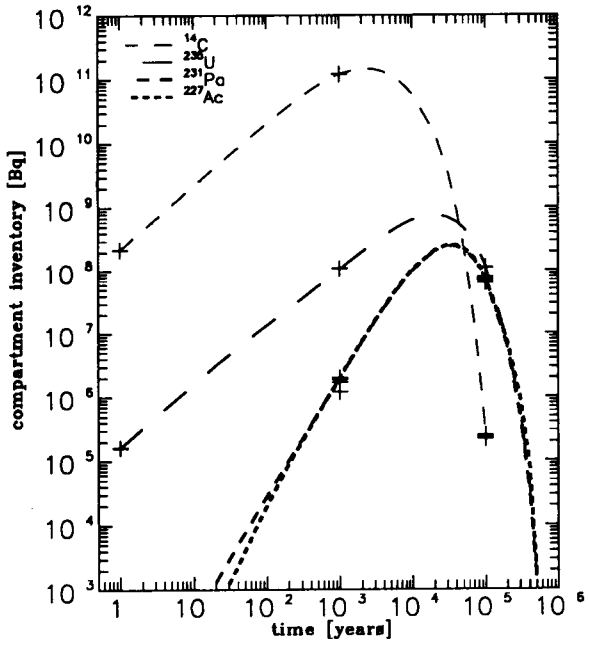
Table 2.1 - Results for the Water, Sediment, Top soil and Deep soil inventories (Bq) for each of the radionuclides, as requested in Questionnaire Table B.1. To illustrated the degree of agreement achieved in the case the results have been normalised to the mean values from all the participants. A '*' indicates a value not provided in the Questionnaire results. The normalisations take these missing values into account.



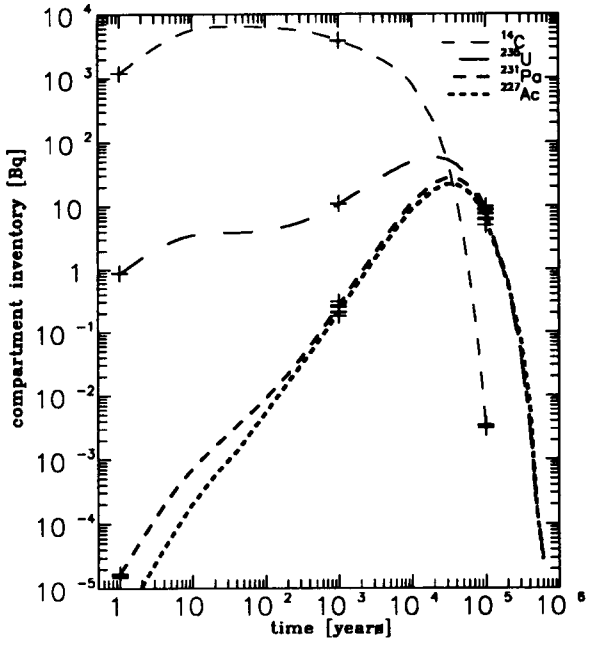
(a) top soil inventories



(b) water inventories



(c) deep soil inventories



(d) sediment inventories

Figure 2.2 – Results for the Water, Sediment, Top Soil and Deep Soil compartment inventories. The curves are taken from Participant A, and the crosses indicate the participant contributions to Questionnaire Table B.1.

^{14}C							
time, [y]	participant	drinking water	freshwater fish	grain	meat	milk	dust inhalation
1	A	1	1	1	1	1	1
	B	1	1	1	1	1	1
	C	1	1	1	1	1	1
	D	1	1	1	1	1	1
	E	1	1	1	1	1	1
	F	1	1	1	1	1	1
	G	1	1	1	1	1	1
10^3	A	1	1	1	1	1	1
	B	1	1	1	1	1	1
	C	1	1	1	1	1	1
	D	1	1	1	1	1	1
	E	1	1	1	1	1	1
	F	1	1	1	1	1	1
	G	1	1	1	1	1	1
10^5	A	1.2	1	1	1.1	1.1	1.1
	B	*	1	1	1	1	*
	C	*	*	1	1	1	*
	D	1.2	1	0.9	0.9	1	1
	E	0.4	1.1	1.1	1.1	1	1.1
	F	1.1	1	1	1	1.1	1
	G	1.1	0.9	0.9	1	1	0.9

^{235}U								
time, [y]	participant	drinking water	freshwater fish	grain	meat	milk	dust inhalation	ext-rnal γ
1	A	1	1	1	1	1	1	1
	B	1	1	1	1	1	1	1
	C	1	1	1	1	1	1	1
	D	1	1	1	1	1	1	1
	E	1	1	1	1	1	1	1
	F	1	1	1	1	1	1	1
	G	1	1	1	1	1	1	1
10^3	A	1	1	1	0.9	1	1	1
	B	1	1	1	0.9	1	1	1
	C	1	1	1	1.5	1	1	1
	D	1	1	1	0.9	1	1	1
	E	1	1	1	0.9	1	1	1
	F	1	1	1	0.9	1	1	1
	G	1	1	1	0.9	1	1	1
10^5	A	1	1	1	0.9	1	1	1
	B	1	1	1	0.9	1	1	1
	C	1	1	1	1.5	1	1	1
	D	1	1.2	1	0.9	1	1	1
	E	1	1	1	0.9	1	1	1
	F	1	1	1	0.9	1	1	1
	G	1	1	1	0.9	1	1	1

Table 2.2 - Dose ratios for annual individual dose (Sv y^{-1}) as requested in Questionnaire Table B.2. The results have been normalised to the average of the contributions. '*' indicates values not returned in the Questionnaire. The missing values have been taken into account in the normalisation.

^{231}Pa								
time, [y]	participant	drinking water	freshwater fish	grain	meat	milk	dust inhalation	external γ
1	A	0.8	1	1.3	1.1	0.8	0.8	1.4
	B	0.8	*	*	*	*	*	*
	C	0.8	*	*	*	*	*	*
	D	0.8	1	1	1	2.1	1.1	1
	E	0.7	1	1	1	0.7	1.2	1
	F	2.4	1	1	1	0.8	1.1	1
	G	0.8	1	0.7	0.9	1	0.8	0.7
10^3	A	1	1	1	1	1	0.9	1
	B	1	1	1	1	1	1	1
	C	0.9	1	1	1	1	0.9	1
	D	1.3	1	1	1	1	1.4	1
	E	0.9	0.9	0.9	1	1	0.9	0.9
	F	1	1	1	1	1	1	1
	G	0.9	1	1	1	1	0.9	1
10^5	A	1	1	1	1	1	1	1
	B	1	1	1	1	1	1	1
	C	1	1	1	1	1	1	1
	D	1	1	1	1	1	1	1
	E	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	F	1	1	1	1	1	1	1
	G	1	1	1	1	1	1	1

^{227}Ac								
time, [y]	participant	drinking water	freshwater fish	grain	meat	milk	dust inhalation	external γ
1	A	1.2	1.3	1.3	1.3	1.3	0.5	2.0
	B	*	*	*	*	*	*	*
	C	*	*	*	*	*	*	*
	D	1	0.9	1	0.9	0.9	1.2	0.8
	E	1	1	1	1	1	1.6	1.1
	F	1	1	1	1	1	1.2	0.8
	G	0.8	0.8	0.8	0.8	0.8	0.5	0.4
10^3	A	1	1	1	1	1	1	1
	B	1	1	1	1	1	1	1
	C	1	1	1	0.9	1	1	1
	D	1	1.1	1	0.9	1	1	1
	E	1	1	1	1	1	1	1
	F	1	1	1	1	1	1	1
	G	1	1	1	1	1	1	1
10^5	A	1	1	1	1	1	1	1
	B	1	1	1	1	1	1	1
	C	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	D	1	1	1	1	1	1	1
	E	1	1	1	1	1	1	1
	F	1	1	1	1	1	1	1
	G	1	1	1	1	1	1	1

Table 2.2 (continued) - Dose ratios for annual individual dose (Sv y^{-1}) as requested in Questionnaire Table B.2. The results have been normalised to the average of the contributions. '*' indicates values not returned in the Questionnaire. The missing values have been taken into account in the normalisation.

In the course of the exercise it was found that many of the participants required several iterations before the final agreement was reached over the compartment contents in Table B.1. Some coding errors were identified and corrected but a significant source of error in the initial calculation of the transfer coefficients by some participants was the units of the input parameters. Throughout the case specification the data are given in terms of metres, kilograms and years. In the input data files of some of the older codes these units were not consistently used, the units being taken from the original source of the data, and the process of converting these data into forms suitable for the codes gave rise to some erroneous initial results, before the data sets were checked and corrected.

2.2.3 **Individual Dose.**

The results for Questionnaire Table B.2 are illustrated in Figure 2.3, where the time evolution of the total annual individual dose arising from ^{14}C and the ^{235}U chain are plotted, summed over exposure pathways and decay chain members, according to equation 1.2. The results from the participants' contributions to Table B.2 are also plotted. As with the compartment inventories, plotted above, the agreement is so close, in most cases, that it is not possible to distinguish the separate values. Table 2.2 gives the results from Table B.2, again normalised to the mean of the contributions.

The full time dependence, as calculated by participant A, of the seven exposure pathways is illustrated in Figure 2.4 for each of the four radionuclides. These plots can be used to compare how the relative importance of the different pathways changes with time. Although this information was not sought in the deterministic Questionnaire, the ranking of the exposure pathways, as a function of time, was requested in the stochastic Questionnaire. These results from the deterministic case provide a useful point of comparison and illustrate some important features of biosphere modelling.

Figure 2.3 and Table 2.2 again indicate the agreement between the participants is, on the whole, very good, especially for the ^{14}C and the ^{235}U. The results for the chain daughters show a less close agreement overall. As with the calculation of the compartment inventories, discussed in Section 2.2.2, such discrepancies as do arise can generally be explained in terms of the internal accuracy of the codes used to solve the compartment model equation, since the doses from each of the exposure pathways are derived from constant factors applied to either the topsoil or river water concentration.

The numerical problems in the results for ^{14}C seen in Table 2.1 are also present in Table 2.2 at 10^5 years, when the compartment inventories are low and falling rapidly. The results for ^{235}U show very good agreement at all times for all the exposure pathways, although the meat pathway shows some unexplained variation. As in Table 2.1, Table 2.2 shows that for ^{231}Pa and ^{227}Ac the numerical variation in the calculation of the compartment inventories for the chain daughters is reflected in the doses by exposure pathway but again it must be noted that this effect is principally seen at the times at which the compartment inventories are low. In the case of the chain daughters this is the earlier times.

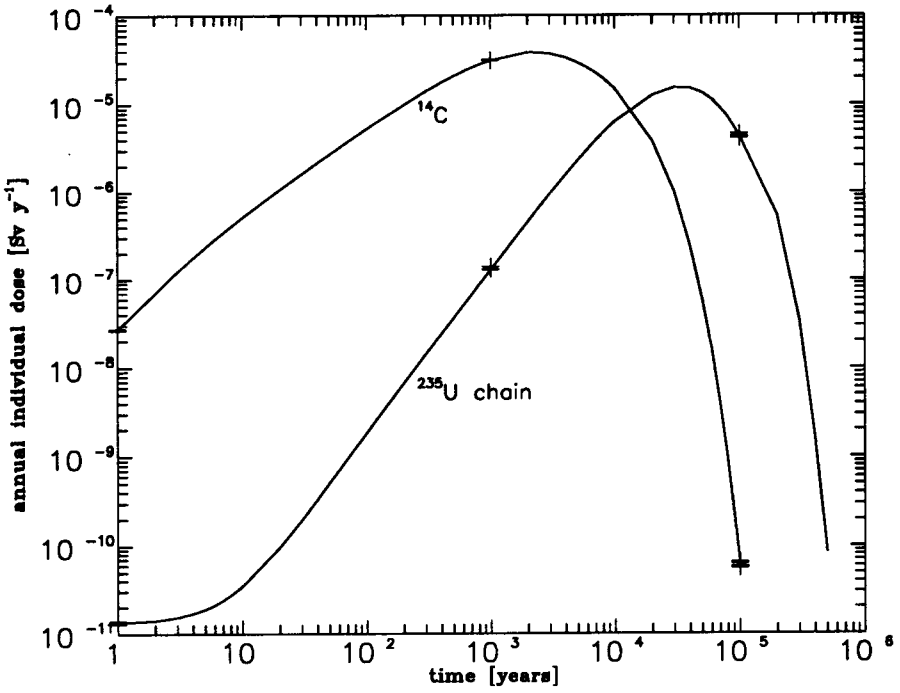


Figure 2.3 – Results from the deterministic central case for the total annual individual dose from both ^{14}C and the ^{235}U chain. The doses are summed over all exposure pathways and decay chain members. The values calculated by the participants at the times requested in Questionnaire Table B.2 are also ploted.

A further point worth noting is the effect of discrepancies on the total dose summed over all pathways. Figure 2.3 indicates that although the variation in the individual pathway results in Table 2.2 might appear to be significant, the combined dose over pathways is relatively unaffected by the variation, since, as is illustrated in Figure 2.4, at any particular time only one single exposure pathway is dominant in determining the individual dose, and, in this case, the dominant pathways do **not** show the sensitivity.

2.2.4 Comments on the Deterministic Central Case Results.

Several important features of the biosphere as a component in waste disposal performance assessments are illustrated in the results from the central case. These relate to the way in which the parts of the biosphere system act as reservoirs of radionuclides, and to how the relative importance of the different exposure pathways changes with time.

A comparison of the source term (Figure 2.1) and the inventories in the river water and deep soil Figure 2.2b and 2.2c illustrate the effect of accumulation in biosphere compartments. The ^{14}C inventory in the water follows a similar trend to the source term, in that it starts off at a plateau level and

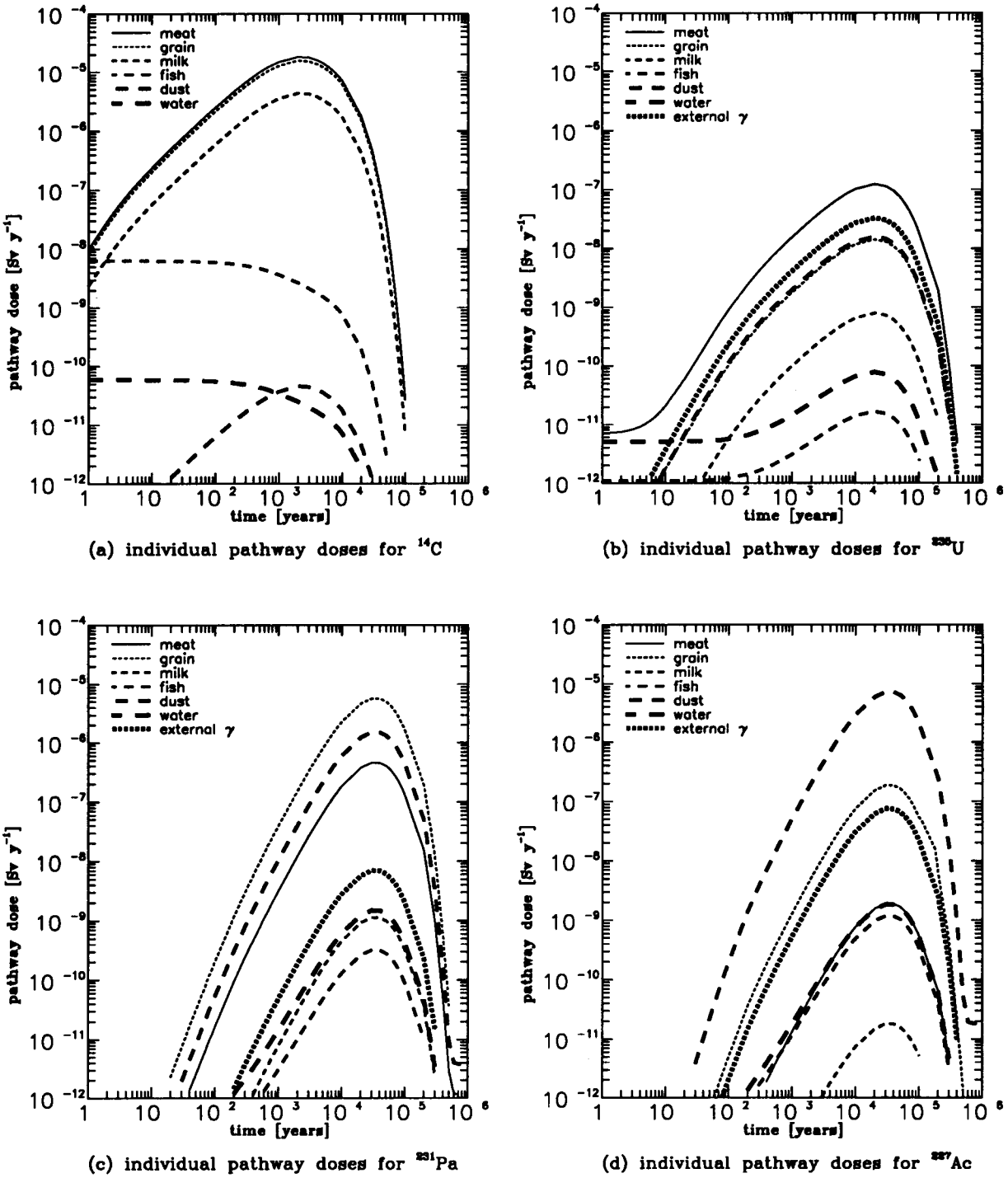
decays away. The ^{235}U however shows an increase in the river water inventory over its initial plateau level beginning at a few hundred years after the release has commenced. In the deep soil compartment the inventories at early times (up to around 5 10^3 years) show the gradual increase as a result of the constant source term.

An important process affecting the accumulation of the radionuclides in the soils is sorption onto solid materials. This is very well demonstrated in the case of ^{235}U. In the Case Specification the water compartment receives activity from the source term directly and from the top soil layer as a result of eroded material being washed into the river. There is also an exchange with the river bed sediment. The relatively high soil-groundwater k_d for ^{235}U means that activity entering the top soil accumulates due to sorption. The erosion of the top soil to the river water therefore constitutes a secondary source term to the river water which is of comparable strength to the main source term at later times when the concentration of ^{235}U in the soil has built up.

The same situation does not arise for the ^{14}C because the sorption is much less so there is not the same degree of accumulation in the top soil. The reasons for this will be examined in greater detail in Chapter 3, which deals with the results of the additional uncertainty analyses carried out by some of the participants.

This feature illustrates the different emphasis on sorption in the biosphere and the geosphere from a performance assessment perspective. In the geosphere high sorption is preferable since it *delays* the transit of the radionuclide along the migration path allowing greater time for radioactive decay and ultimately lower doses on the release of the radionuclide to the biosphere - the process is one of retardation. In the biosphere, however, higher k_ds lead to greater retention and hence slower dilution and dispersion, leading to increased concentrations and which can lead to higher doses.

Figure 2.4 and Table 2.4 give a comparison of the relative importance of the seven exposure pathways as a function of time and this provides a useful way of examining the performance of the Level 1b model, in terms of the accumulation processes at work in the biosphere. As far as the ^{14}C is concerned, there is little variation in the ranking of the pathways with time, the only changes occurring after 2 years, as the build up of activity in the soil means that the dose due to milk consumption becomes a greater contributor to the total dose than the drinking water pathway, and at around 10^3 years where the dose arising from the inhalation of contaminated dust from soil becomes greater than the drinking water dose, as the source term decays away. It is interesting to note that the meat consumption and grain consumption pathways are almost equally important at the time of the peak dose from ^{14}C, with milk consumption accounting for only 11% of the total dose.



(a) individual pathway doses for ^{14}C

(b) individual pathway doses for ^{235}U

(c) individual pathway doses for ^{231}Pa

(d) individual pathway doses for ^{227}Ac

Figure 2.4 – The variation of the individual exposure pathways as a function of time. Data taken from participant A.

time, y	rank	^{14}C pathway	^{14}C dose, Sv y^{-1}	relative contrib.	^{235}U chain pathway	^{235}U chain dose, Sv y^{-1}	relative contrib.
1	1	meat	$1.0\ 10^{-8}$	0.37	meat	$7.1\ 10^{-12}$	0.52
	2	grain	$8.4\ 10^{-9}$	0.31	water	$5.1\ 10^{-12}$	0.38
	3	fish	$6.3\ 10^{-9}$	0.23	fish	$1.1\ 10^{-12}$	0.08
	4	milk	$2.4\ 10^{-9}$	0.09	grain	$1.6\ 10^{-13}$	0.01
	5	water	$5.0\ 10^{-11}$	< 0.005	milk	$4.5\ 10^{-14}$	< 0.005
	6	dust	$2.4\ 10^{-14}$	< 0.005	external γ	$5.0\ 10^{-14}$	< 0.005
	7	-	-	-	dust	$2.0\ 10^{-14}$	< 0.005
10^3	1	meat	$1.5\ 10^{-5}$	0.47	dust	$6.3\ 10^{-8}$	0.49
	2	grain	$1.3\ 10^{-5}$	0.41	grain	$4.3\ 10^{-8}$	0.33
	3	milk	$3.6\ 10^{-6}$	0.11	meat	$1.9\ 10^{-8}$	0.15
	4	fish	$3.7\ 10^{-9}$	< 0.005	external γ	$4.7\ 10^{-9}$	0.04
	5	dust	$3.7\ 10^{-11}$	< 0.005	milk	$1.1\ 10^{-10}$	< 0.005
	6	water	$3.4\ 10^{-11}$	< 0.005	water	$4.7\ 10^{-11}$	< 0.005
	7	-	-	-	fish	$1.8\ 10^{-11}$	< 0.005
10^5	1	meat	$3.0\ 10^{-11}$	0.48	dust	$2.5\ 10^{-6}$	0.57
	2	grain	$2.5\ 10^{-11}$	0.40	grain	$1.7\ 10^{-6}$	0.39
	3	milk	$7.1\ 10^{-12}$	0.11	meat	$1.5\ 10^{-7}$	0.03
	4	fish	$3.2\ 10^{-15}$	< 0.005	external γ	$2.8\ 10^{-8}$	0.01
	5	dust	$7.4\ 10^{-17}$	< 0.005	water	$9.6\ 10^{-10}$	< 0.005
	6	water	$3.0\ 10^{-17}$	< 0.005	milk	$4.3\ 10^{-10}$	< 0.005
	7	-	-	-	fish	$4.3\ 10^{-10}$	< 0.005

Table 2.4 - Ranking of the individual pathway doses at three times for ^{14}C and the ^{235}U chain (summed over chain members). Data taken from Participant A.

The behaviour of the ^{235}U chain is quite different however, and this is mainly due to the ingrowth of the daughters in the top soil from the ^{235}U which accumulates there. In comparing Figures 2.4b to 2.4d it is clearly the ^{231}Pa and ^{227}Ac which are responsible for the two highest contributions to the total dose from the chain. The most important pathways vary from nuclide to nuclide, with the biological and chemical uptake of the elements in plants and animals, and with their different radiotoxicities for the human recipients of dose. At 10^5 years it is the dose due to dust inhalation (predominantly from ^{227}Ac, with an important contribution from the ^{231}Pa) which is the most important pathway, and this arises from the ingrowth of the chain daughters as a result of the sorption of ^{235}U in the top soil. The second most important pathway at this time is that of grain consumption (accounting for 39% of the total chain dose and arising from ^{231}Pa) and the third highest pathway dose is from the consumption of meat (giving a 3% contribution and arising from the ^{231}Pa and the ^{235}U). It should also be noted that in all cases the drinking water dose is much less than the total dose.

2.3 Stochastic Results.

2.3.1 Individual Dose as a Function of Time.

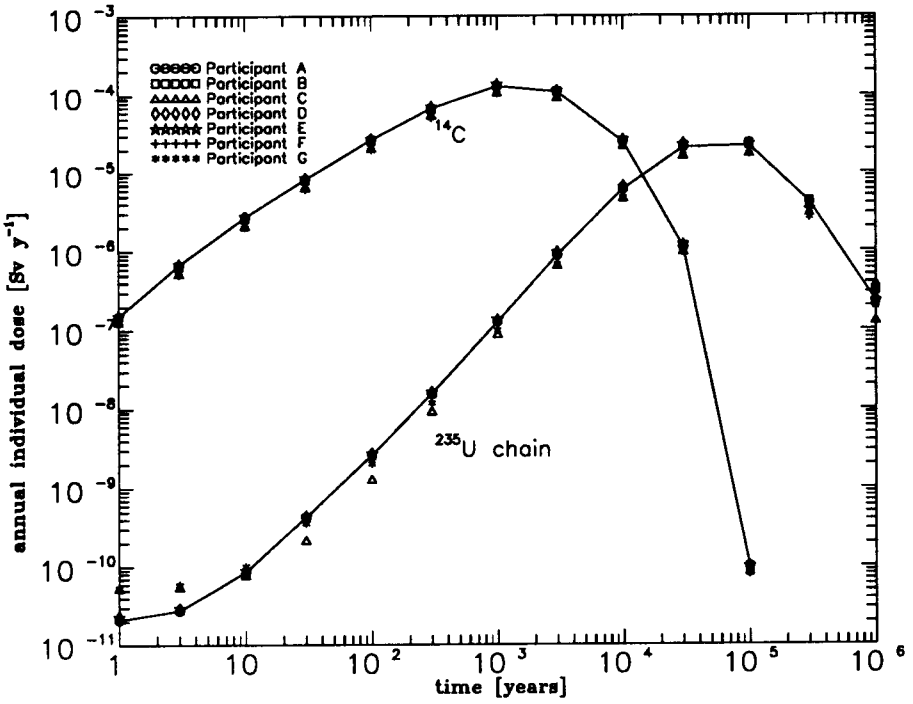
Questionnaire Table B3 requests the means and standard deviations of the annual individual dose as a function of time. These are plotted in Figure 2.5 for each of the participants. In Figure 2.5a, the mean doses are compared and in Figure 2.5b the standard deviations are presented. The results for Questionnaire Table B.3 itself are given in Annex D, Table D.3.

Good agreement between the participants is evident from Figure 2.5, for both ^{14}C and the ^{235}U chain. The results from participants C and G appear to stand out a little from the cluster of the other results. This is surprising, considering the results from the deterministic comparison. The biosphere transport and exposure pathway codes used by the participants have been thoroughly checked and no reason for the differences has been found. The only other common feature of these two codes is that they both used 1000 samples generated by the Sandia implementation of Latin Hypercube Sampling on MicroVAX machines. However when other participants have tried to generate similar results using similar combinations of hardware and software the outlying results apparent in Figure 2.5 have **not** been observed, indicating that there are no intrinsic errors in either the Sandia LHS code or the random number generator on MicroVAX computers. The source of the differences remains unexplained. The question arises whether or not the magnitude of this discrepancy is significant.

