BIOPROTA

Key Issues in Biosphere Aspects of Assessment of the Long-term Impact of Contaminant Releases Associated with Radioactive Waste Management

THEME 2: Task 2:

Modelling the Inhalation Exposure Pathway

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FOREWORD

Assessing the impacts of releases of radioactivity into the environment rely on a great variety of factors. Important among these is an effectively justified level of understanding of radionuclide behaviour in the environment, the associated migration pathways and the processes that contribute to radionuclide accumulation and dispersion among and within specific environmental media. In addition, evaluating the consequences of any radionuclide releases on human health rely on the use of appropriate physiological and dosimetric models for calculating doses and risks. Assessment methods have been developed over several decades based on knowledge of the ecosystems involved, as well as monitoring of previous radionuclide releases to the environment, laboratory experiments and other research.

It is recognised that in some cases data for these assessments are sparse. Particular difficulties arise in the case of long-lived radionuclides, because of the difficulty of setting up relatively long-term monitoring and experimental programmes, and because the biosphere systems themselves will change over the relevant periods, due to natural processes and the potential for interference by mankind.

It is also the case that much radio-ecological research has tended to focus on relatively few radionuclides, eg. Sr-90 and Cs-137. While this research has been relevant to operational effluent discharges and accidental releases, other radionuclides tend to dominate long term impacts as may arise from the migration of radionuclides from solid radioactive waste repositories. Examples include C-14, Cl-36, Se-79, Tc-99, Np-237. The viability of geological disposal concepts and the long-term sustainability of radioactive effluent discharges, together with the safe and effective management of contaminated land and surface stores for solid radioactive wastes can only be considered in the light of a good understanding of the environmental behaviour of such longer lived radionuclides. However, the number of radionuclides involved is relatively small, and the number of important processes associated with migration and accumulation in the biosphere, and the related radiation exposure of humans and other biota, is also relatively limited.

The International Atomic Energy Agency's BIOMASS Theme 1 has provided a basis for identifying, justifying and describing biosphere systems for the purpose of radiological assessment. The development of conceptual and mathematical models has been set out and a protocol developed for the application of data to these models. However the BIOMASS Project did not address the details of uncertainties arising from weaknesses in the information base.

BIOPROTA Concept

BIOPROTA provides a forum to address uncertainties in the assessment of the radiological impact of releases of long-lived radionuclides into the biosphere. The programme of work carried out under the auspices of BIOPROTA focuses on these key radionuclides and the various biosphere migration and accumulation mechanisms relevant to those radionuclides. It is understood that there are radio-ecological and other data and information issues which are common to specific assessments required in many countries. The mutual support within a commonly focused project is intended to make more efficient use of skills and resources, and support a transparent and traceable basis for the choices of parameter values as well as for the wider interpretation of information used in the assessments.

The BIOPROTA Project up to December 2004 has been managed and supported financially by:

Organisation	Representative	Role of organisation	Website
Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA)	Elisabeth Leclerc-Cessac	ANDRA is responsible for the management of radioactive waste in France.	www.andra.fr
Empresa Nacional de Residuos Radiactivos, S.A. (ENRESA)	Julio Astudilio	ENRESA is responsible for the management of radioactive wastes generated in Spain and the decommissioning of nuclear power plants.	www.enresa.es
Nexia Solutions Ltd (formerly BNFL Research & Technology)	Mark Willans	Nexia Solutions is a UK BNFL subsiduary company providing technology solutions and services across the nuclear fuel cycle.	www.nexiasolutions .com
United Kingdom Nirex Limited (Nirex)	Paul Degnan	Nirex is the radioactive waste management agency with responsibility to develop and advise on safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials in the UK.	www.nirex.co.uk
Nuclear Waste Management Organization of Japan (NUMO)	Shigeru Okuyama	NUMO is the implementing body for the final disposal of vitrified high-level waste packaged from the spent fuel reprocessing plant. It is a government approved organization responsible for identification of a disposal site, and for the construction, operation and maintenance of the repository, closure of the facility, and post-closure institutional control.	www.numo.or.jp
Posiva Oy	Ari Ikonen	Posiva is responsible for the management of disposal of spent fuel produced in power reactors in Finland, including siting, licencing, construction and operation of the repository.	www.posiva.fi
Svensk Kärnbränslehantering AB (SKB)	Ulrik Kautsky	SKB is responsible for management of Swedish radioactive waste, planning of waste repositories, waste logistics and site selection, including safety analysis, research and development of methods.	www.skb.se