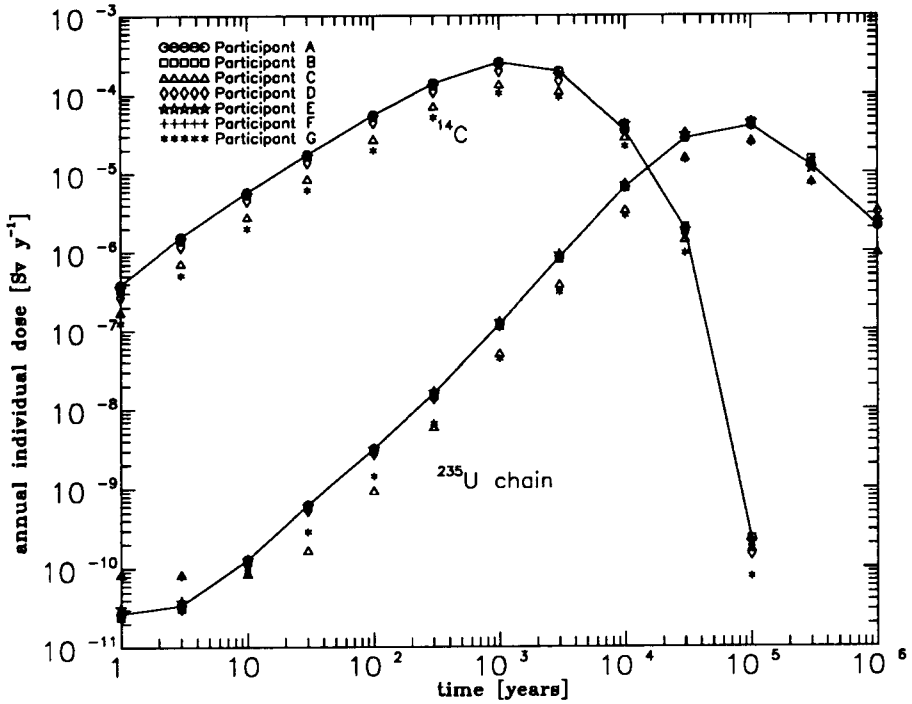
One way to answer this is by reference to the degree of scatter shown in the results from the deterministic central case. Table 2.2 reveals differences of ±10% were observed between the participants for various times, radionuclides and pathways. On this basis, the discrepancies evident in Figure 2.5a do not appear large.

Another basis for comparison is the statistical uncertainty in estimating mean doses from the finite set of sample realisations. Figure 2.6 again shows the mean dose estimates, as in Figure 2.5a, together with the Chebyshev 95% confidence interval (equation 2.1) relating to the results of participant B (1000 sample cases). On this basis, the ^{235}U chain mean doses from participants C and G are seen to deviate from the others by a little more than the uncertainty expected from the statistical scatter.

Thus, the results can be said to be in good agreement. The only remaining unresolved question is why the mean-dose results for the participants other than C and G agree so well, when their deterministic results (Table 2.2 and Figure 2.3) do not agree better with each other than with participant C and G. A hypothesis to account for this difference is that the scatter evident in Table 2.2 may result from a variety of numerical approximation effects. It may be that to some extent, the numerical errors produced by the codes used by participants C and G are systematic, affecting results for all sets of sampled parameters, whereas the errors in the other codes tend to average out, being of mixed sign according to the exact parameters values chosen. This hypothesis, however, cannot be tested from the exercise results as submitted.



(a) contributions for the mean dose



(b) contributions for the standard deviation of dose

Figure 2.5 – Results for Questionnaire Table B.3.

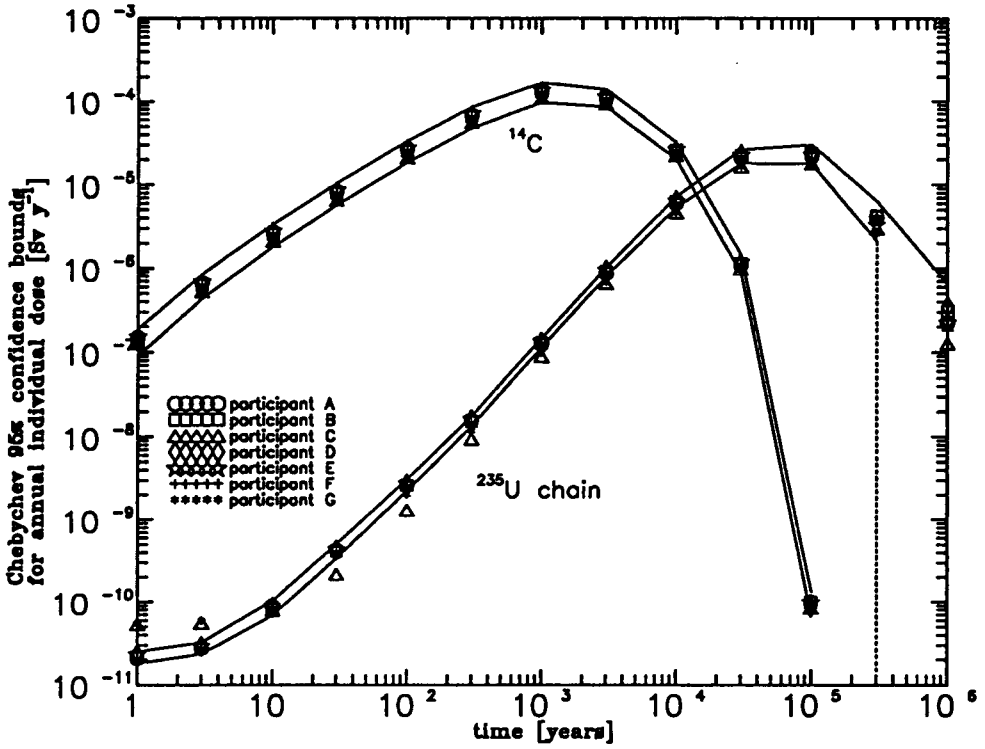


Figure 2.6 – Mean doses from all participants in relation to the Chebyshev 95% confidence interval.

2.3.2 Ranking of the Exposure Pathways as a Function of Time.

The rankings of the exposure pathways contributing to the annual individual doses for ^{14}C and the ^{235}U chain were found to be in excellent agreement: only one pathway was ranked differently by one participant. The exact values of the pathway doses themselves showed some slight variation (see Table D.4 of Annex D) but the rankings were unaffected by this. The results for Questionnaire Table B.4 are illustrated by the rankings provided by participant B (Table 2.5). The extra time points called for in Table B.4 (compared with Table B.2) make it possible to represent graphically the time variation in the relative contribution to the mean dose, for each of the pathways doses. This is shown in Figure 2.7.

In the case of ^{14}C the relative balance quickly becomes established after the start of the release, so that there is little variation after 10 years. The meat and grain consumption pathways each account for around 40% of the mean dose,

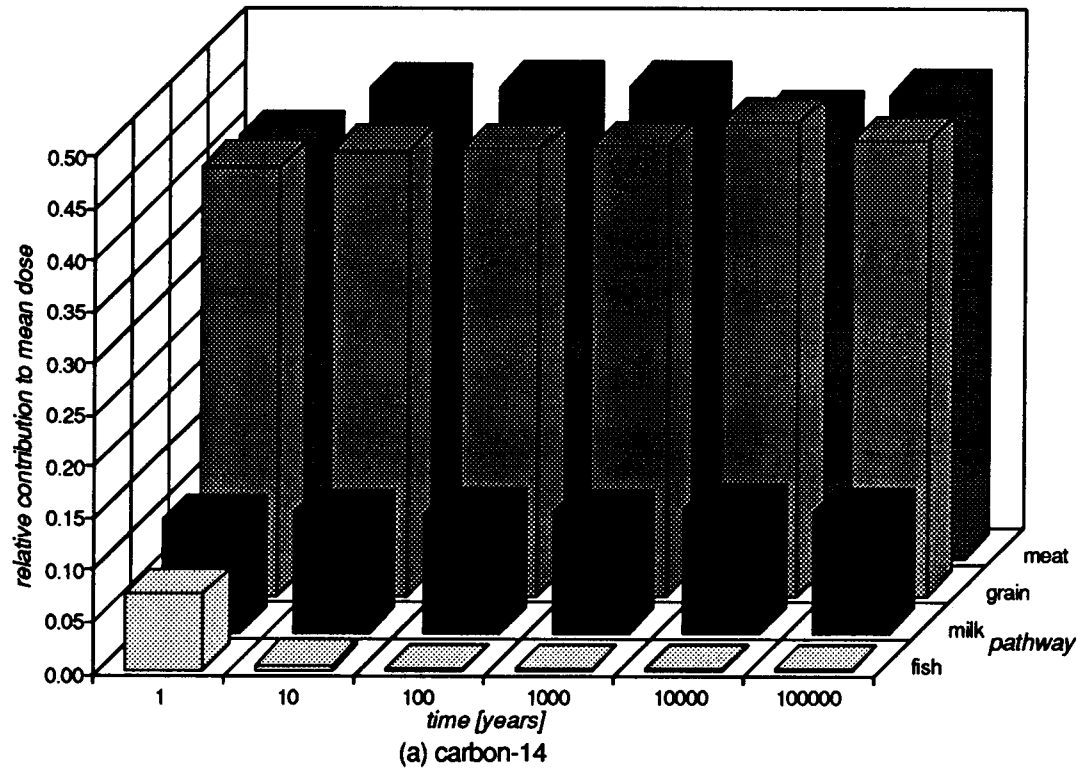
and milk consumption accounts for a further 11%. The results for relative contribution to the mean dose for ^{14}C show the same balance as the central case results. Similarly, contributions to the mean chain dose show considerably more variation in time, but the trends follow the same patterns as those established in the central case, with the pathways associated with the ^{235}U itself dominating the contributions to total dose at earlier times (through the meat, drinking water and external-γ pathways). At the later times the doses associated with the daughters grow in importance as their compartment inventories increase. The important pathways are predominantly the grain pathway for ^{231}Pa and dust inhalation for the ^{227}Ac.

time, y	rank	^{14}C pathway	^{14}C dose, Sv y^{-1}	relative contrib.	^{235}U chain pathway	^{235}U chain dose, Sv y^{-1}	relative contrib.
1	1	meat	$5.5\ 10^{-8}$	0.41	meat	$1.1\ 10^{-11}$	0.51
	2	grain	$5.6\ 10^{-8}$	0.41	water	$8.2\ 10^{-12}$	0.39
	3	milk	$1.5\ 10^{-8}$	0.11	fish	$1.7\ 10^{-12}$	0.08
	4	fish	$9.8\ 10^{-9}$	0.07	grain	$2.9\ 10^{-13}$	0.01
	5	water	$9.6\ 10^{-11}$	< 0.005	external γ	$1.5\ 10^{-13}$	0.01
	6	dust	$1.5\ 10^{-13}$	< 0.005	milk	$7.5\ 10^{-14}$	< 0.005
	7	-	-	-	dust	$7.2\ 10^{-14}$	< 0.005
10^1	1	meat	$1.2\ 10^{-6}$	0.45	meat	$5.2\ 10^{-11}$	0.61
	2	grain	$1.1\ 10^{-6}$	0.43	external γ	$1.1\ 10^{-11}$	0.13
	3	milk	$2.9\ 10^{-7}$	0.11	water	$8.8\ 10^{-12}$	0.10
	4	fish	$1.2\ 10^{-8}$	< 0.005	dust	$5.8\ 10^{-12}$	0.07
	5	water	$1.2\ 10^{-10}$	< 0.005	grain	$5.7\ 10^{-12}$	0.07
	6	dust	$3.0\ 10^{-12}$	< 0.005	fish	$1.8\ 10^{-12}$	0.02
	7	-	-	-	milk	$3.5\ 10^{-13}$	< 0.005
10^2	1	meat	$1.2\ 10^{-5}$	0.45	meat	$1.3\ 10^{-9}$	0.50
	2	grain	$1.1\ 10^{-5}$	0.43	dust	$5.0\ 10^{-10}$	0.19
	3	milk	$2.9\ 10^{-6}$	0.11	grain	$4.3\ 10^{-10}$	0.16
	4	fish	$2.7\ 10^{-8}$	< 0.005	external γ	$3.4\ 10^{-10}$	0.13
	5	dust	$2.8\ 10^{-10}$	< 0.005	water	$2.9\ 10^{-11}$	< 0.005
	6	water	$3.1\ 10^{-11}$	< 0.005	milk	$5.6\ 10^{-12}$	< 0.005
	7	-	-	-	fish	$6.3\ 10^{-12}$	< 0.005

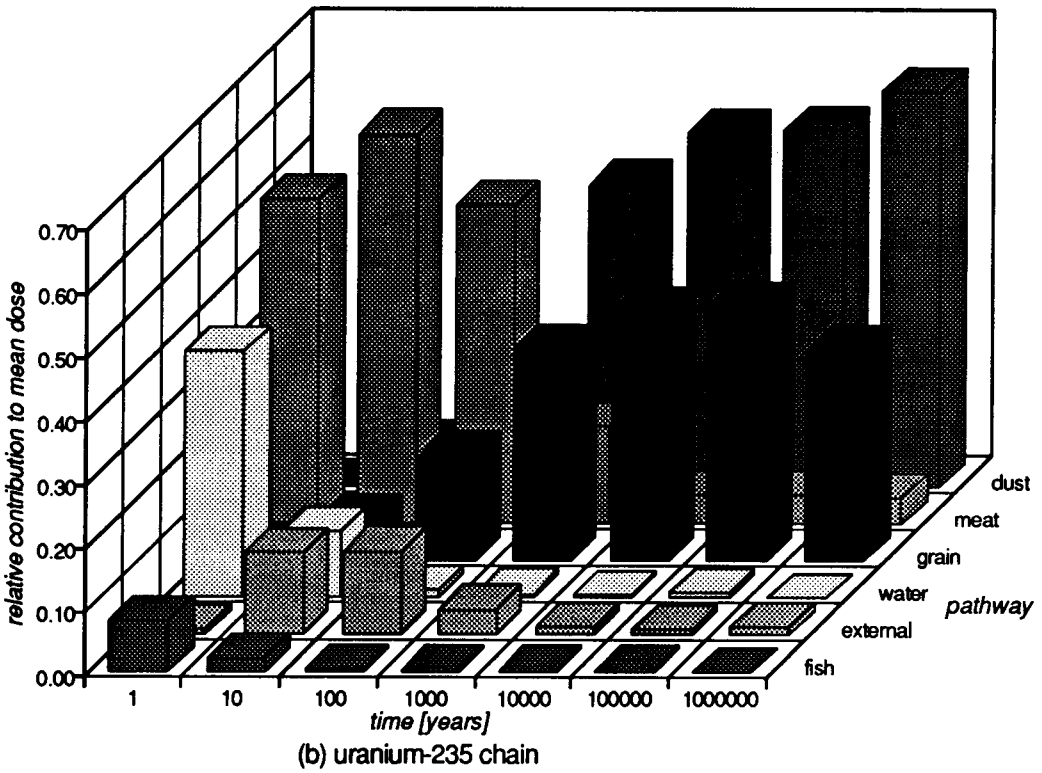
Table 2.5 - Ranking of the individual pathway doses for ^{14}C and the ^{235}U chain (summed over chain members) for the stochastic case, at the times requested in Questionnaire Table B.4. Results for participant B.

time, y	rank	^{14}C pathway	^{14}C dose, Sv y^{-1}	relative contrib.	^{235}U chain pathway	^{235}U chain dose, Sv y^{-1}	relative contrib.
	1	meat	$5.9\ 10^{-5}$	0.45	dust	$6.1\ 10^{-8}$	0.47
	2	grain	$5.7\ 10^{-5}$	0.43	grain	$4.3\ 10^{-8}$	0.33
	3	milk	$1.5\ 10^{-5}$	0.11	meat	$2.0\ 10^{-8}$	0.15
10^3	4	fish	$8.9\ 10^{-8}$	< 0.005	external γ	$5.0\ 10^{-9}$	0.04
	5	water	$9.4\ 10^{-10}$	< 0.005	water	$6.1\ 10^{-9}$	< 0.005
	6	dust	$1.6\ 10^{-10}$	< 0.005	fish	$2.0\ 10^{-10}$	< 0.005
	7	-	-	-	milk	$1.2\ 10^{-10}$	< 0.005
	1	grain	$1.2\ 10^{-5}$	0.46	dust	$3.5\ 10^{-6}$	0.55
	2	meat	$1.1\ 10^{-5}$	0.43	grain	$2.4\ 10^{-6}$	0.39
	3	milk	$3.1\ 10^{-6}$	0.12	meat	$2.8\ 10^{-7}$	0.05
10^4	4	fish	$1.1\ 10^{-8}$	< 0.005	external γ	$5.9\ 10^{-8}$	0.01
	5	water	$9.6\ 10^{-11}$	< 0.005	water	$1.3\ 10^{-8}$	< 0.005
	6	dust	$3.1\ 10^{-11}$	< 0.005	fish	$5.4\ 10^{-9}$	< 0.005
	7	-	-	-	milk	$3.1\ 10^{-10}$	< 0.005
	1	meat	$4.5\ 10^{-11}$	0.45	dust	$1.3\ 10^{-5}$	0.56
	2	grain	$4.4\ 10^{-11}$	0.44	grain	$9.5\ 10^{-6}$	0.40
	3	milk	$1.2\ 10^{-11}$	0.12	meat	$8.0\ 10^{-7}$	0.03
10^5	4	fish	$1.5\ 10^{-14}$	< 0.005	external γ	$1.4\ 10^{-7}$	0.01
	5	dust	-	-	water	$1.3\ 10^{-7}$	0.01
	6	water	-	-	fish	$6.3\ 10^{-9}$	< 0.005
	7	-	-	-	milk	$1.2\ 10^{-11}$	< 0.005
	1	-	-	-	dust	$1.8\ 10^{-7}$	0.62
	2	-	-	-	grain	$1.0\ 10^{-7}$	0.33
	3	-	-	-	meat	$1.2\ 10^{-8}$	0.04
10^6	4	-	-	-	external γ	$1.7\ 10^{-9}$	0.01
	5	-	-	-	water	$5.8\ 10^{-11}$	< 0.005
	6	-	-	-	fish	$2.9\ 10^{-11}$	< 0.005
	7	-	-	-	milk	$2.9\ 10^{-11}$	< 0.005

Table 2.5 (continued) - Ranking of the individual pathway doses for ^{14}C and the ^{235}U chain (summed over chain members), at the times requested in Questionnaire Table B.4. Results for participant B.



(a) carbon-14



(b) uranium-235 chain

Figure 2.7 - time evolution of the exposure pathway contributions to mean dose.

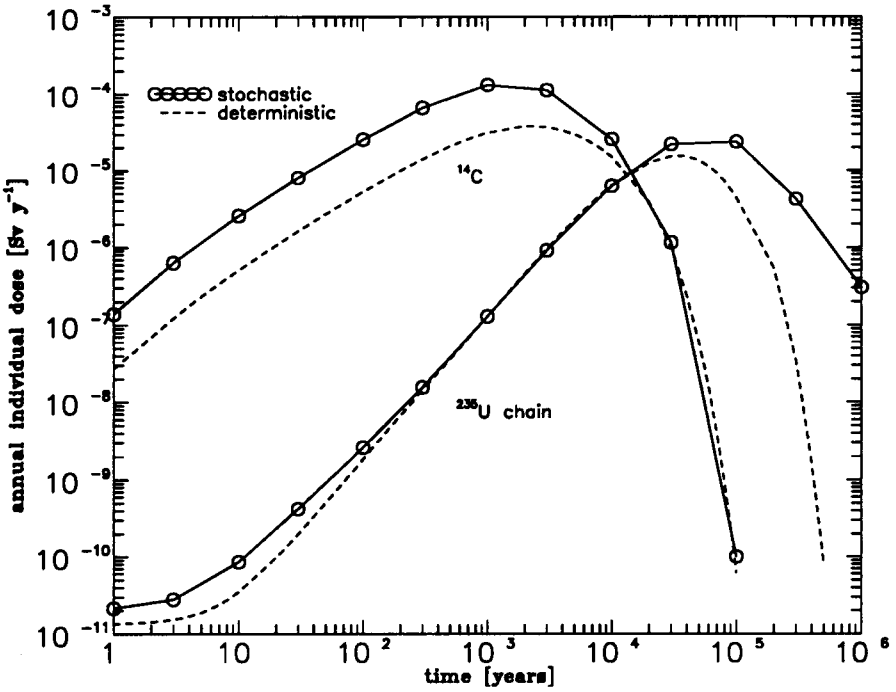


Figure 2.8 – Comparison of the mean doses arising from the stochastic results with the doses from the deterministic central case.

2.4 Comparison of the Deterministic and Stochastic Questionnaire Results.

It is of interest to compare the deterministic central case with the mean doses calculated in the stochastic calculations. In Figure 2.8 the doses from the deterministic central case (participant A) are plotted alongside the mean doses obtained from the stochastic simulation (participant B). For ^{14}C it is clear that at times up to around 10^4 years, at which point the radioactive decay of the nuclide greatly reduces the radiological impact, the mean doses in the stochastic simulations are around an order of magnitude greater than those arrived at in the central case calculations. Furthermore, the time of occurrence of the peak dose is shifted to earlier times by a few hundred years.

The behaviour of the chain dose is somewhat different. At early times, up to 500 years, and before there has been significant ingrowth of the daughters, the mean dose from the stochastic simulations is slightly higher than the central case dose. In the period from 500 years to 10^4, years the central case and mean stochastic doses are in close agreement but beyond this time the two values again diverge, with the mean dose at stochastic 10^6 years being many orders of magnitude greater than the central case dose. Although the peak doses differ by only a factor of two, the peak of the mean stochastic dose arises a few *thousand* years after the peak of the central case dose.

It can be seen that some aspects of the stochastic data set used in the PSACOIN Level 1b case study influence the importance of the retention and accumulation processes in the biosphere, and hence the magnitude of the peak dose and, because the retention processes are affected, the time to reach the peak dose can be altered. The accumulation processes in the biosphere can also be characterised by the time span for which the annual individual dose remains above, say, 90% of the peak value. Table 2.9 illustrates the difference between the two cases.

For ^{14}C the width of the curve is unchanged, only the magnitude of the dose is different. For the chain there is a considerable broadening of the peak, indicating that the time of the peak is strongly influenced by the parameter uncertainty in the case.

nuclide	deterministic case	stochastic case
^{14}C	3 500	3 500
^{235}U chain	$4.4\ 10^4$	$5.6\ 10^5$

Table 2.9 - time span (years) for which the annual individual dose remains above 90% of the peak value.

A comparison of the results for the ranking of the exposure pathways given in Tables 2.4 and 2.5 shows that the parameter uncertainty in the Level 1b data set has little influence on the *ranking* of the exposure pathways, although the overall magnitude of the doses is affected.

2.5 Summary of the Analysis of the Questionnaire Response.

The first aim of the PSACOIN Level 1b case study, to gain experience in the probabilistic modelling of the biosphere, has been met by the contributions of the seven participants who took part in the exercise and the second aim (to help verify the participating codes), has been achieved via the results presented in Tables 2.1 and 2.2 (and D.1 and D.2 of Annex D). These results indicate that the codes used by the participants in the exercise have given good agreement in all the submodels of the case and, that although the results of the case may be dependent on the model structure, this case provides a potentially valuable benchmark of the codes for the solution of both the compartment model transport equation and the exposure pathway model.

The results from the stochastic case (illustrated in Figure 2.5, and given in Tables D.3 and D.4 of Annex D) confirm that the agreement between the participating codes extends to a range of parameter combinations. Not only is there evidence of the correct implementation of the submodels in the case but also the sampling and statistical postprocessing functions behave correctly.

The third of the aims of the exercise (the investigation of the influence of parameter uncertainty of the mean annual individual dose) has been illustrated in the comparison of the deterministic and central case results. The effects of individual model parameters are discussed in the sensitivity analyses in the following chapter.

3. ADDITIONAL ANALYSES.

3.1 Introduction.

In addition to the questionnaire results specified in Annex B, five of the participating organisations contributed additional results. These serve to illustrate the behaviour of the PSACOIN Level 1b biosphere model, which itself contains features common to many biosphere models used for waste disposal assessments. The techniques employed are: a **global sensitivity** analysis, in which all the distributed parameters are allowed to vary through their assigned ranges simultaneously; an extension of the **parametric uncertainty analysis** of the distribution of annual individual dose from the preceding chapter; a **local sensitivity** analysis, in which selected parameters are set to the extremes of the assigned ranges for comparison with the central values, to investigate the effect of different input parameter assumptions for the model representation of the study biosphere. Analysis of these results illustrates the advantages of the modelling approach taken in the study.

3.2 Uncertainty and Global Sensitivity Analysis of the PSACOIN Level 1b Results.

3.2.1 Distribution of Annual Individual Dose.

The influence of the parameter uncertainty specified in the PSACOIN Level 1b data set can be seen in the distribution of annual individual doses which emerge from the full set of stochastic simulations in the Level 1b case. Figure 3.1 gives histograms of the total annual individual dose for both ^{14}C and the ^{235}U chain at times close to the peaks of each of the respective dose-histories given in Figure 2.8. The figure was generated from 1000 Monte Carlo samples by Participant A.

The distribution of doses for ^{14}C at 10^3 years is approximately log-triangular, with a median around 7 10^{-5} Sv y^{-1}, and a mean of around 1.3 10^{-4} Sv y^{-1}. The range in outcomes from the 1000 sample runs covers nearly three and a half orders of magnitude, with some combinations of parameters leading to doses as high as 3 10^{-3} Sv y^{-1}, a value which in itself would exceed regulatory limits. The distribution of the doses from the ^{235}U chain at 10^5 years shows an almost log-uniform distribution, again spanning three and a half orders of magnitude, with a median of 5 10^{-6} Sv y^{-1}, a mean of 2.5 10^{-5} Sv y^{-1}, and a maximum value of around 5 10^{-4} Sv y^{-1}.

Given this uncertainty in the potential outcome of the Level 1b model as a result of the uncertainty of a limited number of input parameters, it is important to identify the parameters contributing most to this uncertainty. This is discussed in the following section. It should be remembered, however, that because of the very simplistic assumptions about the form of the source term, the results presented here are **not** representative of a real site, and that the absolute values of the doses calculated are not typical of those arising from the disposal concepts in operation or under investigation by OECD member states. The

real significance of these calculations is that they illustrate the potential for uncertainty in biosphere modelling results, and can be used to identify important parameters and mechanisms when estimating the doses arising from the transport and accumulation of contaminants in the biosphere.

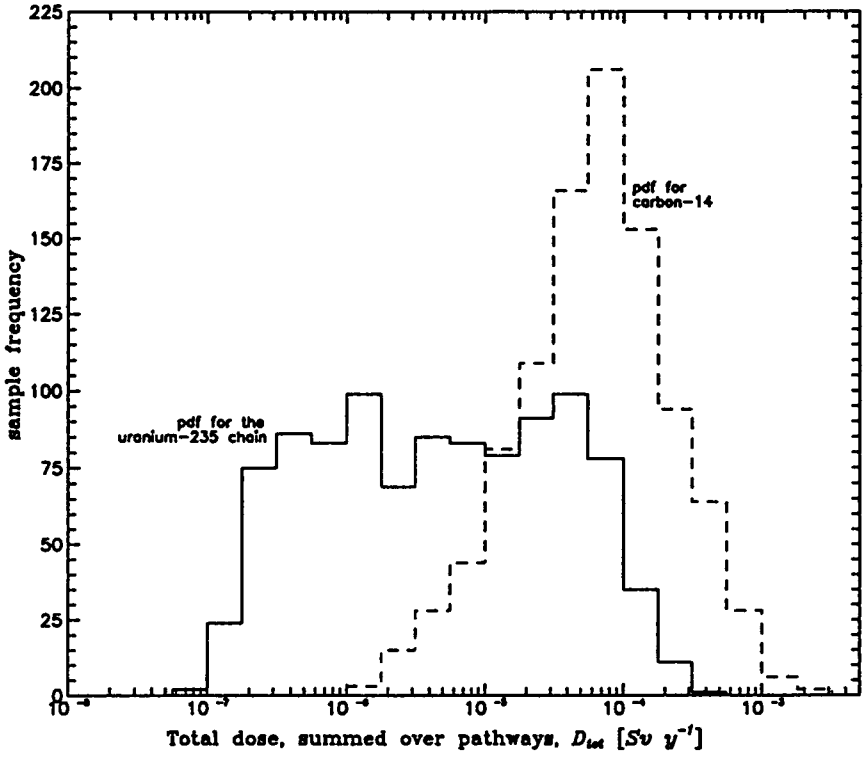


Figure 3.1 – Histograms for the total dose summed over all pathways for each of the ^{14}C and the ^{235}U chain (contribution from Participant A).

3.2.2 Sensitivity of annual individual dose to the input parameters.

3.2.2.1 Parameter sensitivity as a function of time.

Several of the participants contributed details of the correlation between the sampled input data and the doses as a function of time. The following discussion is based on the work of participants A, C, D and E. The model coefficients of determination (R^2) for the annual individual dose are plotted as a function of time for both the raw and rank-transformed data in Figure 3.2. R^2 is crucial to the interpretation of the results by regression correlation measures, as it provides an indication of how much uncertainty in the output has been accounted for by the regression model. The R^2 values on raw data for ^{14}C are not high, but those on rank-transformed data are significant up to around 10^4 years, when the loss by radioactive decay removed almost all of the activity from the system. The same trend can be seen for the ^{235}U chain dose and the R^2 values on

rank-transformed data are high ($R^2 \geq 0.8$) for most of the time range. The rank correlation is therefore used as a sensitivity estimator in the following analysis.

The values of the rank correlation coefficients for all the parameters which showed correlations above the 95% significance level ($C_R \geq 0.18$) are plotted in Figure 3.3. Ten of the input parameters reached this significance level for ^{14}C (above) and nine input parameters did so for the ^{235}U chain (below). This figure allows the influence of each of the *sensitive* parameters to be discussed in turn.

Groundwater velocity v_g:

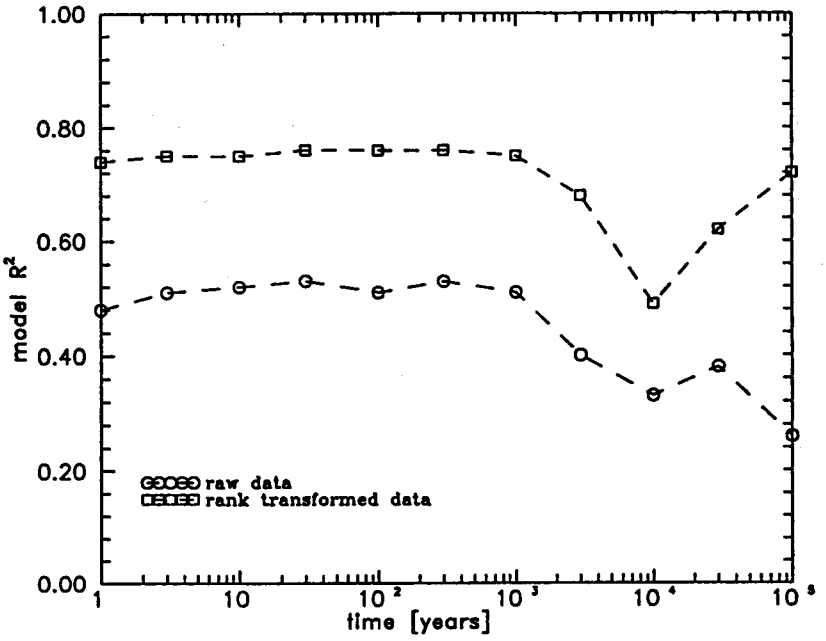
For ^{14}C (for which significant exposure rates only occur up to around 10^4 years, when radioactive decay masks all other FEPs), v_g has a positive correlation up to the time at which the source terms stops releasing more of the nuclide to the biosphere. This means that the effect of v_g is felt strongly ($C_R \approx 0.5$) as a mechanism for the transport of the poorly sorbed contaminant from the deep soil to the surface soil. Beyond 10^4 years the negative correlation indicates that this parameter's principal effect is to wash the ^{14}C out of the biosphere system into the river and hence downstream. In contrast, for the much more strongly sorbed ^{235}U chain members, the influence of v_g is only marginal, the value of C_R peaking between 10^2 and 10^3 years.

Release area A_f and groundwater release angle θ:

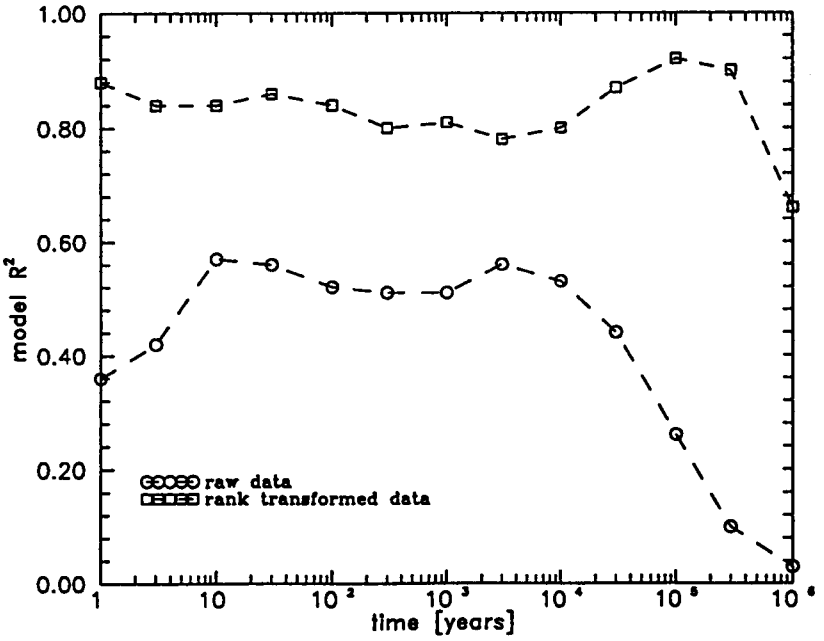
The release area is a diluting factor, and so has an important negative correlation, which is almost constant for ^{14}C. For the ^{235}U chain however, the magnitude varies in time in response to the relative importance of the other parameters. The maximum influence on the dose from the chain arises around 10^3 years. The other geosphere/biosphere interface parameter, the groundwater release angle, is indicated as being moderately important to the ^{14}C dose, where, for similar reasons to the groundwater release velocity, it is important in transferring the mobile species to the surface soil.

Bioturbation, B, and diffusion, D:

In the case of ^{14}C, the rank correlation coefficient for bioturbation is fairly constant up to 10^4 years. For the chain, however, the total dose is very sensitive to the bioturbation rate at early times. This means that, although the doses themselves are not very high (compared to the peak dose), the bioturbation mechanism is potentially important in the upward migration of highly sorbed species, since the bioturbation process is represented in the Level 1b model as acting on the contaminants sorbed onto the solid material. These highly sorbed nuclides are relatively immobile in groundwater because only a small fraction of the total compartment inventory moves in the water phase, and this is confirmed by the insensitivity of the chain dose to the diffusion coefficient. In contrast, the relatively poorly sorbed ^{14}C has a higher sensitivity to the diffusion constant than it does to the bioturbation coefficient.

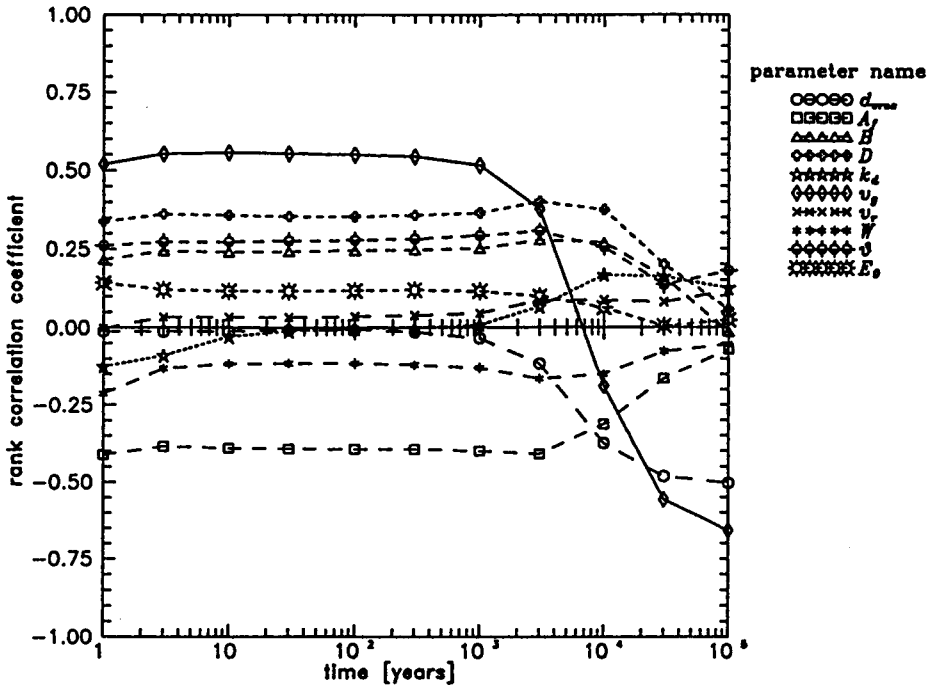


(a) ^{14}C

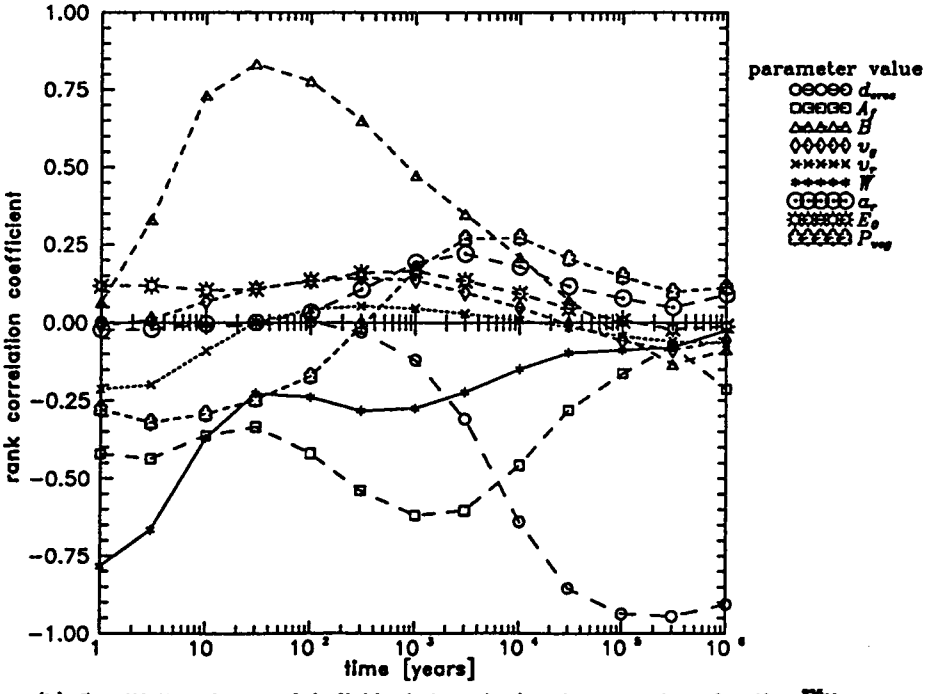


(b) ^{235}U chain

Figure 3.2 – Model coefficient of determination for both the raw data and the rank transformed data for the annual individual dose from the stochastic case. Data from Participant E.



(a) Sensitivity of annual individual dose to input parameters for ^{14}C.



(b) Sensitivity of annual individual dose to input parameters for the ^{235}U chain.

Figure 3.3 – The sensitivity of total dose to input parameters for ^{14}C and the ^{235}U chain. Correlation coefficients greater than 0.18 have a 95% chance of significant influence on the total dose. Data from Participant D.

Soil - groundwater distribution coefficient, k_d:

Somewhat surprisingly, this global sensitivity analysis does not indicate that the results for total dose are very sensitive to the soil k_d. Only the soil k_d for ^{14}C is sensitive, and then only slightly at the very early times when the inventory is increasing and at the very late times when the inventory is effectively zero. At very early times the influence is negative, as it acts to *retard* the transport of contaminants from the deep soil to the surface soil. The influence becomes positive between 10^3 and 10^4 years, where the effect is to *retain* the activity in the surface soil. This emphasises the dual nature of the k_d in the biosphere. Under some circumstances the assumption of low k_d values is *conservative* because the species are then more mobile. In other situations the converse is true: high k_ds are pessimistic because the contaminants are immobile in the parts of the biosphere where doses arise.

Soil erosion rate d_{eros}:

By far the strongest sensitivity of the total dose to any of the input parameters is seen for the chain dose to the soil erosion rate. From 10^4 years onwards the correlation is very strongly negative, and a similar feature is seen in the corresponding plot for ^{14}C, although it is less pronounced. The reason for the influence of this parameter on the doses is that in this model, the effect of soil erosion is to *remove* contaminated material from the surface soil and, because no net erosion is assumed, ie no decrease in surface soil thickness or boundary movement with respect to the deep soil layer, there is effectively *replacement* of the surface soil material by an *uncontaminated* external source of top soil.

River volumetric flow, W, and river water velocity, v_r:

These two parameters, which characterise the aquatic environment in the model, have little influence on the annual individual doses at the times at which the maximum doses occur. For ^{14}C the river water velocity is insignificant at all times. For the ^{235}U chain, it has a mild negative correlation at very early times, when the concentration of the uranium itself is building up, since v_r is a loss term from the system. The influence of the volumetric flow rate (which is effectively a dilution term for activity entering the river water in the model) hovers around the margins of sensitivity after a moderate negative correlation at the times when the ^{14}C water concentration is building up. The effect is much stronger for ^{235}U at the earlier times, and the relative importance of this parameter remains moderate for a long period, reflecting the influence of the cattle drinking water-milk/meat pathway on the total dose from the chain (see Figure 2.7).

Dust concentration, a_r, food-energy intake, E_0, degree of vegetarianism, P_{veg}:

The parameters in the exposure pathways submodel which are varied do not have a great deal of influence on the total dose, summed over all pathways. The total food energy intake verges on being significant throughout much of the time in the ^{14}C plot, with a maximum at the start of the release to the biosphere. In the case of the chain, E_0 has a peak significance around 10^3 years, when the ^{231}Pa and ^{227}Ac grow in and their influence on the total dose becomes greater. Also, the

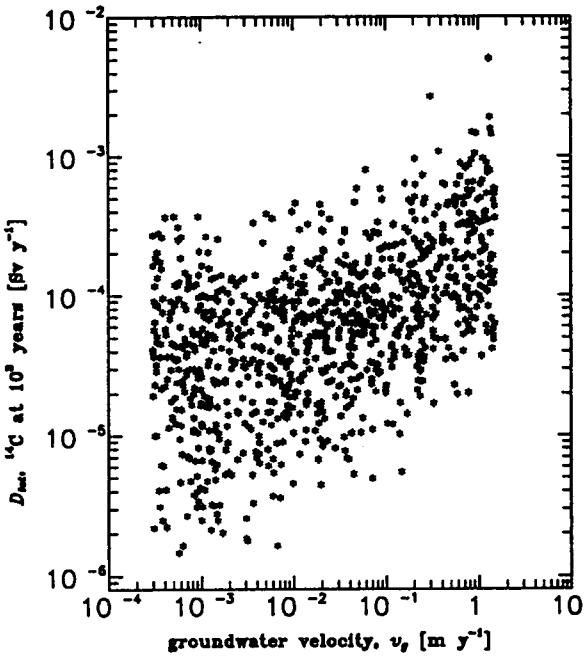
non-food pathways (in particular external dust inhalation) become more significant. This can further be seen, for the chain dose, in the variation of the rank correlation coefficient for the *residential* airborne dust loading, which reaches a maximum around 3 10^3 years. A stronger correlation is seen for P_{veg}, the proportion of meat plus grain consumption taken as grain. At early times, when mainly ^{235}U is present in the system, there is a negative correlation of P_{veg} with the total dose because the exposure to ^{235}U via meat is relatively more important (since $P_{meat} = 1 - P_{veg}$). At later times, however, the positive correlation comes about because the root uptake factor for ^{231}Pa is 20 times higher than that for ^{235}U, so that grain is a more important pathway than meat. This finding is in agreement with the results displayed in Figure 2.7, which illustrates the relative importance of the exposure pathways to the mean dose as a function of time.

3.2.2.2 Sensitive parameters at the times of the peaks of the mean doses.

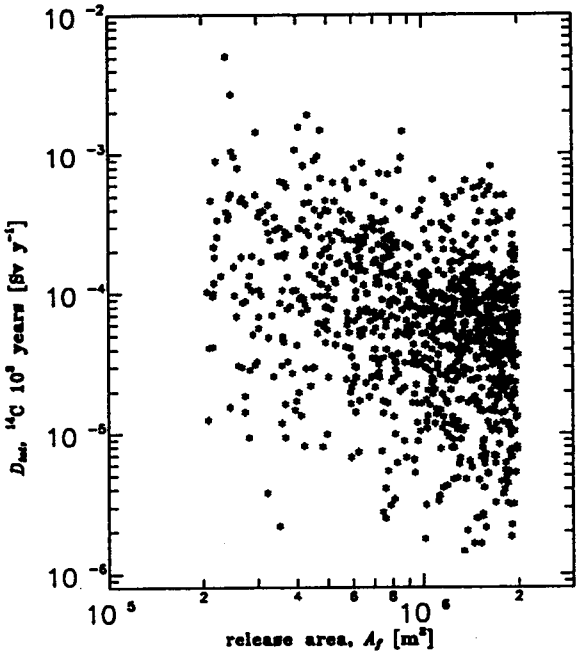
The section above considered how the variation with time of the rank correlation coefficients of the input parameters with the annual doses can be used to illustrate the relative importance of the input parameters at different times, i.e. how the rank correlation coefficients can be used to probe the behaviour of the biosphere system. Also of importance in performance assessment is the sensitivity of the peak values of the annual doses to the uncertain parameters. Table 3.1 shows the most sensitive parameters near the time of the peaks of the respective parent nuclides: 10^3 years for ^{14}C and 10^5 years for the ^{235}U chain.

10^3 years			
carbon-14		uranium-235 chain	
parameter	C_R	parameter	C_R
groundwater flow velocity, v_g	*0.52*	release area, A_f	*-0.62*
release area, A_f	*-0.40*	bioturbation coefficent, B	*0.47*
diffusion coefficient, D	*0.37*	river volumetric flow, W_r	*0.28*
groundwater flow angle, θ	*0.29*	normal dust-air loading, a_r	*0.19*
bioturbation coefficient, B	*0.25*		
10^5 years			
carbon-14		uranium-235 chain	
parameter	C_R	parameter	C_R
groundwater flow velocity, v_g	*-0.66*	soil erosion rate, d_{eros}	*-0.94*
soil erosion rate, d_{eros}	*-0.50*	release area, A_f	*-0.17*
groundwater flow angle, θ	*0.18*		

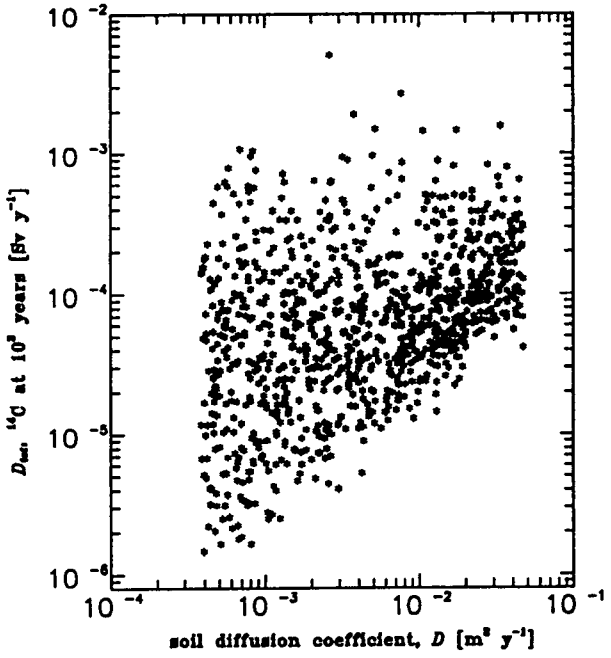
Table 3.1 - Rank correlation coefficients for total dose summed over chain members and exposure pathways. Parameters with a significance greater than 95% are indicated.



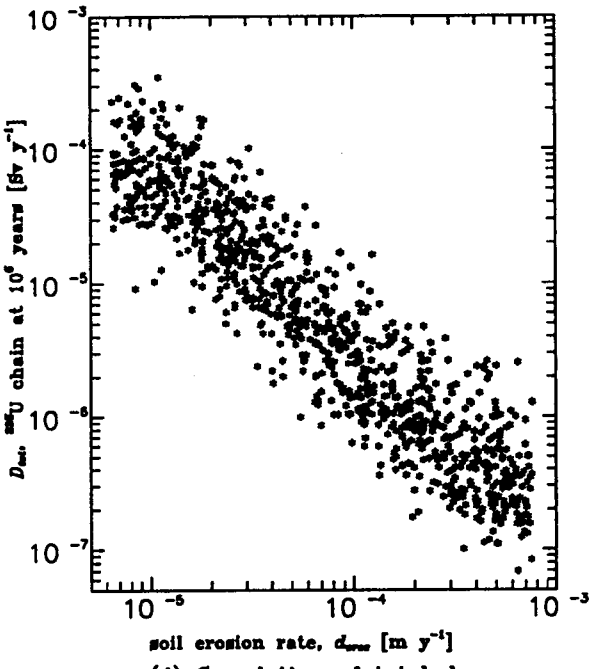
(a) Correlation of total dose for ^{14}C at 10^3 years and groundwater velocity.



(b) Correlation of total dose for ^{14}C at 10^6 years and release area.



(c) Correlation of total dose for ^{14}C at 10^3 years and soil diffusion coefficient.



(d) Correlation of total dose for the ^{238}U chain at 10^6 years and soil erosion rate.

Figure 3.4 – Scatter plots of the most sensitive input parameters for total dose, at times near to the peak of the ^{14}C and the ^{238}U chain. Data from Participant A.

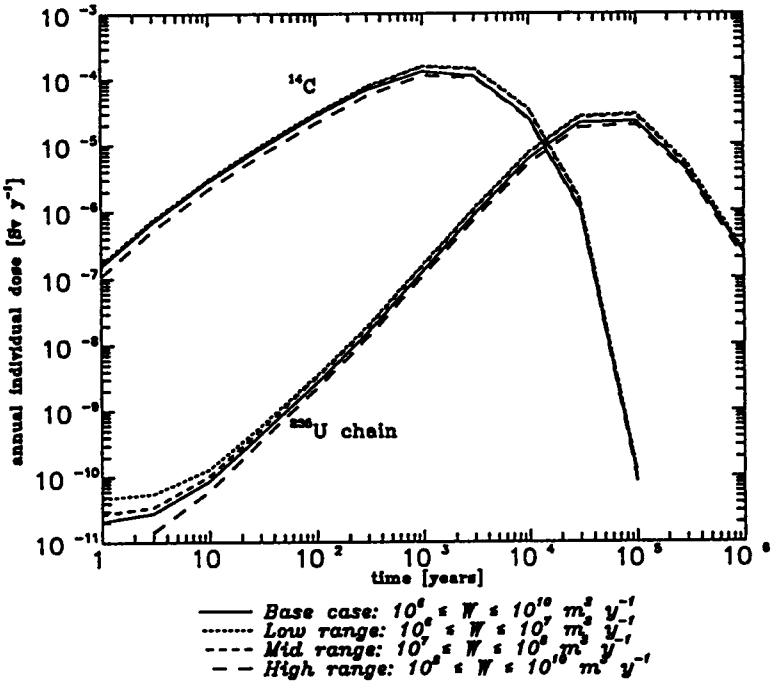
As discussed above, only in the case of the soil erosion rate do any of these parameters dominate the distribution of the peak doses. This is further illustrated in Figure 3.4, which shows scatter plots for the three most significant parameters for ^{14}C at 10^3 years (groundwater velocity, v_g, release area, A_f, and soil diffusion coefficient, D) and the soil erosion rate (d_{eros}) for the chain dose at 10^5 years. These plots show that there is a great deal of scatter, except for the d_{eros} for the ^{235}U chain at 10^5 years. They further illustrates that in biosphere modelling many of the parameters are sensitive at the same time, and it should be remembered that in this model only 26 of the total of 115 input parameters were considered to be uncertain and assigned pdfs.

Figures 3.4a - 3.4c also provide information on the high consequence runs which are seen in the high-dose tail of the ^{14}C dose distribution in Figure 3.2. In Figure 3.4a, the highest dose run (D_{tot} = 5 10^{-3} Sv y^{-1}) occurs for the highest value of the groundwater velocity. Correspondingly, in Figure 3.4b, this result arises from a run with a value of the release area close to its lower limit. Although the soil diffusion coefficient is a sensitive parameter, with a positive rank correlation coefficient, it is not involved in this extreme event. The corresponding value for the diffusion coefficient is in the middle of the range.