Since January 2005, the Project has been additionally managed and supported financially by:

Organisation	Representative	Role of organisation	Website
Electricité de France (EDF)	Carine Damois	EDF is been the main producer of electricity in France. The Laboratoire National Hydraulique et Environnement (LNHE) department works on migration of pollutants in the ground, waste management, water quality, soil contamination, ecotoxicology, ecology, microbiology, health risk assessment, but also fluvial and maritime hydraulics, resource management, industrial flows and combustion, meteorology and air quality.	www.edf.fr

Korea Atomic Energy Research Institute (KAERI)	Yong-Soo Hwang	Kaeri is developing the Korean reference concept for permanent disposal of high-level radioactive waste including spent nuclear fuel and assessing the long term post-closure safety and repository performance.	www.kaeri.re.kr
National Cooperative for the Disposal of Radioactive waste (Nagra)	Frits van Dorp	Nagra has more than 30 years experience in the development of disposal concepts for all categories of radioactive waste. Over the years, Nagra has built up extensive technical know-how and has applied this in site characterisation and performance assessment of deep geological repositories.	www.nagra.ch
Nuclear Research Institute Rez (NRI)	Ales Laciok	In the Czech Republic, NRI is the research, development and engineering organisation responsible for the development of nuclear power technologies, utilization of radionuclides and radiation in industry and medicine, and with a role to undertake fundamental research to support the long-term management and disposal of radioactive wastes.	www.nri.cz

The BIOPROTA output is made available for use of others, but the participants and supporting organisations take no responsibility for the use of the material.

General Objectives

Overall the intention is to make available the best sources of information to justify modelling assumptions. Particular emphasis is placed on key data required for the assessment of long-lived radionuclide migration and accumulation in the biosphere, and the associated radiological impact, following discharge to the environment or release from solid waste disposal facilities.

The project is driven by assessment needs identified from previous and on-going assessment projects. Where common needs are identified within different assessment projects in different countries, a common effort can be applied to finding solutions. Such solutions may readily take account of the BIOMASS Theme 1 Data Protocol, among other things.

The modelling assumptions considered include the treatment of various features, events and processes (FEPs) of the systems under investigation, the mathematical representation of those FEPs and the choice of parameter values to adopt within those mathematical representations.

The work programme has been organised in three themes:

Theme 1: Development of a Specialised Data-Base for Key Radionuclides and Process Data

Theme 2: Modelling Testing and Development Tasks

Theme 3: Site Characterisation, Experiments and Monitoring.

A full list of all the reports that have been produced under each theme is available from the BIOPROTA website (www.bioprota.com).

Objectives of the Inhalation Exposure Pathway Task

The objective of Task 2 within Theme 2 was to investigate the calculation of doses arising from inhalation of particles suspended from soils within which long-lived radionuclides, particularly alpha emitters, have accumulated.

This report includes model descriptions provided by participants and the specification and results of model test calculations designed to investigate the significance of the different model assumptions.

This report has been prepared within the BIOPROTA work programme. The supporting organisations have agreed that BIOPROTA reports will be printed by those organisations in their normal report series. In this case Nexia Solutions Ltd is supporting the printing of this Task report, to make it available for a wide audience. Nexia Solutions Ltd supports the work of BIOPROTA, but does not necessarily endorse the output. Any question concerning this report should be directed towards the contributors. The report can be obtained directly from Nexia Solutions Ltd; it is also available in pdf form at www.bioprota.com along with the other BIOPROTA reports.