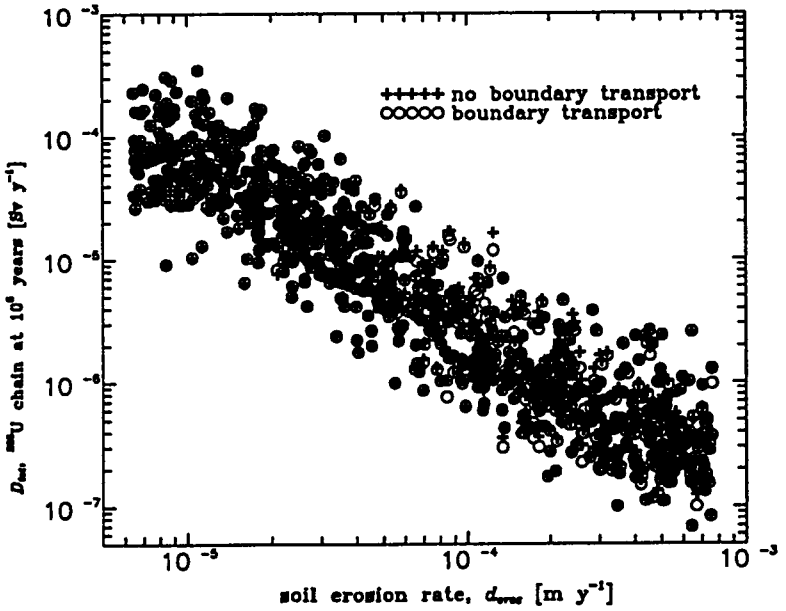
This analysis can be applied to other parts of the system, for example to determine the sensitivity of the doses to the transfer coefficients, or of the transfer coefficients themselves to the input data. This would then lead to an identification of the most significant compartments and transfer coefficients in the system. The resulting C_rs are higher than those found for the relationships between doses and input data, and this arises because the direct linkages between these parts of the biosphere system are more straightforward. In the *process-led approach* used in the Level 1b model however, the direct link between the primary input data (as opposed to the transfer coefficients themselves) gives a better understanding of the fundamental processes leading to the receipt of radiation doses in the biosphere. This aspect of the Level 1b approach is discussed in greater detail in Section 3.4.

3.3 Variations in the Level 1b specification.

The Level 1b data set was compiled using some broad assumptions about the ranges of some of the parameters, for example the aquatic biosphere parameters W (river water volumetric flow, m^3 y^{-1}) and v_r (the river water velocity, m y^{-1}). It could be argued that instead of representing the river flow regime as a single entity with a range of volumetric flow rates from 10^6 m^3 y^{-1} to 10^{10} m^3 y^{-1}, a more suitable way of modelling the Level 1b river would be to split this broad range into smaller ranges representing a small stream (10^6 - 10^7 m^3 y^{-1}), a medium sized regional river, (10^7 - 10^8 m^3 y^{-1}), and a large continental river approaching the coast (10^8 - 10^{10} m^3 y^{-1}). Figure 3.5a indicates that splitting the river flow regime up in this way has little effect on the mean of the annual individual doses. Only at the very earliest times is there a notable difference in the annual doses from ^{235}U, although in general terms the smaller the river throughput, the smaller the dose.



(a) The effect of different river flow regimes on the total dose.



(b) Scatter plot illustrating the lack of influence when soil erosion is treated as a boundary transport problem.
Data are for the ^{238}U chain dose at 10^6 years and the soil erosion rate.

Figure 3.5 – Results for variations on the Basic Level 1b specification. (Data provided by Participant A).

The soil erosion rate (d_{eros} m y^{-1}) is indicated as having a large influence on the doses received at later times. This is because the surface soil would be completely eroded away in 400 to 50000 years, and matrial sorbed onto the soil would be removed with it. However, the volumes of the compartments are assumed to remain constant so that there is an implicit replenishment of the solid material in the soil compartment with *uncontaminated* solid material. The influx arises because, although the transfer coefficient from surface soil to river water is given by

$$\lambda_{13}^{eros} = \frac{d_{eros}}{l_{ss}}, \qquad (3.1)$$

there is no corresponding transfer from the deep soil to the surface soil (equivalent to upward contaminant transport by boundary movement). Figure 3.5b shows the differences in the Level 1b model results when this boundary movement process is included. There is little difference in the scatter plots, but the overlap of the two sets of results is not exact. The most important feature of the plot for the boundary transport model is that it shows exactly the same correlation with the total chain dose as does the base case.

This situation arises because the concentrations of radionuclides in the deep soil are similar to those in the top soil. Underlying this representation is again the assumption of constant compartment volumes. In this variation, the deep soil is implicitly replenished with uncontaminated solid material from beneath (i.e. from the implied geosphere). The assumption of constant thickness for the soils' compartments in the biosphere can be justified if there is no rapid removal of the soils in the region. The fact that the erosion rate over time can lead to the removal of activity from the release area and thus to lower radiological exposures further illustrates the need to examine carefully the nature of the geosphere/biosphere interface in the model region. Strongly sorbed contaminants in the geosphere potentially provide a reservoir which could be released to the biosphere over time as a result of net surface erosion. In such a case, the trend seen in Figure 3.5b could be reversed depending on the k_d of the contaminants in the geosphere.

3.4 The advantages of the PSACOIN Level 1b modelling approach.

3.4.1 Local sensitivity analysis of the transport mechanisms in soils.

The use of the compartment models to represent the transport of contaminants in the biosphere means that the key parts of the transport equation (Equation 1.1) are the characteristic compartment residence times - $1/\kappa_{ij}$ - for species being transferred from compartment i to compartment j. In the development of compartment models in the field of radioecology[3.1, 3.2], these compartmental residence times have been based on the observation of radiotracer movement under experimental or field conditions, and the spatial and temporal scales of such measurements have, for the most part, been considerably different to those relevant to biosphere modelling for radioactive waste disposal assessments, making direct translation of the available data difficult. By careful definition of the spatial extent of the region to be modelled, reasonable consistency can be maintained within the limits of validity of linear compartment models. Over the

extremely long timescales required in waste disposal assessments however, experimental measurements are not practicable and only natural analogues might provide opportunities for model validation studies.

In the course of the *BIOMOVS* study[3.3] participants became were increasingly confident in the use of parameters to describe the compartmental residence times employed under different biosphere conditions. The participants also realised that the features, events and processes (FEPs) involved could be represented by a parameterisation of the FEPs based on an analysis of the characteristic timescales associated with each contributing FEP. This approach makes no demands on the extrapolation of the measured residence times under present day conditions, but instead identifies the processes leading to contaminant transport between the compartments, so that for a given inter-compartmental interaction, the characteristic residence time defines the *fractional transfer rate:* κ_{ij}, which is determined by the rate of transfer of contaminant between compartments:

$$\kappa_{ij} = \frac{1}{N_i} \frac{dN_{ij}}{dt} \tag{3.2}$$

where N_i is the amount of contaminant N in compartment i, and the transfer to compartment j takes place at a rate dN_{ij}/dt. The aim of biosphere modelling for long-term waste disposal assessments is therefore to find generic representations for all the transfer processes identified as relevant to the model.

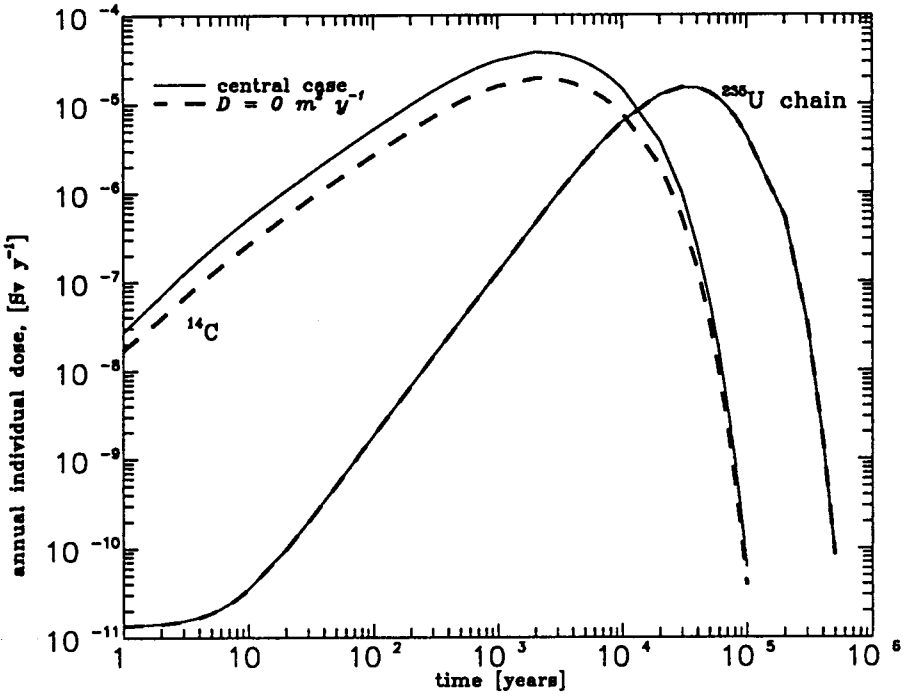
This approach was used in the development of the model which was adopted for the PSACOIN Level 1b exercise - the *MiniBIOS* model developed by the United Kingdom National Radiological Protection Board[3.4]. The parameterisation of the transfer coefficients used here (given in detail in Annex A) provides a method of determining the transfer coefficients for a given site, under given conditions, on the basis of the physical, chemical and biological properties of the site. Use is made of the linear nature of the model, so that the intercompartment transfer coefficients can be written as a linear sum of terms, each one representing the individual processes. To take the example of the surface soil to deep soil transfer coefficient (which was briefly discussed in Section 1.4),

$$\kappa_{12} = \kappa_{12}^{\text{advection}} + \kappa_{12}^{\text{diffusion}} + \kappa_{12}^{\text{bioturbation}}, \tag{3.3}$$

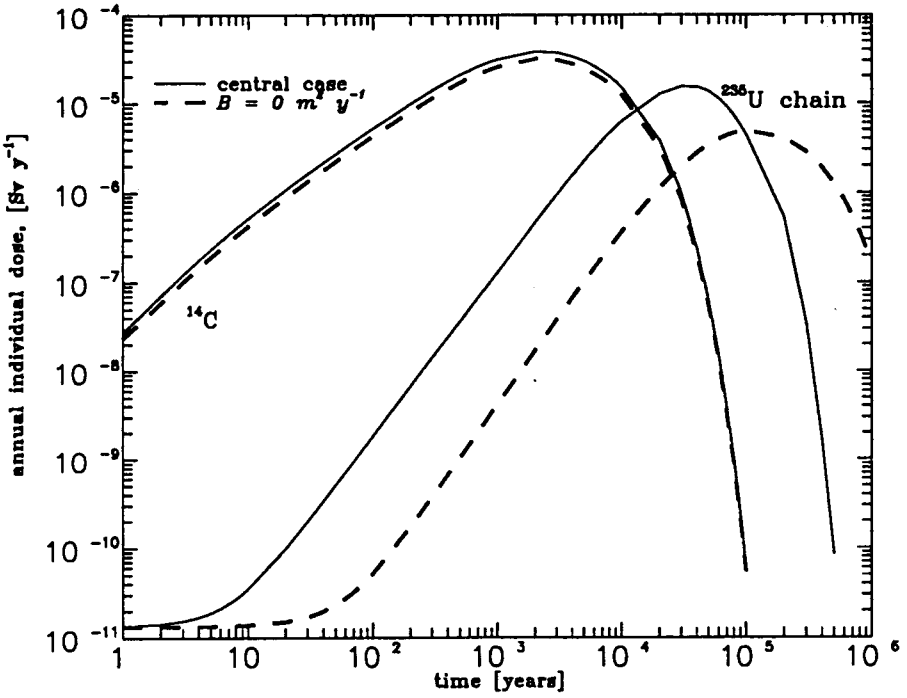
and the *MiniBIOS* parameterisation of the process used in the Level 1b model gives

$$\kappa_{12} = \frac{d_{\text{rain}} + d_{\text{irri}}}{R\ \varepsilon\ l_{ss}} + \frac{(R - 1)B + D}{R\ l_{ss}\ min(l_{ss}, l_{ds})}, \tag{3.4}$$

which identifies the *advective flows* with percolating water (due to rainfall and irrigation) and *diffusion* and *bioturbation* with the appropriate coefficients (D and B respectively). The chemical behaviour of the radionuclides in the system is defined by the retention coefficient, R, which is given by the compartment density, ρ, porosity, ε, and the nuclide solid-liquid distribution coefficient, k_d:

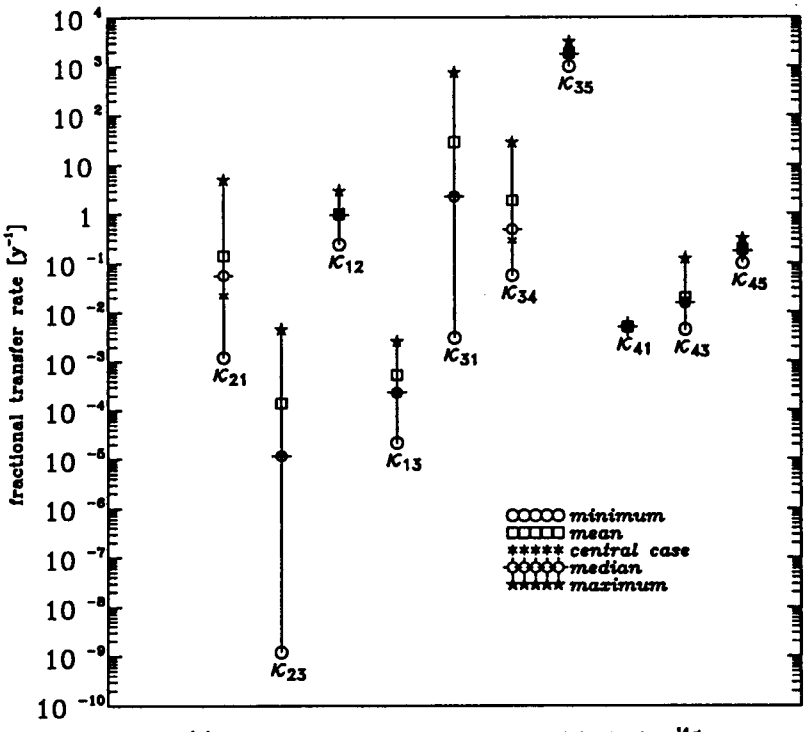


(a) The influence of the diffusion process on the total annual individual dose in the Central Case.

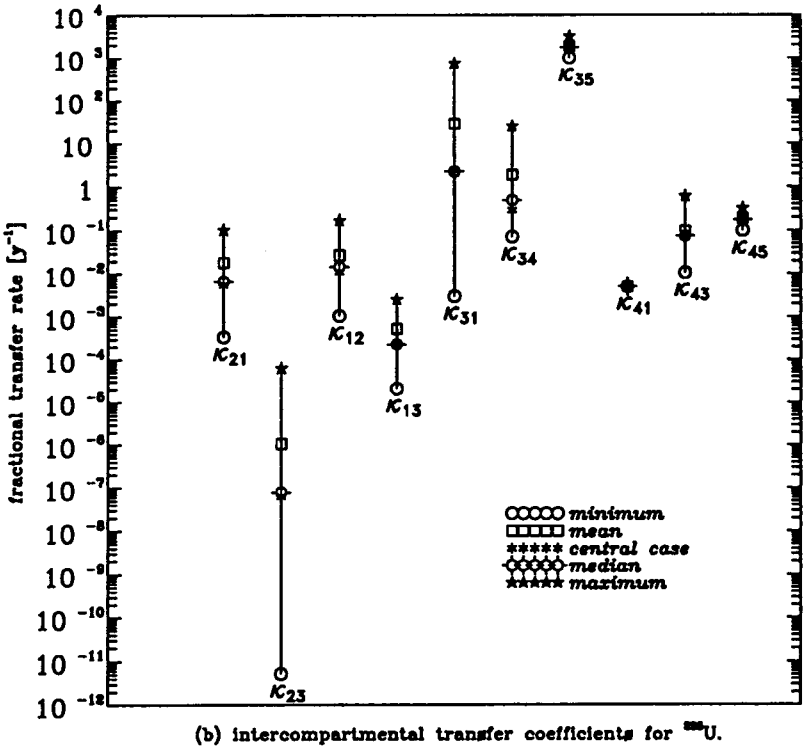


(b) The influence of the bioturbation process on the total annual individual dose in the Central Case.

Figure 3.6 – Results from a *local sensitivity analysis* on the soil diffusion coefficient (D) and the soil bioturbation coefficient (B).



(a) intercompartmental transfer coefficients for ^{14}C.



(b) intercompartmental transfer coefficients for ^{238}U.

Figure 3.7 – The variation in the PSACOIN Level 1b transfer coefficients arising from the variation in the input parameters (data provided by participant C).

$$R = 1 + \frac{\rho}{\varepsilon} k_d \qquad (3.5)$$

The compartment thicknesses are given by l_{ss} for the surface soil, and l_{ds} for the deep soil compartment. The effects of this linearity are illustrated by the local sensitivity analysis contributed by participant A[3.5] and discussed below.

The effects of diffusion and bioturbation (as represented in this model) have been investigated by comparing the results for the total dose summed over pathways and decay chain members, calculated from the deterministic central case with results obtained by setting first the bioturbation coefficient B to zero, and second by setting the diffusion coefficient D to zero. This is equivalent to modelling situations where each of these transfer processes is not taken into account.

Figure 3.6 indicates that diffusion affects only the ^{14}C with the central case value leading to a two-fold increase in the annual individual dose compared to the situation where the process is not included. The bioturbation process, in contrast, affects the doses received from both the ^{14}C and the ^{235}U chain, although the effect on the chain dose is much more significant - a factor of five increase in the peak annual individual dose *and a shift in the time of occurrence of the peak* to earlier times by around 80000 years. This confirms the results of the analysis of the global sensitivity analysis in Section 3.2.2.1.

These results can be understood when the detailed representations of the two transport mechanisms in the Level 1b model are considered. The diffusive term in Equation 3.3 is

$$\kappa_{12}^{diffusion} = \frac{D}{R\ l_{ss}\ min(l_{ss}, l_{ds})}, \qquad (3.6)$$

with a similar expression for the return diffusive transfer, $\kappa_{21}^{diffusion}$, since diffusion is a two-way process. The bioturbative transfer, given by

$$\kappa_{12}^{bioturbation} = \frac{(R - 1)B}{R\ l_{ss}\ min(l_{ss}, l_{ds})}, \qquad (3.7)$$

also has a similar form for the reverse transfer. The difference in the effects of these two terms is that the diffusive term deals with the contaminants in solution whereas the bioturbative term deals with the contaminants sorbed onto the solid material in the respective compartments. The partition of contaminants between the liquid and solid phases is determined by the *retention coefficient, R* (given in Equation 3.4 above), so that the fraction of the contaminant in the compartment in solution is given by $1/R$ and the fraction sorbed onto the compartmental solids is $(R - 1)/R$. The dependence of R on the solid-liquid k_d means that the relatively poorly sorbed ^{14}C is little influenced by the bioturbation process, whereas the members of the ^{235}U chain are much more strongly sorbed, and as a consequence move

predominantly with the solid material involved in the bioturbation. Conversely, the poorly sorbed ^{14}C has a higher fraction remaining in solution, causing diffusion to be an important process. Diffusion is, however, unimportant for the more highly sorbed species since they are bound to solid material.

3.4.2 The range of the transfer coefficients in the Level 1b model.

Participant C has provided data which further illustrate the advantages of the process-led approach taken in the PSACOIN Level 1b exercise. Figure 3.7 indicates the range of values generated in the stochastic calculations for each of the 10 transfer coefficients involved in the transport of radionuclides in the biosphere (excluding the source term). Results for ^{14}C are plotted above, and for ^{235}U below. The means, medians and deterministic central case values are also plotted.

In the absence of a process-led description of the biosphere, one potential alternative would be simply to estimate the ranges of the transfer coefficients themselves, on the basis of expert knowledge. It is an open question whether expert knowledge would generate the range of values, or could adequately characterise the correlations between the transfer coefficients seen here. The figure also illustrates the range in the fractional transfer rates exhibited in the model, from 10^{-11} y^{-1} for κ_{23} (deep soil to river water) to 5 10^{3} y^{-1} for κ_{35} (downstream transport in the river). The influence of the soil k_d, bioturbation and diffusion can again be seen in the differences in the inter-soil compartment transfer rates for the carbon and uranium species (κ_{21} and κ_{12} respectively).

3.5 Summary of the additional analyses.

The additional analyses carried out by participants in the PSACOIN Level 1b exercise have illustrated some important features of biosphere models for radioactive waste disposal assessments. The global sensitivity analysis demonstrates that in the Level 1b model no single parameter dominates the sensitivity of annual individual dose. The sensitivity of dose is fairly evenly distributed among several of the parameters that were chosen to be variable in the exercise. In the context of this exercise, the parameters used in modelling the transport of the radionuclides in the biosphere were shown to have a greater influence on the mean annual individual dose than the sampled parameters in the exposure pathway submodel, which were chosen to represent a range of different exposure rates for the exposure pathways.

The analysis of the important parameters in the system highlights the importance of solid material transport (particularly involving the bioturbation and erosion processes) for the highly sorbing radionuclides. The representation of erosion in the model has also illustrated the importance of modelling assumptions about the geosphere/biosphere interface. Finally, The area of the release from the geosphere is indicated as having a potentially significant effect on the radiological impact of the release.

4. SUMMARY AND CONCLUSIONS

4.1 Principal aims of the PSACOIN Level 1b Exercise.

The aims of the PSACOIN Level 1b exercise have been

1 to gain experience in the application of probabilistic systems assessment methodology to transport and radiological exposure sub-models and hence to methods of estimating the total risk to individuals, or groups of individuals, arising from the release of radionuclides to the biosphere;

2 to contribute to the verification of biosphere transport and exposure sub-models used by the participants in the case;

3 to investigate the effects of uncertainty in the biosphere transport and exposure sub-models on the estimate of mean dose (which is equivalent to risk in this formulation) to individuals simultaneously exposed via several exposure pathways.

The experience gained by the participants in the exercise in applying the case model to the assessments of the radiological consequences of the release of radionuclides to the biosphere when doses can be received via multiple exposure pathways confirms the approach a as practicable modelling option in the context of probabilistic assessments (Aim 1). Some participants used established codes and methodologies, while others used the case to develop, or to further enhance, capabilities in biosphere modelling in the context of probabilistic safety assessments. The responses to the Level 1b Questionnaire, in both deterministic and stochastic phases, showed that good agreement was achieved between the participating codes and methodologies, and this serves to verify the correct working of all the codes and sub-models involved (Aim 2).

Aim 3 is model specific. It concerns the contributions to the overall Level 1b uncertainty estimates from each of the sub-models that make up the case model. Of these three sub-models - source term, biosphere transport and exposure pathways - the latter two contained parameters with associated probability distribution functions from which the sample values for the stochastic runs were generated. For the models and codes used in this study, the uncertainties associated with the biosphere transport processes have a greater influence on the overall uncertainty in the mean annual individual dose than does the influence of human behaviour in respect of the exposure pathways by which radiation doses to the exposed population would be delivered.

4.2 The wider implications of the results from the additional analyses.

The PSACOIN Level 1b Task Group recognises that the results of the

analyses contained in this report depend strongly on the nature of the Level 1b conceptual model. The biosphere represented in the exercise was that of an agricultural region associated with a river and the biosphere transport and exposure pathway sub-models described in the case specification represent only one possible interpretation of the biosphere features, events and processes (FEPs). The parameterisation of the processes is likewise not unique. However, in accordance with the first of the aims, the case can be used as a test-bed for this type of biosphere representation, which is commonly employed in several Member countries of the OECD for waste disposal assessments. The results of this exercise are therefore particularly useful for investigating methods for estimating the total risk to individuals arising from releases of radionuclides to the biosphere and should not be interpreted as being relevant to any one site or any particular type of disposal concept. Consequently the source term was chosen to allow time for various features important in biosphere modelling for waste disposal systems to be illustrated and similarly the radionuclides employed in the study were chosen to illustrate the effects of a broad range of relevant physical, chemical and radiological properties.

That the study was designed to illustrate a broad range of biosphere features is one reason why the analysis in Chapter 3 indicated that no single parameter or group of parameters dominated the sensitivity of the dose to the input parameters. However, the fact that different parameters in the study were significant at different times shows that simplifications of this representation of this particular biosphere would be difficult to justify because such FEPs as are included here (and their corresponding parameterisation) each potentially has a role to play in determining the radiological consequences. The parameterisation in this model provides a means of quantifying the FEPs in the system and, because the sensitivity is equally distributed amongst the parameters, there is no reason to single out any particular parameter (and by implication FEP) as a candidate to be deleted from the FEP list in the model. It might be argued that the relative lack of sensitivity in this model to the sampled parameters in the exposure pathway sub-model could be used to justify a reduction in the number of exposure pathways modelled. However the comparison of the relative importance of the different exposure pathways in Chapter 2 suggests that deletion of pathways could only be done by a consideration of the properties of the individual radionuclides and/or on the basis of the relevant timescale of the assessment.

In biosphere modelling for performance assessments a fundamental problem is the inherent unknowability of the state of the biosphere at the time of the release from the geosphere. In estimating the radiological impact of the release to the biosphere it is important not to underestimate the doses (hence the assumptions underlying the exposure rates used in this exercise). This intention has naturally had a large influence in the way in which currently existing biosphere models have been designed. Traditionally the inclusion and addition of FEPs in biosphere models has proceeded on an ad hoc basis and the same situation arises in the case of the parameterisation of the FEPs. Simplification of biosphere models, or their tuning for specific assessment tasks can only proceed on the basis of a thorough review of the relevant FEPs for biosphere modelling. It is also necessary to review the ways in which the FEPs are modelled. These two objectives are being undertaken in the BIOMOVS II study by the Reference Biospheres Working Group[4.1] and the Complementary Studies Working Group[4.2]. These two groups have been specifically constituted to consider the problems of the long-term modelling of the biosphere for waste disposal assessments, and will

be working closely together in a series of intercomparisons which began in January 1993.

4.3 **Overall Conclusions.**

Although the specification of the PSACOIN Level 1b model is only one representation of the biosphere, and it is not expected be universally applicable to all biosphere systems, the following conclusions can be drawn on the basis of the analysis of the participants' responses to this exercise. (The corresponding Level 1b objective is given in brackets.)

- The different codes and routines used used by the participants to solve the compartment model transport equation performed equally well. This is true not only of the deterministic central case, but also extends to the ranges and combinations of parameters specified in the stochastic phase of the exercise. Some apparently systematic variation was seen in the stochastic results, but it is largely possible to account for this in terms of the scatter seen in the deterministic results. However the precise nature of this feature could not be fully understood with the data available and investigations should continue if similar features are seen in subsequent probabilistic intercomparisons (1, 2);
- The biosphere is a complex system potentially containing many feedback loops. One consequence of this is that no single parameter dominates the uncertainty in the biosphere as modelled here. Different parameters have a significant effect on the overall uncertainty in dose at different times. Thus the issue of timescales becomes important, as well as the influence of the repository release time and the transport time in the geosphere, both of which have **not** been addressed here (1, 3);
- It is not easy to account for the uncertainties in biosphere transport and accumulation processes with simpler models of the biosphere than the one specified in this exercise. However the successful application of the Level 1b model demonstrates that such relatively complex biosphere models can be implemented in PSA codes for waste disposal assessments. The use of such models is recommended since they demonstrate time-dependent features not available from simpler systems (1);
- In this exercise the peak mean dose calculated in the stochastic runs was around a factor of five greater than the peak dose in the deterministic central case (3).;
- The relative importance of the various exposure pathways can vary as a function of time. This feature can be important for decay chains and is particularly apparent when the properties of the daughter radionuclides that govern transport and accumulation in the exposure pathways are different to those of the parent and in this case it was illustrated that doses via the consumption of contaminated drinking water may not in every case provide a reliable (or pessimistic) estimate of the radiological impact of the release of radionuclides to the biosphere (1, 3);
- The analyses here confirm that exposure pathways other than those associated with the transport of groundwater can lead to increased annual doses. This is particularly noticeable when the dose via the inhalation mechanism is calculated (1, 3);

- The transport of sorbed contaminants on solid materials (for example as a result of erosion or bioturbation) is a potentially important process affecting the long-term transport and accumulation of radionuclides in the biosphere (1, 3);
- The nature of the interface between the geosphere and the biosphere requires careful consideration. The size of the recipient area is a significant factor affecting individual doses in the release region. Some of the modelling boundary conditions assumed in this exercise indicate that surface erosion could, in some circumstances, have a role regarding the input of radionuclides to the biosphere from the geosphere, at the interface between the models (1, 3).