Recommended Citation

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1. INTRODUCTION SCOPE AND OBJECTIVES

The objective of Task 2 within the Modelling Theme was to investigate the calculation of doses arising from inhalation of particles resuspended from soils within which long-lived radionuclides, particularly alpha emitters, represented by Pu-239, have accumulated.

The intention was that the comparison of assessment models for this potentially important exposure pathway would:

- improve confidence in the treatment of the relevant processes and data assumptions;
- identify the circumstances in which different processes are important, hence requiring different modelling treatment; and
- identify where important data may be lacking.

The scope of the task did not cover: inhalation of radon and radon daughters released from soils *etc.*, releases of other radioactive gases, or liquid aerosols generated from soils or water surfaces.

Section 2 contains the current model descriptions, site information and the mathematical model used by each participating organisation. Section 3 provides the assessment context for the BIOPROTA test calculation and Section 4 details the results of the test calculation obtained by the various participating organisations. Discussion of some of the key issues and uncertainties is provided in Section 5 and conclusions and suggestions for further work can be found in Section 6. References are provided in Section 7.

Appendix A gives the details of the model equations used.

Appendix B illustrates how the biosphere needs to be described in order to allow the assessment modelling to take place, based on suggestions in BIOMASS [2003].

Appendix C provides supplementary details on the NIREX model, supplied by Mike Thorne and Associates Limited.

Appendix D discusses additional issues considered by ANDRA relating to Cl-36 arising in air from aqueous environments as well as from soils.

2. MODEL DESCRIPTIONS

The assumptions made in structuring and implementing a model will greatly influence the results obtained. This section highlights the differences and similarities between the conceptual and mathematical models used by a number of organisations. The details provided within this section largely relate to models as they were originally created for the site-specific or generic situations addressed by the individual organisations, though there is also some reference to the BIOPROTA Test Calculation, described in Section 3, as a context for model application.

2.1 Conceptual Models

Site-specific conditions influence the choice of conceptual model and input parameter values. The following sub-sections provide details of the assumptions made by each organisation concerning the site modelled. Each subsection also gives a conceptual description of the processes involved that lead to the resuspension of contaminated material and that influence inhalation exposure.

2.1.1 ANDRA

Particulate resuspension from terrestrial surfaces is caused by wind erosion of soil, vehicle traffic on dusty roads, industrial and agricultural activities and combustion of biomass for fuel or land-clearance. The effects of these processes are poorly understood. Even the science of wind erosion, which has been studied extensively, does not permit prediction of the upwardly directed flux of soil particles resuspended by wind action. Thus, the conventional flux dispersion methodology must be abandoned and resuspension and subsequent deposition of dust or soil onto plants and soil surfaces is generally computed using a mass-loading approach. This approach treats all the particulate resuspension processes simultaneously.

The sources of contaminated terrestrial dust to the atmosphere include both soils and plants. Plant dust arises from pollen dispersal, harvesting and food processing, and combustion of biomass as fuel or originating from field clearance. In order to account for both soils and plants as possible sources of dust, the maximum concentration arising from either of the two is used.

No distinction is made between large and small particles; they are assumed to have the same general characteristics, including the same probability of becoming resuspended. Particles are taken to become resuspended into the breathable atmosphere above the soil and a simple resuspension factor is used to represent this process. No relation to wind speed, soil density, soil wetness or other environmental factors is used. No dependence on the chemical or physical form of the Pu-239 is taken into account, except that it is assumed that the plutonium remains in the same form as that for which the Kd in soil had been determined.

2.1.2 CIEMAT

The conventional CIEMAT model has been developed taking into account the BIOMASS ERB2A assessment context and parameter values [BIOMASS, 2003] and the BIOPROTA task specification. The top cultivated soil is contaminated by irrigation water and there is radionuclide loss to deeper layers. No loss by erosion is considered.