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ANNEX A

SPECIFICATION OF THE PSACOIN LEVEL 1B EXERCISE

A.1 The System Model

The system to be modelled can be represented by 3 sub-models, connected as follows:

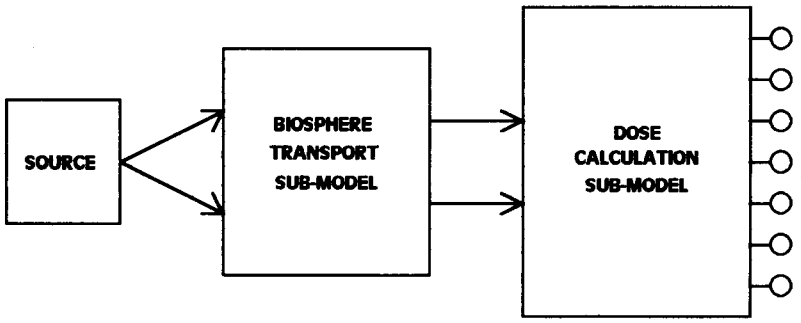

Figure A.1

The source is a simple leaching sub-model similar to that employed in the Level-E exercise. It delivers releases simultaneously to two compartments of the biosphere transport sub-model. The transport sub-model is a 4-box representation of a section of an inland river and adjacent farmland. Two of the compartments participate in directly delivering doses to Man, which arise via seven exposure pathways. The dose calculation sub-model serves to calculate these doses from the biosphere compartment activity levels.

The simple nature of the source term sub-model is such that releases from the source to the biosphere can be described with the same form of linear ordinary differential equations as those for transfers within the biosphere. It is therefore possible to amalgamate the first two sub-models illustrated above into one. In the following descriptions, such a combined approach is used, but this is mainly for unity of notation, and it should be clear how to treat the source term as a separate sub-model if preferred.

A.2 The Source and Biosphere Transport Sub-model(s)

Conceptually, the source term is a box in which the inventories of the four radionuclides (C-14, U-235, Pa 231 and Ac-227) are specified at time $t = 0$, when the release begins. Thereafter, there is a release of each radionuclides at a rate proportional to its current inventory. Similarly, the biosphere comprises four boxes (compartments), within which the radionuclides are assumed to be instantaneously well mixed. Transport occurs between the boxes (and out of the system) at rates specified by the transfer coefficients.

Altogether, then, the model contains five boxes, and we add a sixth as a notional receptacle for transfers outside the system modelled -

(0) Source;
(1) Surface Soil;
(2) Deep Soil;
(3) River Water;
(4) River Sediment;
(5) Elsewhere.

These are illustrated in Figure A.2. The biosphere proper (boxes 1 to 4) and the formulation of inter-box transfer coefficients in terms of physical process, is based on a terrestrial river section of the NRPB model *MiniBIOS*[A.1], which also treats multiple river sections, lakes and the marine environment.

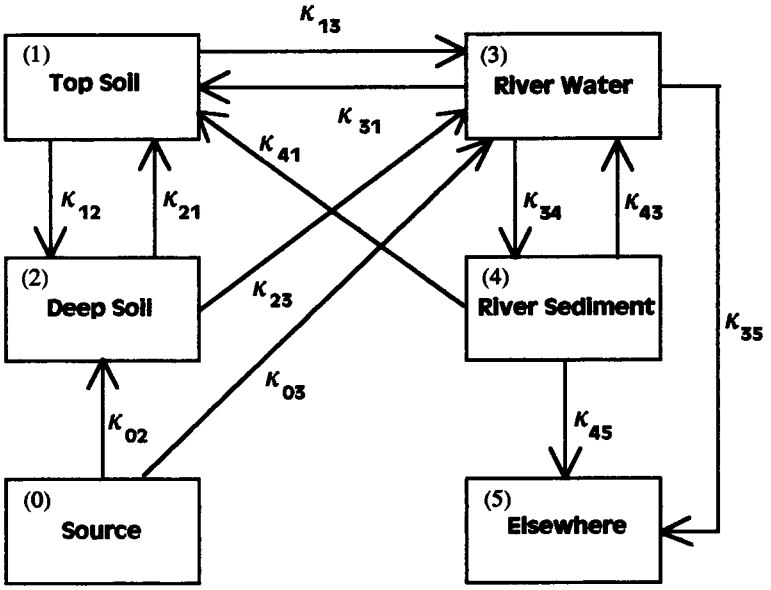

Figure A.2

In the following mathematical description, many parameters are introduced. For convenience, the meanings of the symbols are collected together in Table 1.

Let the content of nuclide n in the ith box be $M_{in}(t)$ moles. The initial inventories $M_{0n}(0)$ in the source box are specified, and those for the other boxes are taken as zero. After $t = 0$, the box contents evolve according to

$$\frac{dM_{in}}{dt} = \sum_{j=0}^{4} \kappa_{ji} M_{jn} - \sum_{j=1}^{5} \kappa_{ij} M_{in} - \lambda_n M_{in} + \lambda_p M_{ip}: \qquad i = 0 \ldots 4 \qquad (1)$$

The first summation represents transfers into box i from the other boxes j, the term in λ_n is loss by radioactive decay, and the final term is in-growth from parent nuclide p (if applicable). The κ_{ij} may be nuclide-dependent, but we do not show this explicitly in the notation.

Source Releases

The releases from the source are taken to enter directly two biosphere boxes, the deep soil and river water. The division is determined by the relative (plan-view) areas of the boxes. Thus

$$\kappa_{02} = \frac{\kappa_{0t} A_f}{A_f + A_r} \tag{2}$$

$$\kappa_{03} = \frac{\kappa_{0t} A_r}{A_f + A_r} \tag{3}$$

where the total fractional release rates κ_{0t} are given for each radionuclide. The other κ_{0j} are zero.

River Transport

In a model describing an entire river system, there would be transport by river flow from one river section to the next, and eventually to the marine environment. In this simple one-section model, this first process represents a loss from the system (transfer to box 5). There is firstly bulk flow of activity in the water phase (in solution, and sorbed into suspended sediments), with

$$\kappa_{35} = \frac{W}{V_r} \tag{4}$$

A second process is that of bed-sediment transfer via viscous drag. It is assumed that the sediment layer effectively moves downstream at a constant fraction of the river-water velocity, so that

$$\kappa_{45} = f_{rs} \kappa_{35} \tag{5}$$

Exchange between the river water and the sediment is based on the enhanced Schaeffer model for river sediments. A boundary layer is considered between the water and sediment - a region of enhanced sediment concentration which exchanges activity with the sediment layer through diffusion and bioturbation. For transfer from river water to river sediment we then have

$$\kappa_{34} = \frac{(R_b - 1) B_s + D_s}{R_b d_r \min(l_b, l_s)} + K v_r \tag{6}$$

(see Table 1 for notation). In the boundary layer, the coefficients for partitioning of activity between sediment and the water are given by

$$R_b = 1 + \alpha_b k_s \tag{7}$$

The interaction of radionuclides in the water column with the bed sediment in the river is given by Schaeffer's parameter K, multiplying v_r, the river water velocity.

The return from the sediment layer to the water-sediment boundary layer is via diffusion and bioturbation only:

$$\kappa_{43} = \frac{(R_s - 1)B_s + D_s}{R_s l_s \min(l_b, l_s)} \tag{8}$$

with the retardation coefficients in the sediment given by

$$R_s = 1 + \frac{(1 - \varepsilon_s)\rho_s}{\varepsilon_s} k_s \tag{9}$$

Transport between River and Soils

Activity in the river water is transferred to the surface-soil box by irrigation, at an annual fractional rate

$$\kappa_{31} = \frac{d_{irri} A_f}{V_r} \tag{10}$$

The transfer of activity from the river sediments to the soils is modelled as a transfer rate κ_{41} based on the dredging frequency, the rate of river meandering and other surface water-course ageing processes.

The process of soil erosion by surface runoff, transferring activity to the river from the surface soil is modelled as a transfer coefficient from the surface soil to the river water given by

$$\kappa_{13} = \frac{d_{eros}}{l_{ss}}. \tag{11}$$

The annual erosion rate d_{eros} is assumed to affect only the top-soil zone. There is no net removal of surface cover, so that erosion does not act to transfer activity from the deep soil to the surface soil. It is assumed that there is a net replenishment of the mass in the surface-soil box by uncontaminated soil from elsewhere.

Soil Transport

The transfer of activity from the surface soil to the deep soil is modelled as three processes: infiltrating water (rainfall and irrigation), porewater diffusion and bioturbation (also modelled as a diffusive process). The transfer coefficient is given by

$$\kappa_{12} = \frac{d_{rain} + d_{irri}}{R\varepsilon l_{ss}} + \frac{(R - 1)B + D}{R l_{ss} \min(l_{ss}, l_{ds})}. \tag{12}$$

Note that d_{rain} is the *infiltrating* annual rainfall (there will be a loss by evapotranspiration). The soil retardation coefficients are

$$R = 1 + \frac{\rho}{\varepsilon} k_d. \tag{13}$$

The second term in eq. (12) is the rate coefficient for diffusive transfer from a box of thickness l_{ss} to one of thickness l_{ds}, with diffusion coefficients B for the bioturbation and D for the porewater diffusion. Note that bioturbation affects activity on the soil particulates, and porewater diffusion affects the activity in the soil-water.

Activity in the deep soil box is transferred to the surface soil box by a combination of diffusion, bioturbation and groundwater flow:

$$\kappa_{21} = \frac{\phi g}{\varepsilon R l_{ds} A_f} + \frac{(R-1)B + D}{R l_{ds} \min(l_{ds}, l_{ss})}. \tag{14}$$

The second term of this expression is the return bioturbation and diffusion rate, similar in form to that in eq. (12). The first term arises from the flow of groundwater through the deep soil box with groundwater velocity v_g inclined at an angle θ to the horizontal (See Figure A.3).

The fraction of the total water flow in the deep soil box which is transferred to the surface soil is given by

$$\phi = \frac{A_f \tan\theta}{l_r l_{ds} + A_f \tan\theta}. \tag{15}$$

The total groundwater flow out of the deep-soil box (vertical and horizontal components) is

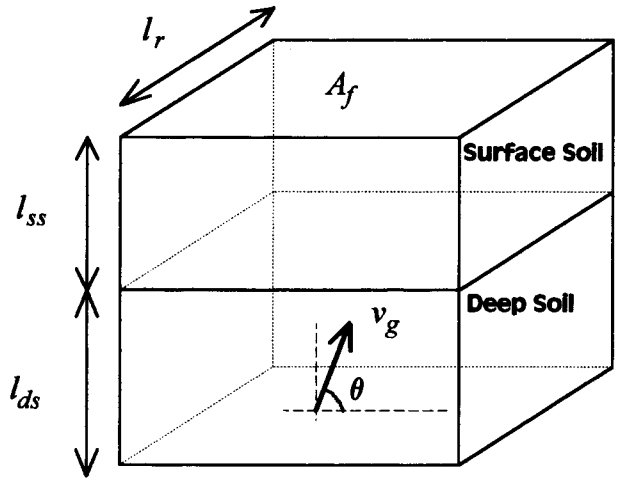

Figure A.3

$$g = v_g\left(l_r l_{ds} \cos\theta + A_f \tan\theta\right). \tag{16}$$

Similarly the fraction of the deep-soil flow which is transferred to the river-water box is given by

$$\kappa_{23} = \frac{(1-\phi)g}{\varepsilon R l_{ds} A_f}. \tag{17}$$

A.3 Source and Biosphere Transport Sub-model Parameters

Table 1 lists all the parameters used in these two sub-models, together with the values or distribution functions to be used for Level 1b. Most of the variable parameters are treated as independent random variables except in the case of the river flow parameters.

In this case, the independent parameters are taken as the volumetric flow rate, W, and the linear flow velocity v_r. From these two, the river cross-sectional area is calculated as

$$X_r = \frac{W}{v_r}, \tag{18}$$

the river volume as

$$V_r = X_r l_r, \tag{19}$$

and the river plan-view area as

$$A_r = w_r l_r. \tag{20}$$

Many pairs of depth and width could make up a given cross-section X_r, but for simplicity we make them both deterministic functions of X_r:

$$d_r = cX_r^p, \tag{21}$$

$$w_r = \frac{X_r}{d_r}. \tag{22}$$

The values $p = ¼$, and $c = ½$ m^{½} are found to give plausible ranges to d_r (0.375 m to 5 m) and w_r (0.843 m to 2 km) as W and v_r vary over their specified ranges.

A.4 The Dose Sub-model

Doses to individual humans are considered, from each of the following pathways:

drinking water;
freshwater fish consumption;
food from a representative crop type (grain);
food from a representative farmed animal (beef cattle);
milk from a representative farmed animal (dairy cattle);
inhalation of contaminated dust;
external γ-irradiation from contaminated soils.

The following formulæ for the doses arising from each pathway are again taken from the NRPB code *MiniBIOS*. The meanings of the symbols used, and the values or distributions they are to take in Level 1b, are shown in Table 2 (some of the symbols from Table 1 are also used).

The dose calculations begin from the (time -varying) activity concentrations (Bq m^{-3}) in the surface-soil and river-water boxes:

$$C_{ss} = \lambda_n N_A \frac{M_{1n}}{l_{ss} A_f}, \tag{23}$$

$$C_{rw} = \lambda_n N_A \frac{M_{3n}}{V_r}, \tag{24}$$

where Avogadro's Number, N_A, is for converting models to atoms (note that the λ_n would here have to be in s^{-1}, not a^{-1}, to give Bq). these concentrations are, of course, nuclide dependent, but we do not show this explicitly.

Drinking water

The river water is assumed to be filtered before drinking, removing activity on suspended sediment. This leaves the drinking water concentration as

$$C_{dw} = \frac{C_{rw}}{1 + \alpha k_s}, \tag{25}$$

where α is the suspended sediment load in the river water. given the individual water consumption per year and the dose per unit intake on ingestion, the drinking-water dose rate is

$$D_{dw} = D_{ing} I_w C_{dw}. \tag{26}$$

Freshwater Fish

Again the concentrations in filtered water are used, multiplied by a concentration factor for freshwater fish. The dose rate from fish consumption is then

$$D_{ff} = D_{ing} I_{ff} K_{ff} C_{dw}. \tag{27}$$

Human Grain Consumption

Contamination internal to the crop is taken up from the soil during growth, and is calculated using a concentration factor. In addition, external contamination can arise from soil stuck to the surfaces of the crop, and interception of spray irrigation water. The total dose from grain consumption then takes the form

$$D_g = D_{ing} I_g \left(\frac{K_g C_{ss}}{\rho} + \frac{f_g S_g C_{ss}}{\rho + \varepsilon \rho_w} + \frac{f_g \mu_g d_{irri} C_{rw}}{Y_g \left(W_g + H_g \right)} \right). \tag{28}$$

In the second term, for external contamination, the denominator is to convert volume of wet soil to weight of dry soil. In the last term, the factor μ_g allows for only a fraction of irrigation being intercepted by the grain crop, whilst the division by (W_g + H_g), the removal rates by weathering and harvesting, gives the equilibrium contamination level.

Animal Produce

Intake by animals through drinking river water and eating pasture is calculated very similarly to that by humans drinking the water and eating the crops (there is, however, no allowance for filtering the water or washing the surface contamination from the pasture). This intake must then be multiplied by factors for the retention of radionuclides in meat and milk. The result for the dose to humans from meat consumption is

$$D_{meat} = D_{ing} I_{meat} K_{meat} \left(I_{wc} C_{rw} + \frac{Z I_{pc} K_p C_{ss}}{\rho} + \frac{S_{cp} I_{pc} C_{ss}}{\rho + \varepsilon \rho_w} + \frac{Z I_{pc} \mu_p d_{irri} C_{rw}}{Y_p (W_p + H_{cp})} \right), \quad (30)$$

where

$$H_{cp} = N_{cattle} \frac{Z I_{pc}}{Y_p} \quad (30)$$

The factor Z converts the daily intake of dry pasture, I_{pc}, to the equivalent weight of fresh grass. A similar expression to eq. (29) holds for the dose from milk consumption.

Soil Inhalation

Surface soil is assumed to be resuspended and subsequently inhaled. The intake is expressed as the sum of two terms - one for a farmer ploughing fields (limited occupancy in a high dust level) and one representing a general member of the public (high occupancy in a relatively low dust level). This gives the dose from dust inhalation as

$$D_{dust} = D_{inh} I_{air} (O_r a_r + O_f a_f) \frac{C_{ss}}{\rho}. \quad (31)$$

External Exposure

The source of irradiation is considered to be γ-emitters in the surface soil. The dose rate is

$$D_{ext} = G C_{ss}, \quad (32)$$

where G is obtained from a sum over photon emissions of the dose rates delivered above a semi-infinite plane, with the nuclides distributed uniformly through the surface-soil thickness, allowing for the energy dependence of absorption by the soil.

A.5 Dose Sub-model Parameters

Table 2 lists the parameters for this sub-model, together with the values or distribution functions to be used for Level 1b.

To enable realistic summing over pathways and radionuclides, the intake and occupancy rates should be correlated so as not to correspond to unduly pessimistic total food consumption, or impossible lifestyles.

We can write the total annual individual energy input from food as

$$E = \sum_{food} \eta_{food} I_{food}, \quad (34)$$

and the fractions of this from each food type as

$$F_{food} = \frac{\eta_{food} I_{food}}{E}, \tag{34}$$

where the η_{food} are energy conversion factors, and the food types to be considered are fish, grain, meat and milk. The proposal is to sample E within a realistic range of energy requirements (2000 to 3500 kcal per day), and (effectively) to sample all but one of the F_{food}. This last step should ideally be based on information about dietary patterns, but the following should be realistic enough for the purposes of the present exercise.

The fractions F_{ff} and F_{milk} are each independently sampled between 0 and 10%. The fraction of the remainder allocated to grain is sampled between 0 and 100%, and F_{meat} is then determined. Thus,

$$I_{ff} = F_{ff} \frac{E}{\eta_{ff}}, \tag{35}$$

$$I_{milk} = F_{milk} \frac{E}{\eta_{milk}}, \tag{36}$$

$$I_g = P_{veg}\left(1 - F_{ff} - F_{milk}\right)\frac{E}{\eta_{ff}}, \tag{37}$$

$$I_{meat} = \left(1 - P_{veg}\right)\left(1 - F_{ff} - F_{milk}\right)\frac{E}{\eta_{ff}}, \tag{38}$$

where P_{veg} is sampled between 0 and 1.

Similarly, we take the total fluid ingestion rate, I_{fluid}, to be specified, and set I_w from this total and the consumption of milk:

$$I_w = I_{fluid} - I_{milk}. \tag{39}$$

The occupancy factors O_f and O_r are also constrained to add to one:

$$O_r = 1 - O_f \tag{40}$$

with O_f being sampled.

Reference

[A.1] *User Guide for MiniBIOS_1A*, J S Martin, S F Mobbs, R A Klos and I M Barraclough, NRPB-M283, NRPB, Chilton, United Kingdom, 1992.

Table 1

Parameters for the Source and Biosphere Transport Sub-models

Parameter distributions are indicated using the code U(a,b): uniform; LU(a,b): log-uniform; N(a,b): normal; LN(a,b): log-normal. In each case, the (a,b) are the lower and upper limits of the distribution. Normal and log-normal distributions are truncated at 3 standard deviations (of the logarithm in the case of log-normal), then re-normalised.

Symbol	Meaning	Value, Distribution or Equation	Units
A_f	Area of farmland adjacent to the river	U(2.0E5, 2.0E6)	m^2
A_r	Plan-view area of the river section	Eq. (20)	m^2
B	Soil bioturbation coefficient	LU(3.0E-5, 1.0E-2)	m^2/a
B_s	Sediment bioturbation coefficient	3.2E-5	m^2/a
c	Coefficient in Eq. (21)	0.5	$m^{\frac{1}{2}}$
D	Soil diffusion coefficient	LU(3.8E-4, 4.7E-2)	m^2/a
d_{eros}	Annual soil erosion	LU(6.4E-6, 7.6E-4)	m/a
d_{irri}	Annual depth of irrigation water	U(0.1, 0.15)	m/a
D_s	Sediment diffusion coefficient	3.2E-2	m^2/a
d_r	Depth of the river	Eq. (21)	m
d_{rain}	Annual infiltration of rainwater	N(0.14, 0.49)	m/a
f_{rs}	Sediment flow rate fraction	1.0E-4	–
g	Groundwater flow out of deep soil	Eq. (16)	m^3/a
K	Schaeffer sediment parameter	LU(1.0E-10, 1.0E-5)	m^{-1}

k_d	Soil-groundwater distribution coefficients	C-14: LN(2.0E-4, 3.0E-3) U-235: LN(1.0E-2, 4.0) Pa-231: LN(5.0E-2, 10.0) Ac-227: LN(1.0E-3, 50.0)	m^3/kg
k_s	Sediment-water distribution coefficients	C-14: LN(3.0E-2, 3.0) U-235: LN(5.0E-3, 0.5) Pa-231: LN(0.5, 50.0) Ac-227: LN(1.0, 100.0)	m^3/kg
l_b	Thickness of sediment boundary layer	0.1	m
l_{ds}	Deep soil thickness	0.33	m
l_r	Length of the river section	1000	m
l_s	Thickness of sediment	0.1	m
l_{ss}	Surface soil thickness	0.3	m
$M_{0n}(0)$	Initial Source inventory for nuclide n	C-14: 0.1 U-235: 300.0 Pa-231: 0.0 Ac-227: 0.0	mol
$M_{in}(t)$	Contents of nuclide n in box i	Eq. (1)	mol
p	Exponent in Eq. (21)	1	–
R	Soil retardation coefficient	Eq. (13)	–
R_b	Boundary-layer sediment-water partition coefficient	Eq. (7)	–
R_s	Sediment-water partition coefficient	Eq. (9)	–
v_g	Groundwater flow velocity	LU(3.0E-4, 1.5)	m/a
V_r	Volume of the river section	Eq. (19)	m^3
v_r	Velocity of river flow	LU(1.0E6, 3.16E6)	m/a
W	Volumetric flow-rate of the river	LU(1.0E6, 1.0E10)	m^3/a

w_r	Width of the river	Eq. (22)	m
X_r	Cross-sectional area of the river	Eq. (18)	m^2
α_b	Suspended sediment load in boundary layer	0.1	kg/m^3
ε	Soil porosity	0.4	–
ε_s	Sediment porosity	0.75	–
θ	Angle of groundwater flow	LU(1°, 90°)	–
κ_{ij}	Transfer coefficients from box i to box j	Eqs. (2) – (17)	a^{-1}
κ_{41}	Sediment-to-land transfer coefficient	5.0E-3	a^{-1}
κ_{0i}	Total release rates from source	C-14: 1.0E-3 U-235: 3.0E-5 Pa-231: 3.0E-5 Ac-227: 3.0E-5	a^{-1}
λ_n	Decay constant for nuclide n	C-14: 1.21E-4 U-235: 9.85E-10 Pa-231: 2.12E-5 Ac-227: 3.18E-2	a^{-1}
ρ	Soil dry density	1.5E3	kg/m^3
ρ_s	Sediment dry density	2.6E3	kg/m^3
ϕ	Deep-soil to surface-soil transfer fraction	Eq. (15)	–

Table 2

Parameters for the Dose Calculation Sub-model

Parameter distributions are indicated as in Table 1.

Symbol	Meaning	Value, Distribution or Equation	Units
a_f	High dust level (farm)	U(2.0E-6, 5.0E-5)	kg/m^3
a_r	Normal dust level	U(1.0E-7, 2.0E-6)	kg/m^3
C_{dw}	Activity concentrations in drinking water	Eq. (25)	Bq/m^3
C_{rw}	Activity concentrations in river-water box	Eq. (24)	Bq/m^3
C_{ss}	Activity concentrations in surface-soil box	Eq. (23)	Bq/m^3
D_{dust}	Dose from dust inhalation	Eq. (31)	Sv/a
D_{dw}	Dose from drinking water	Eq. (26)	Sv/a
D_{ext}	Dose from external exposure	Eq. (32)	Sv/a
D_{ff}	Dose from freshwater fish	Eq. (27)	Sv/a
D_g	Dose from grain consumption	Eq. (28)	Sv/a
D_{ing}	Dose per unit activity ingested	C-14: 5.6E-10 U-235: 6.6E-8 Pa-231: 2.9E-6 Ac-227: 4.0E-6	Sv/Bq
D_{inh}	Dose per unit activity inhaled	C-14: 5.6E-10 U-235: 1.7E-6 Pa-231: 3.5E-4 Ac-227: 1.8E-3	Sv/Bq
D_{meat}	Dose from meat consumption	Eq. (29)	Sv/a
D_{milk}	Dose from milk consumption	as Eq. (29)	Sv/a
E	Annual individual food energy requirement	U(3.1E6, 5.4E6)	kJ/a
F_{ff}	Fraction of food energy from fish	U(0, 0.1)	–

F_g	Fraction of food energy from grain	Eqs. (34), (37)	–
f_g	Fraction of external grain contamination remaining after food processing	0.15	–
F_{meat}	Fraction of food energy from meat	Eqs. (34), (38)	–
F_{milk}	Fraction of food energy from milk	U(0, 0.1)	–
G	Dose efficiency for irradiation by soil	C-14: 0.0 U-235: 2.8E-11 Pa-231: 1.3E-11 Ac-227: 1.5E-10	Sv a^{-1}/ Bq m^{-3}
H_{cp}	Removal rate of contamination from pasture by cropping	Eq. (30)	a^{-1}
H_g	Removal rate of contamination from grain by harvesting	1.0	a^{-1}
I_{air}	Breathing rate	8.4E3	m^3/a
I_{ff}	Annual consumption of fish	Eq. (35)	kg/a
I_g	Annual consumption of grain	Eq. (37)	kg/a
I_{fluid}	Annual intake of fluid	1.35	m^3/a
I_{meat}	Annual consumption of meat (beef)	Eq. (38)	kg/a
I_{milk}	Annual consumption of milk	Eq. (36)	m^3/a
I_{pc}	Annual consumption of dry fodder by cow	4.4E3	kg/a
I_w	Annual consumption of drinking water	Eq. (39)	m^3/a
I_{wc}	Annual consumption of water by cow	20.0	m^3/a
K_{ff}	Concentration factor for freshwater fish	C-14: 5.0 U-235: 1.0E-2 Pa-231: 1.0E-2 Ac-227: 3.0E-2	m^3/kg

K_g	Concentration factor for grain	C-14: 3.0E1 U-235: 2.0E-3 Pa-231: 4.0E-2 Ac-227: 1.0E-3	–
K_{meat}	Fraction of nuclides retained in meat per rate of ingestion by cow	C-14: 2.7E-4 U-235: 8.2E-5 Pa-231: 2.7E-6 Ac-227: 5.5E-8	a/kg
K_{milk}	Fraction of nuclides retained in milk per rate of ingestion by cow	C-14: 1.4E-1 U-235: 1.1E-3 Pa-231: 1.4E-5 Ac-227: 1.1E-6	a/m^3
K_p	Concentration factor for pasture (from dry-weight soil to wet-weight plant)	C-14: 5.0 U-235: 2.0E-3 Pa-231: 4.0E-2 Ac-227: 1.0E-3	–
N_A	Avogadro's number	6.022E23	mol^{-1}
N_{cattle}	Stocking density of cattle	2.0E-4	m^{-2}
O_f	Occupancy in high dust level (farm)	U(0, 0.03)	–
O_r	Occupancy in normal dust level	Eq. (40)	–
P_{veg}	Proportion of grain+meat consumption taken as grain	U(0, 1)	–
S_{cp}	Soil contamination of pasture (wet soil weight per weight of dry fodder)	4.0E-2	–
S_g	Soil contamination on grain (wet soil weight per weight of crop)	9.0E-5	–
W_g	Removal rate of irrigation water from grain by weathering	8.4	a^{-1}
W_p	Removal rate of irrigation water from pasture by weathering	18.0	a^{-1}
Y_g	Yield of grain	0.4	kg/m^2

Y_g	Yield of (wet) pasture	0.1	kg/m^2
Z	Weight of fresh grass equivalent to unit weight of dry fodder	5.0	–
α	Suspended sediment load in river water	0.01	kg/m^3
η_{ff}	Energy conversion factor for fish	7.8E3	kJ/kg
η_g	Energy conversion factor for grain	1.4E4	kJ/kg
η_{meat}	Energy conversion factor for meat	1.2E4	kJ/kg
η_{milk}	Energy conversion factor for milk	2.8E6	kJ/m^3
μ_g	Interception factor for irrigation water on grain	0.05	–
μ_p	Interception factor for irrigation water on pasture	0.25	–
ρ_w	Density of water	1000	kg/m^3

ANNEX B

THE PSACOIN LEVEL 1B QUESTIONNAIRE.

B1 Results for analysis by The Level 1b Task Group.

The data requested for analysis represents the minimum information that each participant should provide for the Level 1b study. Participants are however at liberty to provide as much more information (in the form of tables, plots and comment) as possible.

Four sets of information are requested: two from the deterministic central case and two from the probabilistic analysis. The required information is described below, along with suggested structures for the results files. NB participants are requested, wherever possible, to provide these data in machine-readable form.

B2 Results from the Central Case Study.

B2.1 Biosphere compartment inventories.

As an aid to code verification a deterministic case should be run using the central values of the sampled parameters given in Tables A1 and A2.

The inventory of each radionuclide (in Bq) in each of the four biosphere compartments should be given at 10^0, 10^3 and 10^5 y. The suggested structure for this information is given in Table B1.

These results will demonstrate the correct working of the code used to solve the biosphere transport equation in equation (1) of the case specification.

B2.2 Doses from individual exposure pathways.

The results for individual dose from each radionuclide in each of the 7 exposure pathways should also be given at 10^0, 10^3 and 10^5 y, see Table B2. This will verify that the coding of the exposure submodel is correct.

B3 Results for the probabilistic case.

B3.1 Total individual dose.

In the probabilistic case the total individual dose for ^{14}C, summed over pathways, and the total individual dose from the ^{235}U chain, summed over nuclides and pathways, should be calculated at 1 10^n and 3 10^n years, for n = 0,6. The standard deviation of these numbers and the 95% confidence intervals should also be provided.

The suggested structure is shown in Table B3.

B3.2 **Ranking of the contributions to total dose by exposure pathway.**

At each of the decades (10^n years, n = 0,6) the rankings of the individual pathways contributing to the total dose, and the values of the doses, for ^{14}C and the ^{235}U chain should be given using the format shown in Table B4.

B4 Aids to verification.

B4.1 Derivation of the biosphere transport sub-model transfer coefficients for the central case.

In the biosphere transport submodel, as specified here, the transport factors connecting the environmental compartments are derived from other, more simple, process-related data, such as volumetric flows, diffusion coefficients etc. Such an approach must be used when real assessments of biosphere transport are undertaken. The consequence for PSACOIN Level 1b is that it is necessary for participants to code the derivation of the transfer coefficients from the data provided in the specification (rather than sampling from the distributions of transport coefficients themselves).

Most of the transfer coefficients depend on one or more of the sampled parameters defined in Table A1. Therefore, to allow participants to verify the correct derivation of the transfer coefficients (from equations (2) to (17)), their **central values** are given in the Table B5. The values of the sampled parameters used to generate this table are taken to be the central values of the ranges given in Table A1.

A Lotus 1-2-3 compatible spreadsheet is available from the Task Group to illustrate the derivation of these transfer coefficients.

Participants should note that these values of the transfer are the ones that should be used to derive the deterministic results requested in Section B1.

B4.2 Biosphere-Box-Content-to-Dose Conversion Factors.

B4.2.1 Values for the central case.

In principle the distribution of activity in the biosphere arising from the transport calculations can be converted to individual doses by applying linear conversion factors to the river water and surface soil compartment activity inventories, so that in general the total dose, summed over pathways p and nuclides n can be written as

$$D_{tot} = \sum_{n,p} (\chi^p_{h,ss} A_{ss} + \chi^p_{h,rw} A_{rw}) \qquad (1)$$

where A_{Ss} and A_{rw} are respectively the inventories of the surface soil and river water compartments in Bq.

As with the biosphere transport submodel transfer coefficients, the dose conversion factors, χ (Sv y^{-1} Bq^{-1}), depend in a complex way on a variety of different factors, such as dose per unit intake and exposure rates, as well as on parameters determining the uptake by and accumulation in plants and animals. A detailed derivation of doses from each of the seven exposure pathways is given in in equations (23) to (40) of the main text.

To aid to the verification of the coding of the exposure-pathway submodel the values of the conversion factors for **central values** of the sampled parameters in Table 2 (and Table 1 where appropriate) are listed below in Table B6.

A Lotus 1-2-3 compatible spreadsheet is also available from the Task Group to illustrate the derivation of these conversion factors.

B4.2.2 Values for the probabilistic case.

It is recognised that coding the detail of the exposure pathway submodel, specifically for PSAC Level 1b, may pose problems for participants who have to create a new exposure pathway code from scratch. To enable such groups to participate in the exercise without the a large coding overhead, the above conversion factors can be split into linear combinations so that ξ_p and ζ_p in the following expressions contain all the fixed parameters for the wholly deterministic and partly probabilistic fractions respectively. Thus the expression for the the drinking water pathway can be written as

$$D_{dw} = (\xi_{rw} + EF_{milk}\zeta_{rw})\frac{A_{rw}}{1 + \alpha K_s} \tag{2}$$

and similarly the remaining six exposure pathways are given by

$$D_{ff} = EF_{ff}\zeta_{rw}\frac{A_{rw}}{1 + \alpha K_s} \tag{3}$$

$$D_g = P_{veg}E(1 - F_{ff} - F_{milk})(\xi_{ss}A_{ss} + \zeta_{rw}d_{irri}A_{rw}) \tag{4}$$

$$D_{meat} = (1 - P_{veg})E(1 - F_{ff} - F_{milk})[\xi_{ss}A_{ss} + (\xi_{rw} + \zeta_{rw}d_{irri}A_{rw})] \tag{5}$$

$$D_{milk} = EF_{milk}[\xi_{ss}A_{ss} + (\xi_{rw} + \zeta_{rw}d_{irri}A_{rw})] \tag{6}$$

$$D_{dust} = \zeta_{ss}[O_f a_f + (1 - O_f)a_r]A_{ss} \tag{7}$$

$$D_{ext} = \xi_{ss}\ A_{ss} \tag{8}$$

The values for ξ_p and ζ_p for each of the nuclides and the following pathways are given in Table B7.

Title: PSACOIN Level 1b radionuclide inventories - deterministic case
sub-title: ^{14}C *inventories*
1.0E+00 water sediment topsoil deepsoil
1.0E+03 ... ...
1.0E+05 ... ...
sub-title: ^{235}U *inventories*
1.0E+00 water sediment topsoil deepsoil
1.0E+03 ... ...
1.0E+05 ... ...
sub-title: ^{231}Pa *inventories*
1.0E+00 water sediment topsoil deepsoil
1.0E+03 ... ...
1.0E+05 ... ...
sub-title: ^{227}Ac *inventories*
1.0E+00 water sediment topsoil deepsoil
1.0E+03 ... ...
1.0E+05 ... ...

Table B1 - Format for the deterministic case box-inventory results.

Title: PSACOIN Level 1b individual doses by pathway - deterministic case							
sub-title: ^{14}C *doses*							
1.0E+00	D_{dw}	D_{ff}	D_{grain}	D_{meat}	D_{milk}	D_{dust}	D_{ext}
1.0E+03	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
1.0E+05	...	...	...	...	...	...	...
sub-title: ^{235}U *doses*							
1.0E+00	D_{dw}	D_{ff}	D_{grain}	D_{meat}	D_{milk}	D_{dust}	D_{ext}
1.0E+03	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
1.0E+05	...	...	...	...	...	...	...
sub-title: ^{231}Pa *doses*							
1.0E+00	D_{dw}	D_{ff}	D_{grain}	D_{meat}	D_{milk}	D_{dust}	D_{ext}
1.0E+03	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
1.0E+05	...	...	...	...	...	...	...
sub-title: ^{227}Ac *doses*							
1.0E+00	D_{dw}	D_{ff}	D_{grain}	D_{meat}	D_{milk}	D_{dust}	D_{ext}
1.0E+03	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
1.0E+05	...	...	...	...	...	...	...

Table B2 - Format for the deterministic case dose pathway results.

1.0E+00	*D(^{14}C)*	*σ(^{14}C)*	*P_{95}(^{14}C)*	*D(chain)*	*σ(chain)*	*P_{95}(chain)*
3.0E+00	...	...	...	...	...	...
1.0E+01	...	...	...	...	...	...
3.0E+01	...	...	...	...	...	...
1.0E+02	...	...	...	...	...	...
...	...	...	...	...	...	...
...	...	...	...	...	...	...
...	...	...	...	...	...	...
1.0E+06	...	...	...	...	...	...

Table B3 - Format for the probabilistic results for total individual dose.

1.0E+00	*1*	*pathway 1:*	*^{14}C $D_{pathway}$*	*pathway 1: chain*	*$D_{pathway}$*
1.0E+00	*2*	*pathway 2:*	*^{14}C $D_{pathway}$*	*pathway 2: chain*	*$D_{pathway}$*
...	.	...	...	...	...
1.0E+00	*7*	*pathway 7:*	*^{14}C $D_{pathway}$*	*pathway 7: chain*	*$D_{pathway}$*
1.0E+01	*1*	*pathway 1:*	*^{14}C $D_{pathway}$*	*pathway 1: chain*	*$D_{pathway}$*
1.0E+01	*2*	*pathway 2:*	*^{14}C $D_{pathway}$*	*pathway 2: chain*	*$D_{pathway}$*
...	.	...	...	...	...
1.0E+01	*7*	*pathway 7:*	*^{14}C $D_{pathway}$*	*pathway 7: chain*	*$D_{pathway}$*
...	.	...	...	...	...
...	.	...	...	...	...
...	.	...	...	...	...
...	.	...	...	...	...
1.0E+06	*1*	*pathway 1:*	*^{14}C $D_{pathway}$*	*pathway 1: chain*	*$D_{pathway}$*
1.0E+06	*2*	*pathway 2:*	*^{14}C $D_{pathway}$*	*pathway 2: chain*	*$D_{pathway}$*
...	.	...	...	...	...
1.0E+06	*7*	*pathway 7:*	*^{14}C $D_{pathway}$*	*pathway 7: chain*	*$D_{pathway}$*

Table B4 - Format for the probabilistic results for the ranking of exposure pathways

transfer coefficient, y^{-1}		^{14}C	^{235}U	^{231}Pa	^{227}Ac
source to deep soil	κ_{02}	$9.64\ 10^{-4}$	$2.89\ 10^{-5}$	$2.89\ 10^{-5}$	$2.89\ 10^{-5}$
source to river water	κ_{03}	$3.60\ 10^{-5}$	$1.08\ 10^{-6}$	$1.08\ 10^{-6}$	$1.08\ 10^{-6}$
surface soil to deep soil	κ_{12}	$9.55\ 10^{-1}$	$1.10\ 10^{-2}$	$7.49\ 10^{-3}$	$1.05\ 10^{-2}$
surface soil to river water	κ_{13}	$2.32\ 10^{-4}$	$2.32\ 10^{-4}$	$2.32\ 10^{-4}$	$2.32\ 10^{-4}$
deep soil to surface soil	κ_{21}	$2.18\ 10^{-2}$	$5.62\ 10^{-3}$	$5.56\ 10^{-3}$	$5.61\ 10^{-3}$
deep soil to river water	κ_{23}	$1.22\ 10^{-5}$	$6.33\ 10^{-8}$	$1.79\ 10^{-8}$	$5.65\ 10^{-8}$
river water to surface soil	κ_{31}	2.45	2.45	2.45	2.45
river water to sediment	κ_{34}	$2.83\ 10^{-1}$	$2.89\ 10^{-1}$	$2.12\ 10^{-1}$	$1.73\ 10^{-1}$
river downstream (loss)	κ_{35}	$1.78\ 10^{3}$	$1.78\ 10^{3}$	$1.78\ 10^{3}$	$1.78\ 10^{3}$
sediment to surface soil	κ_{41}	$5.00\ 10^{-3}$	$5.00\ 10^{-3}$	$5.00\ 10^{-3}$	$5.00\ 10^{-3}$
sediment to river water	κ_{43}	$1.55\ 10^{-2}$	$7.53\ 10^{-2}$	$3.94\ 10^{-3}$	$3.57\ 10^{-3}$
sediment downstream (loss)	κ_{45}	$1.78\ 10^{-1}$	$1.78\ 10^{-1}$	$1.78\ 10^{-1}$	$1.78\ 10^{-1}$

Table B5 - Values of the transfer coefficients for the central case parameter values.

exposure pathway	conversion factor Sv Bq^{-1} y^{-1}	^{14}C	^{235}U	^{231}Pa	^{227}Ac
drinking water	$\chi_{n,rw}$	$1.3\ 10^{-14}$	$1.5\ 10^{-12}$	$6.3\ 10^{-11}$	$8.3\ 10^{-11}$
freshwater fish	$\chi_{n,rw}$	$1.4\ 10^{-12}$	$3.2\ 10^{-13}$	$1.3\ 10^{-11}$	$5.3\ 10^{-11}$
grain	$\chi_{n,rw}$	$4.6\ 10^{-15}$	$3.7\ 10^{-17}$	$3.2\ 10^{-14}$	$1.1\ 10^{-15}$
	$\chi_{n,ss}$	$3.5\ 10^{-16}$	$4.1\ 10^{-14}$	$1.8\ 10^{-12}$	$2.5\ 10^{-12}$
meat	$\chi_{n,rw}$	$5.4\ 10^{-15}$	$3.2\ 10^{-16}$	$2.6\ 10^{-15}$	$1.1\ 10^{-17}$
	$\chi_{n,ss}$	$5.8\ 10^{-14}$	$2.0\ 10^{-12}$	$3.0\ 10^{-12}$	$8.2\ 10^{-14}$
milk	$\chi_{n,rw}$	$1.3\ 10^{-15}$	$2.0\ 10^{-18}$	$6.2\ 10^{-18}$	$1.1\ 10^{-19}$
	$\chi_{n,ss}$	$1.4\ 10^{-14}$	$1.3\ 10^{-14}$	$7.1\ 10^{-15}$	$7.8\ 10^{-16}$
dust inhalation	$\chi_{n,ss}$	$1.4\ 10^{-20}$	$4.1\ 10^{-17}$	$8.5\ 10^{-15}$	$4.4\ 10^{-14}$
external γ	$\chi_{n,ss}$	0	$8.5\ 10^{-17}$	$3.9\ 10^{-17}$	$4.5\ 10^{-16}$

Table B6 - Values of the biosphere-box-content-dose conversion factors for the central case.

exposure pathway	conversion factor	^{14}C	^{235}U	^{231}Pa	^{227}Ac
drinking water	ξ_{rw} Sv $y^{-1}Bq^{-1}$	$4.2\ 10^{-5}$	$5.0\ 10^{-3}$	$2.2\ 10^{-1}$	$3.0\ 10^{-1}$
	ζ_{rw} Sv $kJ^{-1}Bq^{-1}$	$2.0\ 10^{-8}$	$1.3\ 10^{-9}$	$5.8\ 10^{-8}$	$8.0\ 10^{-8}$
freshwater fish	ξ_{rw} Sv kJ^{-1} Bq^{-1}	$2.0\ 10^{-8}$	$4.7\ 10^{-9}$	$2.1\ 10^{-7}$	$8.6\ 10^{-7}$
grain	$\xi_{ss}x$ Sv $kg^{-1}Bq^{-1}$	$2.6\ 10^{-10}$	$2.1\ 10^{-12}$	$1.8\ 10^{-9}$	$6.4\ 10^{-11}$
	ζ_{rw} Sv y $kg^{-1}m^{-2}Bq^{-1}$	$4.5\ 10^{-12}$	$5.2\ 10^{-10}$	$2.3\ 10^{-8}$	$3.2\ 10^{-8}$
meat	ξ_{ss} Sv $kJ^{-1}Bq^{-1}$	$3.1\ 10^{-10}$	$1.8\ 10^{-11}$	$1.5\ 10^{-10}$	$6.5\ 10^{-13}$
	ξ_{rw} Sv $kJ^{-1}Bq^{-1}$	$1.4\ 10^{-11}$	$5.0\ 10^{-11}$	$7.3\ 10^{-10}$	$2.1\ 10^{-11}$
	ζ_{rw} Sv y $kJ^{-1}m^{-2}Bq^{-1}$	$6.3\ 10^{-10}$	$2.2\ 10^{-8}$	$3.2\ 10^{-8}$	$9.1\ 10^{-10}$
milk	ξ_{ss} Sv $kJ^{-1}Bq^{-1}$	$6.8\ 10^{-13}$	$1.0\ 10^{-15}$	$3.3\ 10^{-15}$	$5.6\ 10^{-17}$
	ξ_{rw} Sv $kJ^{-1}Bq^{-1}$	$3.1\ 10^{-14}$	$2.9\ 10^{-14}$	$1.6\ 10^{-14}$	$1.8\ 10^{-15}$
	ζ_{rw} Sv y $kJ^{-1}m^{-2}Bq^{-1}$	$1.4\ 10^{-12}$	$1.3\ 10^{-12}$	$7.2\ 10^{-13}$	$7.8\ 10^{-14}$
dust inhalation	ξ_{ss} Sv $y^{-1}m^{-1}kg^{-1}Bq^{-1}$	$1.0\ 10^{-3}$	3.1	$6.5\ 10^{2}$	$3.3\ 10^{3}$
external γ	ζ_{ss} Sv $y^{-1}m^{-2}Bq^{-1}$	0	$9.2\ 10^{-6}$	$4.3\ 10^{-6}$	$4.9\ 10^{-5}$

Table B7 - Values of the biosphere-box-content-to-dose conversion factors for the probabilistic case.

ANNEX C

Descriptions of Participating Codes.

Participant A:	**Paul Scherrer Institute,**
Code:	*MiniBIOS/ACTIVI/SYVAC.*
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Three individual computer codes were employed by PSI in the implementation of this exercise. A code for the system of transfer coefficients defined in the input specification (ie the *MiniBIOS* model transport model) was interfaced with the *ACTIVI* code. *ACTIVI* is the transport equation solving part of the *BIOPATH* suite of environmental analysis programs and the *IMPEX* routines within *ACTIVI* were employed. In order to run the stochastic phase of the intercomparison both of these stand-alone codes were incorporated into *SYVAC 3.05* as subroutines. The calculations were performed on a MicroVAX 3800.

For the main analysis *SYVACs'* internal Monte Carlo sampling routines where used, involving 1000 samples. Additional analysis was performed using the Sandia National Laboratories Latin Hypercube sampling program. For this phase 200 samples were used.

As part of the ongoing development of probabilistic safety assessment a set of post-processing statistical analysis routines, *POSTPROC-II*, has been developed.

Participant B:	**AEA Technology,**
Code:	*MASCOT-3B.*
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This exercise was run entirely using existing standard submodels in *MASCOT*. The source term was provided using *MASCOTs* Simple Leaching submodel, which delivers a constant, nuclide-dependent fraction per unit time of the decayed inventory, remaining in the repository. The source term output was divided into two parts, to provide fluxes into the river water and deep soil compartments in the required ratio, using the Distributor submodel. Finally, the Compartment Biosphere submodel was used to calculate, not only time-dependent inventories of the radionuclides in

the four boxes, but also the doses arising via the different pathways. All of these submodels can be solved analytically after Laplace transformation of the time variable. *MASCOT* calculates the Laplace-transformed outputs by multiplying the submodel responses (equivalent to convoluting the source term with the unit impulse response of the transport submodel). The time-domain outputs are obtained by a numerical inversion algorithm due to Talbot.

Most of the complexity of the Level 1b specification is in the formulæ for calculating the transfer coefficients and the pathway doses per unit box inventories. These formulæ, including PDFs for the sampled parameters and constants for the others, were coded into the *MASCOT* input file and interpreted at run time. The processes of sampling from the PDFs, and applying the algebraic formulæ to produce values for all the submodel coefficients for each realisation, are carried out using the built-in facilities of *MASCOT.*

Participant C: **CIEMAT,**
Code: *PRYMA METHODOLOGY version 1b.2.*
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The starting point of this methodology is the IMA code. It was developed for the scenario A4 of BIOMOVS exercise and verified in it. The version 1b.2 is a new one specially developed for the Level 1B exercise of the NEA/OECD.

Its structure consists of several modules that include the codes used for the calculations. The method provides best estimate and probabilistic results. The methodology propagates the uncertainties of the parameters through the different modules and submodules and allows the carrying out of sensitivity analysis in the different models. It is implemented on a VAX 3300 and run under the VMS operating system.

There are five important modules with the subsequent codes in them:

Executive Module: *GESTOR.*
This module manages all files and codes included in the methodology and it is the interface between users and the information system. It is written in DCL command Language and it was developed in IMA/CIEMAT.

Preprocessor Module:
The generation of the Sample Spaces is done with the *PRISM* (from Studsvik, Sweden) or LHS (from Sandia Laboratories, USA) codes. These do a simple Monte Carlo or Latin Hypercube Sampling with the theoretical distributions of the input parameters.

Environmental Transfer Module:
This module is divided in two submodules:
(1) The first one calculates the transfer coefficients of the environmental

model. It is done with the code of the same name, from IMA/CIEMAT.

(2) The second one is the environmental model. It calculates the environmental concentrations of radionuclides. It uses the *BIOPATH* code (from Studsvik, Sweden). A semianalytical numerical method (*LINDIF*) was selected for solving the transport equations.

Dose Pathway Module:
This module calculates the dose for each pathway with the *DOSE PATHWAY LEVEL1B* code written at IMA/CIEMAT.

Postprocessor Module.
This module allows the carrying out of sensitivity and uncertainty analysis of each of the outputs from the different modules and submodules. It can also process the output data set to present the results in the right way. For the sensitivity analysis the codes *PCC-SRC* (from Sandia Laboratories, USA) and *SPOP* (from Environmental Institute of ISPRA research Center, CEC) are used. The uncertainty analysis is done with the codes *SPOP* (Ispra), *STATGRAPHICS* and some programs developed by IMA/CIEMAT. The VMS version of *LOTUS 1-2-3* has also been used in the calculations.

Participant D:	**Studsvik Nuklear,**
Code:	*BIOPATH/PRISM.*
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The exercise was run on existing codes, developed at Studsvik. Subprograms within the *BIOPATH* code package were used for solving the differential equations. Two solution methods were applied; *LINDIF* - a semi-analytical method; and *IMPEX* which is an implicit numerical solution method.

BIOPATH is a set of codes for use in general environmental modelling situations. The probabilistic calculations were carried out using the *PRISM*-system in connection with the *ACTIVI* (containing the *IMPEX* and *LINDIF* subroutines) part of *BIOPATH. PRISM* has been developed to be a general tool for statistical error propagation, using latin-hypercube sampling for generation of parameter values and it also includes correlation and regression analyses to identify relations between parameters and responses. The calculations were performed on an IBM-PC.

The source term in the scenario description was handled as one compartment, implying that the annual source of radioactivity entering the model was treated in the same way as the transfers between the compartments.

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Code: *CIRCLE, version 2.1.*
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CIRCLE has been developed to simulate the environmental transfer of radionuclides. *CIRCLE* is a mathematical tool to solve a set of rate equations which describe the system model considered. The user can select one of the three numerical methods for solving the rate equations: the exponential approximation, the Runge-Kutta formula by Fehlberg, or Gear method for stiff problems. *CIRCLE* is a flexible program to allow the user to input the values of transfer rate coefficients directly or by algebraic formulæ. It allows the user to implement the stochastic calculations with use of the *PREP* utility in the *LISA* package.

Participant F: **AECL Whiteshell,**
Code: *SYVAC 3.08.*
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AECL Whiteshell Code for the PSACOIN Level 1B Exercise.

Method of Solution: SYVAC3 has long had built-in routines to solve for the amount of nuclide in a single compartment, given an arbitrary input and arbitrary output capacity, and linear loss rates. The routines have been extensively and successfully used in various AECL models. The PSACOIN Level 1B exercise was first attempted by using these routines iteratively to solve for the multiple interconnected compartments. Results were unsatisfactory.

Goertzel and Tralli give an efficient solution to the equations for a linear multi-compartment system in the form of a matrix equation involving convolution of matrix exponentials (Goertzel, Gerald, and Nunzio Tralli. 1960. Some Mathematical

Methods of Physics. McGraw-Hill Book Company Inc.. Toronto, Canada). They show that the matrix exponentials can be readily found if the eigenvalues and eigenvectors of the matrix expressing the interactions between the compartments are known. The chief difficulty in implementing this solution is calculating the exponential of an arbitrary matrix. In SYVAC3, that matrix would be generated with randomly-generated data. While not impossible, developing robust code to solve for eigenvalues and eigenvectors that could cover all cases would be a challenge.

Instead, Terry Andres expressed the matrix exponentials in terms of a scaled Taylor series expansion, truncated to achieve a specified level of accuracy given the maximum magnitude of interaction between the compartments. (See, e.g. Cleve Moler and Charles van Loan, Society for Industrial and Applied Mathematics Review, Vol. 20, No.4, October 1978, pp. 801-836).

The solution has been coded as a new routine, *MULTIC* (*MULTI*ple *C*ompartment), that will be installed in *SYVAC3*, and a Level 1B model code has been developed that is compatible with the *SYVAC3* executive. The complete executable code is called *SYVAC309-L1B201* (*SY*stems *V*ariability *A*ssessment *C*ode, Generation 3, Version *09* - PSAC *L*evel *1B* Exercise, Generation *2*, Version *01*). We had 254 sampled and calculated parameters, and 1557 consequence parameters (more than required to supply the minimum results, but the effect on run time should be negligible).

The simulations were performed on Vax 6510 and 6440 computers. We limited SYVAC to a maximum of 150 time points per time series, included 13 fixed times at which results had to be generated, and used a target fractional error of 0.5% for all time series. A set of 250 simulations took about 38.5 CPU hours (52 hours real time) on the 6510, and about 69.5 CPU hours (97 hours real time) on the 6440. Four sets of 250 simulations were carried out.

Participant G:	**National Radiological Protection Board,**
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The *ESP* code (*Executive Sampling Procedure*) uses Latin hypercube sampling to select paramenter values from the ranges specified and can be run with a variety of submodels. The version of *ESP* set up for this intercomparison contained the *MiniBIOS* submodel. *MiniBIOS* is a simplified version of the biosphere code *BIOS* developed by the NRPB. It is a box model of the biosphere and includes transport of radionuclides in the deep soil, surface soil, marine and freshwater bodies and transfer from sea to land via seaspray. The *MiniBIOS* model has three components: the first takes the input data and calculates the transfer coefficients between the boxes (*MiniPREP*), the second calculates the time dependence of the inventories in the boxes (*MiniBIOS*), and the third calculated the doses arising from these inventories (*MiniBIOS*). *MiniPREP* and *MiniREAD* are in FORTRAN, *MiniBIOS* itself uses the Harwell code *FACSIMILE* to solve the differential equations and hence is

written in "*FACSIMILE*". *FACSIMILE* uses Gears' method to solve the differential equations and chooses its own timesteps depending upon the input parameters. A special version of *MiniREAD* was created for this intercomparison to provide the required output.

ANNEX D

RESPONSES TO THE PSACOIN LEVEL 1B QUESTIONNAIRE.

The following sets of tables provide the complete set of participants' responses to the PSACOIN Level 1b Questionnaire. The format of the tables is given in Annex B.

D.1 Responses to Questionnaire Table B1

		^{14}C compartment inventories, [Bq]				^{235}U compartment inventories, [Bq]			
participant	time, [y]	water	sediment	topsoil	deepsoil	water	sediment	topsoil	deepsoil
A	1	4.70E+03	1.20E+03	1.80E+06	2.20E+08	3.40E+00	8.70E-01	4.60E+02	1.60E+05
PSI	1000	2.70E+03	3.80E+03	2.80E+09	1.20E+11	9.70E+00	1.10E+01	4.90E+07	1.10E+08
Switzerland	100000	2.30E-03	3.30E-03	5.50E+03	2.40E+05	7.60E+00	8.50E+00	5.70E+07	1.10E+08
B	1	4.66E+03	1.20E+03	1.81E+06	2.21E+08	3.41E+00	8.68E-01	4.64E+02	1.63E+05
AEA Technology	1000	2.70E+03	3.86E+03	2.76E+09	1.21E+11	9.67E+00	1.08E+01	4.88E+07	1.06E+08
UK	100000	2.19E-03	3.13E-03	5.11E+03	2.24E+05	7.55E+00	8.45E+00	5.66E+07	1.13E+08
C	1	4.70E+03	1.20E+03	1.80E+06	2.20E+08	3.40E+00	9.00E-01	4.60E+02	1.60E+05
IMA	1000	2.70E+03	3.90E+03	2.80E+09	1.20E+11	9.70E+00	1.10E+01	4.90E+07	1.10E+08
Spain	100000	*	*	5.10E+03	2.20E+05	7.60E+00	8.50E+00	5.70E+07	1.10E+08
D1	1	4.70E+03	1.20E+03	1.80E+06	2.20E+08	3.40E+00	8.70E-01	4.60E+02	1.60E+05
Studsvik	1000	2.70E+03	3.90E+03	2.80E+09	1.20E+11	9.70E+00	1.10E+01	4.90E+07	1.10E+08
Sweden	100000	2.20E-03	3.10E-03	5.10E+03	2.20E+05	7.60E+00	8.50E+00	5.70E+07	1.10E+08
D2	1	4.70E+03	1.20E+03	1.80E+06	2.20E+08	3.40E+00	8.70E-01	4.60E+02	1.60E+05
Studsvik	1000	2.70E+03	3.90E+03	2.80E+09	1.20E+11	9.70E+00	1.10E+01	4.90E+07	1.10E+08
Sweden	100000	2.20E-03	3.10E-03	5.10E+03	2.20E+05	7.60E+00	8.50E+00	5.70E+07	1.10E+08
E	1	4.66E+03	1.20E+03	1.76E+06	2.20E+08	3.42E+00	8.71E-01	4.64E+02	1.63E+05
JAERI	1000	2.70E+03	3.87E+03	2.75E+09	1.21E+11	9.69E+00	1.08E+01	4.87E+07	1.06E+08
Japan	100000	2.47E-03	3.53E-03	5.74E+03	2.51E+05	7.56E+00	8.45E+00	5.65E+07	1.13E+08
F	1	4.70E+03	1.20E+03	1.80E+06	2.20E+08	3.40E+00	8.70E-01	4.70E+02	1.60E+05
AECL	1000	2.70E+03	3.90E+03	2.80E+09	1.20E+11	9.70E+00	1.10E+01	4.90E+07	1.10E+08
Canada	100000	2.20E-03	3.10E-03	5.10E+03	2.20E+05	7.60E+00	8.50E+00	5.70E+07	1.10E+08
G	1	4.70E+03	1.20E+03	1.80E+06	2.20E+08	3.40E+00	8.70E-01	4.60E+02	1.60E+05
NRPB	1000	2.70E+03	3.80E+03	2.70E+09	1.20E+11	9.70E+00	1.10E+01	4.90E+07	1.10E+08
UK	100000	2.20E-03	3.10E-03	5.00E+03	2.20E+05	7.60E+00	8.50E+00	5.70E+07	1.10E+08

		^{231}Pa compartment inventories, [Bq]				^{227}Ac compartment inventories, [Bq]			
participant	time, [y]	water	sediment	topsoil	deepsoil	water	sediment	topsoil	deepsoil
A	1	7.20E-05	1.70E-05	1.40E-02	3.80E+00	1.40E-06	3.70E-07	4.00E-04	9.40E-0
PSI	1000	2.30E-01	2.60E-01	1.20E+06	2.00E+06	2.20E-01	2.10E-01	1.10E+06	2.00E+0
Switzerland	100000	6.70E+00	7.60E+00	5.00E+07	7.00E+07	6.40E+00	6.20E+00	4.80E+07	7.30E+0
B	1	7.24E-05	1.62E-05	9.78E-03	3.45E+00	1.14E-06	2.30E-07	1.54E-04	5.42E-02
AEA Technology	1000	2.32E-01	2.62E-01	1.24E+06	1.80E+06	2.16E-01	2.08E-01	1.14E+06	2.00E+06
UK	100000	6.57E+00	7.46E+00	4.93E+07	6.82E+07	6.18E+00	5.99E+00	4.63E+07	7.12E+07
C	1	*	*	*	1.70E+00	*	*	*	*
IMA	1000	2.00E-01	3.00E-01	1.20E+06	2.00E+06	2.00E-01	2.00E-01	1.10E+06	1.90E+06
Spain	100000	6.80E+00	7.70E+00	5.10E+07	7.00E+07	6.70E+00	6.50E+00	5.00E+07	7.70E+07
D1†	1	7.20E-05	7.20E-06	3.30E-03	1.70E+00	*	*	*	*
Studsvik	1000	2.20E-01	2.50E-01	1.20E+06	1.90E+06	1.80E-01	1.80E-01	9.20E+05	1.70E+06
Sweden	100000	7.70E+00	8.70E+00	5.80E+07	8.00E+07	9.40E+00	9.10E+00	7.00E+07	1.10E+08
D2†	1	7.20E-05	1.60E-05	9.80E-03	3.40E+00	1.10E-06	2.30E-07	1.60E-04	5.50E-02
Studsvik	1000	2.30E-01	2.60E-01	1.20E+06	2.00E+06	2.20E-01	2.10E-01	1.10E+06	2.00E+06
Sweden	100000	6.60E+00	7.50E+00	4.90E+07	6.80E+07	6.20E+00	6.00E+00	4.60E+07	7.10E+07
E	1	6.77E-05	1.50E-05	1.02E-02	3.22E+00	1.14E-06	2.51E-07	2.21E-04	6.10E-02
JAERI	1000	2.16E-01	2.45E-01	1.16E+06	1.86E+06	2.17E-01	2.09E-01	1.14E+06	2.00E+06
Japan	100000	6.14E+00	9.97E+00	4.59E+07	6.35E+07	6.20E+00	6.01E+00	4.63E+07	7.12E+07
F	1	7.30E-05	1.60E-05	9.90E-03	3.50E+00	1.10E-06	2.30E-07	1.60E-04	5.60E-02
AECL	1000	2.30E-01	2.60E-01	1.20E+06	2.00E+06	2.20E-01	2.10E-01	1.10E+06	2.00E+06
Canada	100000	6.60E+00	7.50E+00	5.00E+07	6.90E+07	6.30E+00	6.10E+00	4.70E+07	7.20E+07
G	1	7.00E-05	9.30E-06	6.50E-03	1.80E+00	9.60E-07	9.80E-08	7.70E-05	1.90E-02
NRPB	1000	2.30E-01	2.60E-01	1.20E+06	2.00E+06	2.10E-01	2.10E-01	1.10E+06	2.00E+06
UK	100000	6.60E+00	7.50E+00	4.90E+07	6.80E+07	6.20E+00	6.00E+00	4.60E+07	7.10E+07

Table D1 - Results for Questionnaire Table B1.
Compartment inventories for each of the radionuclides at three specified times. Entries marked '*' indicate either a zero value was returned or that no value was submitted.

† Participant D submitted results calculated by two different solution methods for this table. Method 2 was used in the subsequent calculations.

D.2 Responses to Questionnaire Table B2

		^{14}C annual individual dose [Sv y^{-1}] by exposure pathway						
participant	time, [y]	water	fish	grain	meat	milk	dust	γ-irrad.
A	1	5.89E-11	6.30E-09	8.37E-09	1.00E-08	2.39E-09	2.44E-14	*
PSI	1000	3.44E-11	3.68E-09	1.28E-05	1.49E-05	3.55E-06	3.73E-11	*
Switzerland	100000	2.97E-17	3.18E-15	2.54E-11	2.97E-11	7.06E-12	7.41E-17	*
B	1	5.89E-11	6.30E-09	8.37E-09	9.94E-09	2.46E-09	2.44E-14	*
AEA Technology	1000	3.42E-11	3.66E-09	1.28E-05	1.48E-05	3.65E-06	3.73E-11	*
UK	100000	*	2.97E-15	2.37E-11	2.74E-11	6.76E-12	*	*
C	1	5.90E-11	6.30E-09	8.40E-09	1.00E-08	2.50E-09	2.40E-14	*
IMA	1000	3.40E-11	3.70E-09	1.30E-05	1.50E-05	3.60E-06	3.70E-11	*
Spain	100000	*	*	2.40E-11	2.70E-11	6.80E-12	*	*
D	1	6.10E-11	6.60E-09	8.30E-09	1.00E-08	2.40E-09	2.50E-14	*
Studsvik	1000	3.50E-11	3.80E-09	1.30E-05	1.50E-05	3.60E-06	3.90E-11	*
Sweden	100000	2.90E-17	3.10E-15	2.30E-11	2.60E-11	6.60E-12	7.10E-17	*
E	1	5.89E-11	6.30E-09	8.18E-09	9.72E-09	2.40E-09	2.39E-14	*
JAERI	1000	3.42E-11	3.66E-09	1.28E-05	1.48E-05	3.64E-06	3.72E-11	*
Japan	100000	1.12E-17	3.34E-15	2.66E-11	3.08E-11	7.59E-12	7.76E-17	*
F	1	5.90E-11	6.30E-09	8.40E-09	1.00E-08	2.50E-09	2.40E-14	*
AECL	1000	3.40E-11	3.70E-09	1.30E-05	1.50E-05	3.70E-06	3.70E-11	*
Canada	100000	2.80E-17	3.00E-15	2.40E-11	2.70E-11	6.80E-12	6.90E-17	*
G	1	5.90E-11	6.30E-09	8.40E-09	1.00E-08	2.40E-09	2.40E-14	*
NRPB	1000	3.40E-11	3.60E-09	1.30E-05	1.50E-05	3.60E-06	3.70E-11	*
UK	100000	2.70E-17	2.90E-15	2.30E-11	2.70E-11	6.60E-12	6.80E-17	*
		^{235}U annual individual dose [Sv y^{-1}] by exposure pathway						
participant	time, [y]	water	fish	grain	meat	milk	dust	γ-irrad.
A	1	5.1E-12	1.1E-12	1.5E-13	7.0E-12	4.5E-14	1.9E-14	4.0E-14
PSI	1000	1.4E-11	3.1E-12	1.8E-09	1.5E-08	9.8E-11	2.0E-09	4.2E-09
Switzerland	100000	1.1E-11	2.4E-12	2.1E-09	1.8E-08	1.1E-10	2.3E-09	4.9E-09
B	1	5.1E-12	1.1E-12	1.5E-13	7.0E-12	4.5E-14	1.9E-14	4.0E-14
AEA Technology	1000	1.4E-11	3.1E-12	1.8E-09	1.6E-08	9.9E-11	2.0E-09	4.2E-09
UK	100000	1.1E-11	2.4E-12	2.1E-09	1.8E-08	1.1E-10	2.3E-09	4.8E-09
C	1	5.1E-12	1.1E-12	1.5E-13	7.1E-12	4.5E-14	1.9E-14	4.0E-14
IMA	1000	1.5E-11	3.1E-12	1.8E-09	2.5E-08	1.0E-10	2.0E-09	4.1E-09
Spain	100000	1.1E-11	2.4E-12	2.1E-09	2.9E-08	1.2E-10	2.3E-09	4.8E-09
D	1	5.1E-12	1.1E-12	1.6E-13	6.9E-12	4.5E-14	1.9E-14	3.9E-14
Studsvik	1000	1.5E-11	3.1E-12	1.8E-09	1.6E-08	9.8E-11	2.0E-09	4.2E-09
Sweden	100000	1.1E-11	2.4E-12	2.1E-09	1.8E-08	1.1E-10	2.3E-09	4.8E-09
E	1	5.1E-12	1.1E-12	1.5E-13	7.0E-12	4.5E-14	1.9E-14	3.9E-14
JAERI	1000	1.4E-11	3.1E-12	1.8E-09	1.6E-08	9.9E-11	2.0E-09	4.1E-09
Japan	100000	1.1E-11	2.4E-12	2.1E-09	1.8E-08	1.2E-10	2.3E-09	4.8E-09
F	1	5.1E-12	1.1E-12	1.5E-13	7.0E-12	4.5E-14	1.9E-14	3.9E-14
AECL	1000	1.5E-11	3.1E-12	1.8E-09	1.6E-08	1.0E-10	2.0E-09	4.1E-09
Canada	100000	1.1E-11	2.4E-12	2.1E-09	1.8E-08	1.2E-10	2.3E-09	4.8E-09
G	1	5.1E-12	1.1E-12	1.6E-13	7.1E-12	4.5E-14	1.9E-14	4.1E-14
NRPB	1000	1.4E-11	3.1E-12	1.8E-09	1.5E-08	9.8E-11	2.0E-09	4.3E-09
UK	100000	1.1E-11	2.4E-12	2.1E-09	1.8E-08	1.1E-10	2.3E-09	5.0E-09

Table D2 - Results for Questionnaire Table B2.
Annual individual dose by exposure pathway and radionuclide at three specified times. Entries marked '*' indicate either a zero value was returned or that no value was submitted.

		^{231}Pa annual individual dose [Sv y^{-1}] by exposure pathway						
participant	time, [y]	water	fish	grain	meat	milk	dust	γ-irrad.
A	1	4.5E-15	9.7E-16	5.7E-16	2.5E-16	5.9E-19	5.5E-17	5.4E-19
PSI	1000	1.4E-11	3.1E-12	4.0E-08	3.2E-09	7.7E-12	1.0E-08	4.9E-11
Switzerland	100000	4.2E-10	9.0E-11	1.6E-06	1.3E-07	3.1E-10	4.2E-07	2.0E-09
B	1	4.5E-15	*	*	*	*	*	*
AEA Technology	1000	1.4E-11	3.1E-12	4.0E-08	3.2E-09	7.9E-12	1.0E-08	4.9E-11
UK	100000	4.1E-10	8.8E-11	1.6E-06	1.3E-07	3.1E-10	4.2E-07	1.9E-09
C	1	4.5E-15	*	*	*	*	*	*
IMA	1000	1.4E-11	3.1E-12	4.1E-08	3.0E-09	7.8E-12	1.0E-08	4.8E-11
Spain	100000	4.2E-10	9.1E-11	1.7E-06	1.3E-07	3.2E-10	4.3E-07	2.0E-09
D	1	4.5E-15	9.4E-16	4.4E-16	2.4E-16	5.7E-19	8.3E-17	3.8E-19
Studsvik	1000	1.4E-11	3.0E-12	3.8E-08	3.1E-09	7.4E-12	1.6E-08	4.7E-11
Sweden	100000	4.2E-10	8.6E-11	1.6E-06	1.3E-07	3.0E-10	4.2E-07	1.9E-09
E	1	4.2E-15	9.0E-16	4.5E-16	2.2E-16	5.5E-19	8.7E-17	4.0E-19
JAERI	1000	1.4E-11	2.9E-12	3.7E-08	3.0E-09	7.3E-12	9.8E-09	4.6E-11
Japan	100000	3.8E-10	8.2E-11	1.5E-06	1.2E-07	2.9E-10	3.9E-07	1.8E-09
F	1	1.4E-14	9.7E-16	4.4E-16	2.4E-16	5.8E-19	8.3E-17	3.9E-19
AECL	1000	1.5E-11	3.1E-12	4.0E-08	3.2E-09	7.9E-12	1.1E-08	4.9E-11
Canada	100000	4.1E-10	8.9E-11	1.6E-06	1.3E-07	3.2E-10	4.2E-07	2.0E-09
G	1	4.4E-15	9.4E-16	3.3E-16	2.2E-16	5.4E-19	5.5E-17	2.6E-19
NRPB	1000	1.4E-11	3.1E-12	4.0E-08	3.2E-09	7.8E-12	1.0E-08	4.9E-11
UK	100000	4.1E-10	8.8E-11	1.6E-06	1.3E-07	3.1E-10	4.2E-07	2.0E-09
		^{227}Ac annual individual dose [Sv y^{-1}] by exposure pathway						
participant	time, [y]	water	fish	grain	meat	milk	dust	γ-irrad.
A	1	1.2E-16	7.6E-17	4.0E-18	1.2E-19	1.2E-21	3.3E-18	1.8E-19
PSI	1000	1.8E-11	1.1E-11	1.3E-09	1.3E-11	1.2E-13	4.9E-08	5.2E-10
Switzerland	100000	5.3E-10	3.4E-10	5.3E-08	5.4E-10	5.1E-12	2.0E-06	2.1E-08
B	1	*	*	*	*	*	*	*
AEA Technology	1000	1.8E-11	1.1E-11	1.3E-09	1.3E-11	1.2E-13	4.9E-08	5.1E-10
UK	100000	5.1E-10	3.3E-10	5.2E-08	5.3E-10	5.0E-12	2.0E-06	2.1E-08
C	1	*	*	*	*	*	*	*
IMA	1000	1.7E-11	1.1E-11	1.2E-09	1.2E-11	1.2E-13	4.7E-08	4.9E-10
Spain	100000	5.6E-10	3.6E-10	5.6E-08	5.8E-10	5.5E-12	2.2E-06	2.3E-08
D	1	9.1E-17	5.8E-17	3.0E-18	9.2E-20	8.8E-22	7.0E-18	7.0E-20
Studsvik	1000	1.8E-11	1.2E-11	1.2E-09	1.2E-11	1.2E-13	4.8E-08	5.0E-10
Sweden	100000	5.1E-10	3.3E-10	5.1E-08	5.1E-10	5.1E-12	2.0E-06	2.1E-08
E	1	9.4E-17	6.0E-17	3.0E-18	9.6E-20	9.1E-22	9.6E-18	1.0E-19
JAERI	1000	1.8E-11	1.1E-11	1.3E-09	1.3E-11	1.2E-13	5.0E-08	5.2E-10
Japan	100000	5.1E-10	3.3E-10	5.2E-08	5.3E-10	5.0E-12	2.0E-06	2.1E-08
F	1	9.4E-17	6.0E-17	3.0E-18	9.5E-20	9.1E-22	7.1E-18	7.4E-20
AECL	1000	1.8E-11	1.1E-11	1.3E-09	1.3E-11	1.2E-13	5.0E-08	5.2E-10
Canada	100000	5.2E-10	3.3E-10	5.2E-08	5.3E-10	5.1E-12	2.0E-06	2.1E-08
G	1	7.9E-17	5.1E-17	2.4E-18	7.9E-20	7.6E-22	3.3E-18	3.4E-20
NRPB	1000	1.8E-11	1.1E-11	1.3E-09	1.3E-11	1.2E-13	4.9E-08	5.0E-10
UK	100000	5.1E-10	3.3E-10	5.2E-08	5.2E-10	5.0E-12	2.0E-06	2.1E-08

Table D2 (continued) - Results for Questionnaire Table B2.

Annual individual dose by exposure pathway and radionuclide at three specified times. Entries marked '*' indicate either a zero value was returned or that no value was submitted.

D.3 Responses to Questionnaire Table B3

	A, PSI, Switzerland: 1000 samples, Monte Carlo.					
	^{14}C			^{235}U chain		
time, [y]	mean, μ	std. dev., σ	Cheb. 95%, T_{95}	mean, μ	std. dev., σ	Cheb. 95%, T_{95}
1	1.5E-07	3.8E-07	5.4E-08	2.1E-11	2.7E-11	3.8E-12
3	6.7E-07	1.6E-06	2.2E-07	2.8E-11	3.4E-11	4.9E-12
10	2.7E-06	5.8E-06	8.2E-07	8.6E-11	1.3E-10	1.8E-11
30	8.3E-06	1.8E-05	2.5E-06	4.3E-10	6.3E-10	8.8E-11
100	2.7E-05	5.5E-05	7.8E-06	2.6E-09	3.2E-09	4.5E-10
300	6.8E-05	1.4E-04	2.0E-05	1.5E-08	1.6E-08	2.2E-09
1000	1.3E-04	2.6E-04	3.6E-05	1.3E-07	1.2E-07	1.7E-08
3000	1.1E-04	2.0E-04	2.8E-05	8.8E-07	8.5E-07	1.2E-07
10000	2.5E-05	3.5E-05	5.0E-06	6.0E-06	6.6E-06	9.4E-07
30000	1.1E-06	1.9E-06	2.7E-07	2.1E-05	2.8E-05	3.9E-06
100000	1.0E-10	2.3E-10	3.2E-11	2.2E-05	4.0E-05	5.6E-06
300000	5.1E-13	7.2E-13	1.0E-13	4.1E-06	1.2E-05	1.7E-06
1000000	*	*	*	2.2E-07	2.1E-06	3.0E-07
	B, AEA Technology, UK: 1000 sample, Monte Carlo.					
	^{14}C			^{235}U chain		
time, [y]	mean, μ	std. dev., σ	Cheb. 95%, T_{95}	mean, μ	std. dev., σ	Cheb. 95%, T_{95}
1	1.4E-07	3.5E-07	4.9E-08	2.1E-11	2.5E-11	3.5E-12
3	6.3E-07	1.4E-06	2.1E-07	2.8E-11	3.1E-11	4.5E-12
10	2.6E-06	5.4E-06	7.7E-07	8.6E-11	1.2E-10	1.7E-11
30	8.0E-06	1.7E-05	2.3E-06	4.2E-10	5.8E-10	8.2E-11
100	2.6E-05	5.3E-05	7.4E-06	2.6E-09	2.9E-09	4.2E-10
300	6.6E-05	1.3E-04	1.9E-05	1.5E-08	1.5E-08	2.1E-09
1000	1.3E-04	2.5E-04	3.5E-05	1.3E-07	1.1E-07	1.6E-08
3000	1.1E-04	1.9E-04	2.7E-05	9.1E-07	8.1E-07	1.1E-07
10000	2.6E-05	4.2E-05	5.9E-06	6.2E-06	6.5E-06	9.3E-07
30000	1.1E-06	2.0E-06	2.9E-07	2.2E-05	2.9E-05	4.1E-06
100000	1.0E-10	2.3E-10	3.3E-11	2.4E-05	4.4E-05	6.2E-06
300000	1.0E-20	1.0E-20	1.0E-20	4.2E-06	1.5E-05	2.1E-06
1000000	1.0E-20	1.0E-20	1.0E-20	3.0E-07	2.4E-06	3.4E-07
	C, IMA, Spain: 1000 samples, LHS.					
	^{14}C			^{235}U chain		
time, [y]	mean, μ	std. dev., σ	Cheb. 95%, T_{95}	mean, μ	std. dev., σ	Cheb. 95%, T_{95}
1	1.3E-07	1.7E-07	2.5E-08	5.4E-11	8.5E-11	1.2E-11
3	5.3E-07	7.3E-07	1.0E-07	5.6E-11	8.5E-11	1.2E-11
10	2.1E-06	2.8E-06	4.0E-07	7.9E-11	8.6E-11	1.2E-11
30	6.6E-06	8.7E-06	1.2E-06	2.2E-10	1.7E-10	2.4E-11
100	2.1E-05	2.8E-05	3.9E-06	1.3E-09	9.4E-10	1.3E-10
300	5.6E-05	7.2E-05	1.0E-05	9.4E-09	6.0E-09	8.4E-10
1000	1.1E-04	1.3E-04	1.9E-05	8.9E-08	5.1E-08	7.2E-09
3000	9.3E-05	1.1E-04	1.6E-05	6.6E-07	3.9E-07	5.4E-08
10000	2.2E-05	2.9E-05	4.1E-06	4.7E-06	3.4E-06	4.8E-07
30000	9.8E-07	1.4E-06	2.1E-07	1.6E-05	1.6E-05	2.3E-06
100000	8.6E-11	1.7E-10	2.5E-11	1.8E-05	2.6E-05	3.7E-06
300000	9.2E-22	2.5E-21	3.5E-22	3.0E-06	7.8E-06	1.1E-06
1000000	1.0E-23	1.0E-23	1.0E-23	1.3E-07	9.7E-07	1.4E-07

Table D3 - Results for Questionnaire Table B3.

Means, standard deviations and Chebyshev 95% confidence limit, T_{95} given by

$$T_{95} = \sqrt{\frac{1}{0.05N}}\sigma,$$

where N is the number of samples. The confidence interval is $\mu \pm T_{95}$.

Entries marked '*' indicate either a zero entry or that no value was returned.

	D, Studsvik, Sweden: 200 samples LHS.					
	^{14}C			^{235}U chain		
time, [y]	mean, μ	std. dev., σ	Cheb. 95%, T_{95}	mean, μ	std. dev., σ	Cheb. 95%, T_{95}
1	1.4E-07	2.7E-07	8.6E-08	2.3E-11	2.7E-11	8.6E-12
3	6.5E-07	1.2E-06	3.8E-07	2.9E-11	3.2E-11	1.0E-11
10	2.7E-06	4.6E-06	1.5E-06	8.6E-11	1.1E-10	3.5E-11
30	8.3E-06	1.4E-05	4.4E-06	4.3E-10	5.4E-10	1.7E-10
100	2.6E-05	4.5E-05	1.4E-05	2.7E-09	2.8E-09	8.9E-10
300	6.8E-05	1.1E-04	3.5E-05	1.6E-08	1.4E-08	4.4E-09
1000	1.3E-04	2.0E-04	6.3E-05	1.3E-07	1.2E-07	3.8E-08
3000	1.1E-04	1.5E-04	4.8E-05	9.4E-07	8.6E-07	2.7E-07
10000	2.5E-05	3.8E-05	1.2E-05	6.5E-06	7.0E-06	2.2E-06
30000	1.1E-06	1.7E-06	5.4E-07	2.3E-05	3.1E-05	9.8E-06
100000	8.7E-11	1.5E-10	4.8E-11	2.3E-05	4.2E-05	1.3E-05
300000	7.3E-22	2.0E-19	6.3E-20	3.5E-06	1.3E-05	4.1E-06
1000000	1.0E-20	1.0E-20	1.0E-20	3.5E-07	3.1E-06	9.8E-07
	E, JAERI, Japan: 1000 Samples, Monte Carlo.					
	^{14}C			^{235}U chain		
time, [y]	mean, μ	std. dev., σ	Cheb. 95%, T_{95}	mean, μ	std. dev., σ	Cheb. 95%, T_{95}
1	1.5E-07	3.5E-07	5.0E-08	2.3E-11	3.2E-11	4.5E-12
3	7.0E-07	1.5E-06	2.1E-07	3.0E-11	3.9E-11	5.5E-12
10	2.8E-06	5.5E-06	7.8E-07	9.0E-11	1.3E-10	1.8E-11
30	8.7E-06	1.7E-05	2.4E-06	4.4E-10	6.1E-10	8.7E-11
100	2.8E-05	5.2E-05	7.4E-06	2.7E-09	3.2E-09	4.5E-10
300	7.1E-05	1.3E-04	1.8E-05	1.6E-08	1.7E-08	2.3E-09
1000	1.4E-04	2.3E-04	3.3E-05	1.4E-07	1.3E-07	1.8E-08
3000	1.1E-04	1.8E-04	2.5E-05	9.5E-07	9.4E-07	1.3E-07
10000	2.7E-05	4.2E-05	6.0E-06	6.5E-06	7.3E-06	1.0E-06
30000	1.2E-06	1.9E-06	2.7E-07	2.3E-05	3.1E-05	4.4E-06
100000	1.0E-10	2.1E-10	3.0E-11	2.3E-05	4.4E-05	6.3E-06
300000	1.4E-14	4.1E-13	5.8E-14	3.3E-06	1.1E-05	1.6E-06
1000000	6.9E-15	2.0E-13	2.9E-14	2.3E-07	2.3E-06	3.3E-07
	F, AECL, Canada, 1000 samples, Monte Carlo.					
	^{14}C			^{235}U chain		
time, [y]	mean, μ	std. dev., σ	Cheb. 95%, T_{95}	mean, μ	std. dev., σ	Cheb. 95%, T_{95}
1	1.3E-07	2.7E-07	3.8E-08	2.2E-11	2.7E-11	3.8E-12
3	6.1E-07	1.2E-06	1.7E-07	2.8E-11	3.2E-11	4.5E-12
10	2.5E-06	4.5E-06	6.4E-07	8.1E-11	1.1E-10	1.6E-11
30	7.8E-06	1.4E-05	2.0E-06	4.0E-10	5.6E-10	7.9E-11
100	2.5E-05	4.4E-05	6.2E-06	2.6E-09	3.0E-09	4.2E-10
300	6.5E-05	1.1E-04	1.6E-05	1.5E-08	1.5E-08	2.1E-09
1000	1.3E-04	2.0E-04	2.8E-05	1.3E-07	1.2E-07	1.7E-08
3000	1.1E-04	1.5E-04	2.1E-05	9.0E-07	8.5E-07	1.2E-07
10000	2.5E-05	3.6E-05	5.1E-06	6.2E-06	6.8E-06	9.6E-07
30000	1.1E-06	1.7E-06	2.4E-07	2.2E-05	2.9E-05	4.1E-06
100000	7.9E-11	1.5E-10	2.1E-11	2.2E-05	4.3E-05	6.1E-06
300000	1.8E-19	4.7E-19	6.7E-20	3.4E-06	1.2E-05	1.7E-06
1000000	*	*	*	1.7E-07	1.6E-06	2.3E-07

Table D3 (continued) - Results for Questionnaire Table B3.

Means, standard deviations and Chebyshev 95% confidence limit, T_{95}, given by

$$T_{95} = \sqrt{\frac{1}{0.05N}}\sigma,$$

where N is the number of samples. The confidence interval is $\mu \pm T_{95}$.

Entries marked '*' indicate either a zero entry or that no value was returned.

	G, NRPB, UK, 1000 samples, LHS.					
	^{14}C			^{235}U chain		
time, [y]	mean, μ	std. dev., σ	Cheb. 95%, T_{95}	mean, μ	std. dev., σ	Cheb. 95%, T_{95}
1	1.3E-07	1.7E-07	2.4E-08	5.4E-11	8.0E-11	1.1E-11
3	5.1E-07	7.2E-07	1.0E-07	5.9E-11	8.0E-11	1.1E-11
10	2.0E-06	2.7E-06	3.9E-07	1.0E-10	9.2E-11	1.3E-11
30	6.2E-06	8.4E-06	1.2E-06	3.6E-10	2.9E-10	4.1E-11
100	2.0E-05	2.6E-05	3.7E-06	2.0E-09	1.4E-09	2.0E-10
300	5.1E-05	6.8E-05	9.6E-06	1.2E-08	6.6E-09	9.3E-10
1000	1.0E-04	1.3E-04	1.9E-05	9.8E-08	4.3E-08	6.1E-09
3000	9.3E-05	1.2E-04	1.7E-05	6.8E-07	3.0E-07	4.3E-08
10000	2.2E-05	3.1E-05	4.4E-06	4.7E-06	2.9E-06	4.0E-07
30000	9.6E-07	1.6E-06	2.3E-07	1.7E-05	1.5E-05	2.1E-06
100000	7.8E-11	1.5E-10	2.1E-11	1.7E-05	2.4E-05	3.4E-06
300000	1.7E-21	*	*	2.6E-06	7.4E-06	1.0E-06
1000000	*	*	*	1.9E-07	2.3E-06	3.3E-07

Table D3 (continued) - Results for Questionnaire Table B3.

Means, standard deviations and Chebyshev 95% confidence limit, T_{95}, given by

$$T_{95} = \sqrt{\frac{1}{0.05N}}\sigma,$$

where N is the number of samples. The confidence interval is $\mu \pm T_{95}$.

Entries marked '*' indicate either a zero entry or that no value was returned.

D.4 Responses to Questionnaire Table B4

	A, PSI, Switzerland				B, AEA Technology, UK			
	^{14}C		^{235}U chain		^{14}C		^{235}U chain	
time, [y]	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway
1	7.5E-08	Meat	1.1E-11	Meat	7.5E-08	Meat	1.1E-11	Meat
	6.1E-08	Grain	7.9E-12	Water	6.1E-08	Grain	7.9E-12	Water
	1.8E-08	Milk	1.5E-12	Fish	1.8E-08	Milk	1.5E-12	Fish
	9.0E-09	Fish	2.7E-13	Grain	9.0E-09	Fish	2.7E-13	Grain
	9.4E-11	Water	2.0E-13	External γ	9.4E-11	Water	2.0E-13	External γ
	2.4E-13	Dust	1.0E-13	Dust	2.4E-13	Dust	1.0E-13	Dust
	0	External γ	7.0E-14	Milk	0	External γ	7.0E-14	Milk
10	1.5E-06	Meat	4.1E-13	Milk	1.5E-06	Meat	6.9E-11	Meat
	1.2E-06	Grain	1.6E-12	Fish	1.2E-06	Grain	1.5E-11	External γ
	3.5E-07	Milk	7.2E-12	Grain	3.5E-07	Milk	8.4E-12	Water
	1.1E-08	Fish	8.0E-12	Dust	1.1E-08	Fish	8.0E-12	Dust
	1.2E-10	Water	8.4E-12	Water	1.2E-10	Water	7.2E-12	Grain
	4.4E-12	Dust	1.5E-11	External γ	4.4E-12	Dust	1.6E-12	Fish
	0	External γ	6.9E-11	Meat	0	External γ	4.1E-13	Milk
100	1.5E-05	Meat	1.6E-09	Meat	1.5E-05	Meat	1.6E-09	Meat
	1.2E-05	Grain	6.4E-10	Dust	1.2E-05	Grain	6.4E-10	Dust
	3.5E-06	Milk	5.0E-10	Grain	3.5E-06	Milk	5.0E-10	Grain
	3.3E-08	Fish	4.1E-10	External γ	3.3E-08	Fish	4.1E-10	External γ
	3.3E-10	Water	2.3E-11	Water	3.3E-10	Water	2.3E-11	Water
	4.3E-11	Dust	9.7E-12	Milk	4.3E-11	Dust	9.7E-12	Milk
	0	External γ	6.0E-12	Fish	0	External γ	6.0E-12	Fish
1000	7.2E-05	Meat	7.4E-08	Dust	7.2E-05	Meat	7.4E-08	Dust
	6.1E-05	Grain	4.6E-08	Grain	6.1E-05	Grain	4.6E-08	Grain
	1.7E-05	Milk	2.2E-08	Meat	1.7E-05	Milk	2.2E-08	Meat
	1.2E-07	Fish	5.6E-09	External γ	1.2E-07	Fish	5.6E-09	External γ
	1.2E-09	Water	4.6E-10	Water	1.2E-09	Water	4.6E-10	Water
	2.0E-10	Dust	2.0E-10	Fish	2.0E-10	Dust	2.0E-10	Fish
	0	External γ	1.3E-10	Milk	0	External γ	1.3E-10	Milk
10000	1.2E-05	Grain	3.9E-06	Dust	1.2E-05	Grain	3.9E-06	Dust
	1.1E-05	Meat	2.4E-06	Grain	1.1E-05	Meat	2.4E-06	Grain
	3.2E-06	Milk	3.0E-07	Meat	3.2E-06	Milk	3.0E-07	Meat
	8.8E-09	Fish	6.3E-08	External γ	8.8E-09	Fish	6.3E-08	External γ
	8.4E-11	Water	9.8E-09	Water	8.4E-11	Water	9.8E-09	Water
	3.0E-11	Dust	4.6E-09	Fish	3.0E-11	Dust	4.6E-09	Fish
	0	External γ	1.2E-09	Milk	0	External γ	1.2E-09	Milk
100000	5.6E-11	Meat	1.3E-05	Dust	5.6E-11	Meat	1.3E-05	Dust
	4.1E-11	Grain	7.7E-06	Grain	4.1E-11	Grain	7.7E-06	Grain
	1.3E-11	Milk	7.8E-07	Meat	1.3E-11	Milk	7.8E-07	Meat
	6.6E-15	Fish	1.4E-07	External γ	6.6E-15	Fish	1.4E-07	External γ
	1.1E-16	Dust	9.4E-09	Water	1.1E-16	Dust	9.4E-09	Water
	7.0E-17	Water	3.6E-09	Fish	7.0E-17	Water	3.6E-09	Fish
	0	External γ	2.0E-09	Milk	0.0E+00	External γ	2.0E-09	Milk
1000000	8.7E-14	Meat	9.3E-08	Dust	8.7E-14	Meat	9.3E-08	Dust
	8.5E-14	Grain	3.5E-08	Grain	8.5E-14	Grain	3.5E-08	Grain
	2.3E-14	Milk	6.9E-09	Meat	2.3E-14	Milk	6.9E-09	Meat
	1.1E-16	Fish	8.7E-10	External γ	1.1E-16	Fish	8.7E-10	External γ
	1.0E-18	Water	1.1E-10	Water	1.1E-10	Water	1.1E-10	Water
	2.4E-19	Dust	1.7E-11	Fish	2.4E-19	Dust	1.7E-11	Fish
	0	External γ	6.9E-12	Milk	0.0E+00	External γ	6.9E-12	Milk

Table D4 - Results for Questionnaire Table B4.

Ranking of contibutions to mean annual individual dose by exposure pathway at specified times.

	C, IMA, Spain				D, Studsvik, Sweden			
	^{14}C		^{235}U chain		^{14}C		^{235}U chain	
time, [y]	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway
1	7.7E-08	Meat	2.8E-11	Meat	6.1E-08	Meat	1.2E-11	Meat
	4.4E-08	Grain	2.1E-11	Water	5.3E-08	Grain	8.6E-12	Water
	2.6E-08	Fish	4.5E-12	Fish	1.6E-08	Milk	1.9E-12	Fish
	1.1E-08	Milk	1.5E-13	Grain	1.1E-08	Fish	3.0E-13	Grain
	2.4E-10	Water	1.1E-13	External γ	1.0E-10	Water	1.4E-13	External γ
	1.2E-13	Dust	5.5E-14	Dust	1.5E-13	Dust	7.7E-14	Milk
	0	External γ	2.9E-14	Milk	0	External γ	6.8E-14	Dust
10	9.5E-07	Meat	3.5E-11	Meat	1.2E-06	Meat	5.2E-11	Meat
	9.0E-07	Grain	2.1E-11	Water	1.1E-06	Grain	1.1E-11	External γ
	2.3E-07	Milk	8.4E-12	External γ	3.3E-07	Milk	9.5E-12	Water
	2.6E-08	Fish	5.0E-12	Grain	1.3E-08	Fish	5.8E-12	Grain
	2.4E-10	Water	4.6E-12	Fish	1.2E-10	Water	5.6E-12	Dust
	2.4E-12	Dust	4.4E-12	Dust	3.2E-12	Dust	2.1E-12	Fish
	0	External γ	7.7E-14	Milk	0	External γ	3.5E-13	Milk
100	9.6E-06	Meat	3.7E-10	Grain	6.3E-05	Meat	1.3E-09	Meat
	9.1E-06	Grain	3.6E-10	Dust	5.4E-05	Grain	5.0E-10	Dust
	2.4E-06	Milk	2.8E-10	Meat	1.6E-05	Milk	4.4E-10	Grain
	2.5E-08	Fish	2.6E-10	External γ	3.3E-08	Fish	3.5E-10	External γ
	2.4E-10	Water	2.6E-11	Water	2.8E-10	Water	3.4E-11	Water
	2.4E-11	Dust	6.3E-12	Milk	1.6E-10	Dust	8.7E-12	Milk
	0	External γ	1.6E-12	Fish	0	External γ	8.2E-12	Fish
1000	1.2E-05	Meat	4.4E-08	Dust	6.3E-05	Meat	6.2E-08	Dust
	4.7E-05	Grain	3.6E-08	Grain	5.4E-05	Grain	4.4E-08	Grain
	1.2E-05	Milk	5.2E-09	Meat	1.6E-05	Milk	2.1E-08	Meat
	1.8E-08	Fish	3.8E-09	External γ	1.2E-07	Fish	5.2E-09	External γ
	1.7E-10	Water	1.1E-10	Fish	1.0E-09	Water	6.8E-10	Water
	1.2E-10	Dust	4.0E-11	Water	1.0E-10	Dust	2.4E-10	Fish
	0	External γ	2.5E-11	Milk	0	External γ	1.2E-10	Milk
10000	1.0E-05	Meat	2.5E-06	Dust	1.2E-05	Meat	3.7E-06	Dust
	9.7E-06	Grain	2.0E-06	Grain	1.0E-05	Grain	2.5E-06	Grain
	2.5E-06	Milk	1.4E-07	Meat	2.9E-06	Milk	3.0E-07	Meat
	9.4E-10	Fish	4.4E-08	External γ	1.2E-08	Fish	6.3E-08	External γ
	2.6E-11	Dust	1.4E-09	Milk	1.1E-10	Water	1.3E-08	Water
	8.7E-12	Water	6.2E-10	Water	8.9E-17	Dust	5.8E-09	Fish
	0	External γ	4.2E-10	Fish	0	External γ	1.2E-09	Milk
100000	3.8E-11	Meat	9.8E-06	Dust	4.3E-11	Meat	1.3E-05	Dust
	3.8E-11	Grain	7.5E-06	Grain	3.4E-11	Grain	9.0E-06	Grain
	1.0E-11	Milk	4.7E-07	Meat	1.0E-11	Milk	7.1E-07	Meat
	1.1E-15	Fish	1.1E-07	External γ	1.4E-14	Fish	1.4E-07	External γ
	1.0E-16	Dust	1.3E-09	Milk	1.1E-16	Water	1.5E-08	Water
	1.1E-17	Water	1.3E-09	Water	8.9E-17	Dust	6.8E-09	Fish
	0	External γ	6.1E-10	Fish	0	External γ	2.4E-09	Milk
1000000	*	*	6.3E-08	Dust	*	*	1.9E-07	Dust
	*	*	6.1E-08	Grain	*	*	1.4E-07	Grain
	*	*	5.0E-09	Meat	*	*	1.3E-08	Meat
	*	*	8.7E-10	External γ	*	*	2.3E-09	External γ
	*	*	1.0E-11	Milk	*	*	2.9E-11	Milk
	*	*	4.8E-10	Water	*	*	8.7E-12	Water
	*	*	1.6E-12	Fish	*	*	2.1E-12	Fish

Table D4 (continued) - Results for Questionnaire Table B4.

Ranking of contibutions to mean annual individual dose by exposure pathway at specified times.
Entries marked '*' indicate that no values were returned.

	E, JAERI, Japan				F, AECL, Canada			
	^{14}C		^{235}U chain		^{14}C		^{235}U chain	
time, [y]	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway
1	6.8E-08	Meat	1.2E-11	Meat	5.4E-08	Meat	1.1E-11	Meat
	5.8E-08	Grain	8.7E-12	Water	5.3E-08	Grain	8.2E-12	Water
	1.7E-08	Milk	1.9E-12	Fish	1.5E-08	Milk	1.8E-12	Fish
	1.1E-08	Fish	3.1E-13	Grain	1.1E-08	Fish	2.8E-13	Grain
	1.0E-10	Water	1.5E-13	External γ	9.7E-11	Water	1.4E-13	External γ
	1.7E-13	Dust	8.0E-14	Milk	1.4E-13	Dust	7.2E-14	Milk
	0.0E+00	External γ	7.5E-14	Dust	0	External γ	6.5E-14	Dust
10	1.3E-06	Meat	5.5E-11	Meat	1.1E-06	Grain	4.9E-11	Meat
	1.1E-06	Grain	1.1E-11	External γ	1.1E-06	Meat	1.0E-11	External γ
	3.3E-07	Milk	9.3E-12	Water	2.9E-07	Milk	8.8E-12	Water
	1.3E-08	Fish	6.2E-12	Grain	1.3E-08	Fish	5.4E-12	Grain
	1.2E-10	Water	6.0E-12	Dust	1.2E-10	Water	5.2E-12	Dust
	3.4E-12	Dust	2.0E-12	Fish	2.9E-12	Dust	2.0E-12	Fish
	0.0E+00	External γ	3.6E-13	Milk	0	External γ	3.1E-13	Milk
100	1.3E-05	Meat	1.4E-09	Meat	1.1E-05	Grain	1.3E-09	Meat
	1.1E-05	Grain	5.1E-10	Dust	1.1E-05	Meat	4.8E-10	Dust
	3.3E-06	Milk	4.6E-10	Grain	3.0E-06	Milk	4.2E-10	Grain
	3.0E-08	Fish	3.6E-10	External γ	3.6E-08	Fish	3.4E-10	External γ
	3.2E-10	Water	2.9E-11	Water	3.1E-10	Water	2.8E-11	Water
	3.4E-11	Dust	8.9E-12	Milk	3.0E-11	Dust	8.1E-12	Milk
	0.0E+00	External γ	7.1E-12	Fish	0	External γ	7.5E-12	Fish
1000	6.6E-05	Meat	6.4E-08	Dust	5.8E-05	Meat	6.0E-08	Dust
	5.6E-05	Grain	4.5E-08	Grain	5.4E-05	Grain	4.2E-08	Grain
	1.6E-05	Milk	2.1E-08	Meat	1.5E-05	Milk	2.0E-08	Meat
	9.5E-08	Fish	5.3E-09	External γ	1.2E-07	Fish	5.0E-09	External γ
	1.0E-09	Water	5.8E-10	Water	1.0E-09	Water	5.9E-10	Water
	1.7E-10	Dust	2.4E-10	Fish	1.5E-10	Dust	2.4E-10	Fish
	0	External γ	1.2E-10	Milk	0	External γ	1.1E-10	Milk
10000	1.3E-05	Meat	3.6E-06	Dust	1.2E-05	Meat	3.4E-06	Dust
	1.1E-05	Grain	2.5E-06	Grain	1.0E-05	Grain	2.4E-06	Grain
	3.1E-06	Milk	3.1E-07	Meat	2.8E-06	Milk	2.8E-07	Meat
	1.1E-08	Fish	6.2E-08	External γ	1.2E-08	Fish	6.0E-08	External γ
	1.0E-10	Water	1.3E-08	Water	1.0E-10	Water	1.3E-08	Water
	3.2E-11	Dust	6.7E-09	Fish	2.9E-11	Dust	6.0E-09	Fish
	0	External γ	1.2E-09	Milk	0	External γ	1.1E-09	Milk
100000	4.8E-11	Meat	1.3E-05	Dust	3.7E-11	Meat	1.2E-05	Dust
	4.0E-11	Grain	8.9E-06	Grain	3.4E-11	Grain	8.9E-06	Grain
	1.2E-11	Milk	8.0E-07	Meat	9.0E-12	Milk	7.3E-07	Meat
	1.7E-14	Fish	1.5E-07	External γ	1.4E-14	Fish	1.4E-07	External γ
	1.4E-16	Water	1.5E-08	Water	1.3E-16	Water	1.5E-08	Water
	1.2E-16	Dust	7.7E-09	Fish	9.4E-17	Dust	6.9E-09	Fish
	0	External γ	2.3E-09	Milk	0	External γ	2.0E-09	Milk
1000000	5.2E-15	Meat	1.3E-07	Dust	*	*	8.9E-08	Dust
	1.2E-15	Milk	8.3E-08	Grain	*	*	7.4E-08	Grain
	5.9E-16	Grain	6.3E-09	Meat	*	*	5.0E-09	Meat
	6.3E-19	Fish	1.3E-09	External γ	*	*	1.0E-09	External γ
	9.6E-21	Dust	9.6E-11	Water	*	*	2.5E-11	Water
	7.0E-21	Water	3.6E-11	Fish	*	*	1.6E-11	Milk
	0	External γ	1.7E-11	Milk	*	*	8.2E-12	Fish

Table D4 (continued) - Results for Questionnaire Table B4.

Ranking of contibutions to mean annual individual dose by exposure pathway at specified times.
Entries marked '*' indicate that no values were returned.

	G, NRPB, UK			
	^{14}C		^{235}U chain	
time, [y]	mean annual individual dose [Sv y^{-1}]	exposure pathway	mean annual individual dose [Sv y^{-1}]	exposure pathway
1	4.8E-08	Meat	2.8E-11	Meat
	4.0E-08	Grain	2.1E-11	Water
	2.6E-08	Fish	4.4E-12	Fish
	1.2E-08	Milk	6.1E-13	Grain
	2.4E-10	Water	1.8E-13	Milk
	1.2E-13	Dust	1.1E-13	External γ
	0	External γ	5.4E-14	Dust
10	9.5E-07	Meat	5.9E-11	Meat
	8.1E-07	Grain	2.1E-11	Water
	2.3E-07	Milk	8.6E-12	External γ
	2.5E-07	Fish	4.7E-12	Grain
	2.4E-10	Water	4.5E-12	Fish
	2.4E-12	Dust	4.3E-12	Dust
	0	External γ	3.7E-13	Milk
100	9.4E-06	Meat	1.0E-09	Meat
	8.0E-06	Grain	3.7E-10	Dust
	2.3E-06	Milk	3.3E-10	Grain
	2.5E-08	Fish	2.7E-10	External γ
	2.3E-10	Water	2.6E-11	Water
	2.3E-11	Dust	6.4E-12	Milk
	0	External γ	6.3E-12	Fish
1000	5.0E-05	Meat	4.6E-08	Dust
	4.2E-05	Grain	3.2E-08	Grain
	1.2E-05	Milk	1.5E-08	Meat
	1.8E-08	Fish	3.9E-09	External γ
	1.6E-10	Water	1.1E-10	Water
	1.2E-10	Dust	8.7E-11	Milk
	0	External γ	4.1E-11	Fish
10000	1.1E-05	Meat	2.6E-06	Dust
	9.0E-06	Grain	1.8E-06	Grain
	2.6E-06	Milk	2.2E-07	Meat
	9.2E-10	Fish	4.5E-08	External γ
	2.6E-11	Dust	1.4E-09	Water
	8.6E-12	Water	8.4E-10	Milk
	0	External γ	6.2E-10	Fish
100000	3.7E-11	Meat	9.7E-06	Dust
	3.2E-11	Grain	6.8E-06	Grain
	9.0E-12	Milk	6.0E-07	Meat
	1.1E-15	Fish	1.1E-07	External γ
	9.3E-17	Dust	1.7E-09	Milk
	1.0E-17	Water	1.3E-09	Water
	0	External γ	5.9E-10	Fish
1000000	*	*	1.0E-07	Dust
	*	*	8.1E-08	Grain
	*	*	6.6E-09	Meat
	*	*	9.9E-10	External γ
	*	*	1.7E-11	Milk
	*	*	6.8E-12	Water
	*	*	3.0E-12	Fish

Table D4 (continued) - Results for Questionnaire Table B4.

Ranking of contibutions to mean annual individual dose by exposure pathway at specified times.
Entries marked '*' indicate that no values were returned.

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