The inhalation dose is computed considering the concentration of the radionuclide in air above the top soil compartment. Top soil particles are resuspended into the breathable atmosphere due to ploughing and the wind. Inhalation is modelled simply, considering different occupancy and breathing rates, and different dust levels in air. A low dust level is applied for most of the year, a high dust level is associated with working and an average value is also used, taking account of occupancy factors and breathing rates appropriately.

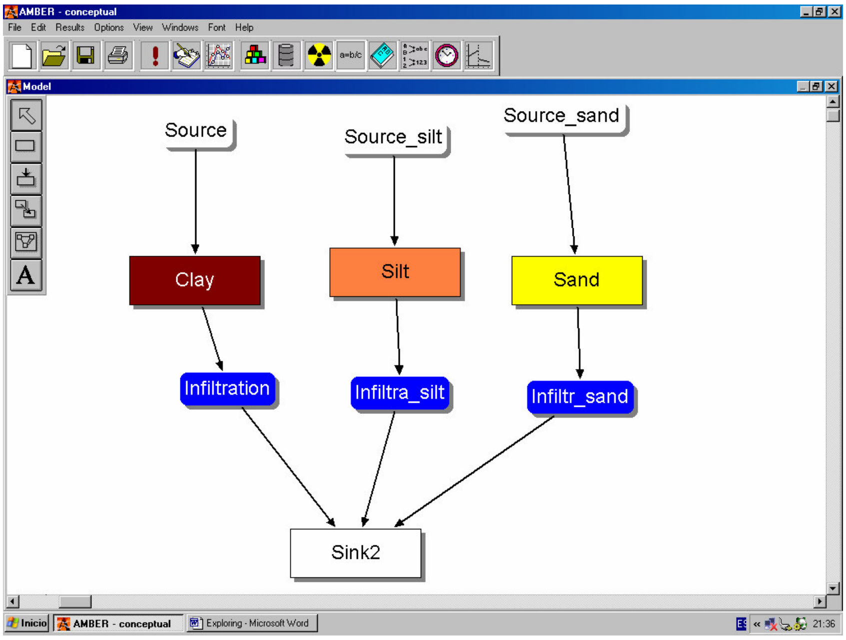
CIEMAT has also explored the effect of grain size distribution of soil particles on inhalation dose, by using a specific particle-size model (the particle size M model). Calculations were undertaken for a granitic rock. This was because a granitic site is one of the possible sites for development of a Spanish repository. The texture of soils developed on granitic rocks (including sienite, diorite and gabbro) is presented in Table 1, based on data in MMA [1996].

Table 1: Percentages of clay, silt and sand for soils developed over granitic rocks

	Grain size (µm)	Range (%)	Best estimate range (%)
Clay	< 2	0-40	5-33
Silt	2- 50	5-70	10-30
Sand	50-2000	30-40	60-85

The conceptual particle size M model implemented in the AMBER code is presented in Figure 2. AMBER is a flexible software tool that facilitates the modelling of the processes that takes account of the loss of activity from the soil via infiltration.

Figure 1: CIEMAT conceptual model



The model intercomparison was made with both the standard and the particle size M models. In the standard model, no distinction was made between particle sizes and the same Kd value was applied to all soil material, including that which was resuspended.

2.1.3 EPRI

The EPRI model is intended for application to Yucca Mountain, USA, where the climate is classified as a subtropical arid desert (ZB III in Walter [1984]). The soil type is well mixed, calcareous and gravely with fine sands to sandy loams. Groundwater is abstracted from a well and used for irrigation and is the source term for contamination. For modelling purposes, a unit area of 1 m^2 is taken to be contaminated.

The processes of how contamination in soil is partitioned into the breathable atmosphere are poorly understood. Concentrations of dust in the atmosphere can vary rapidly and the processes involved in the generation and maintenance are complex. Consequently, no explicit representations of atmospheric transfer processes are incorporated. Consideration has been given to the resuspension of soil particulates due to ploughing, walking, other outdoor activities, and to indoor exposures resulting from soil brought inside. However, no explicit account of how these processes lead to resuspension is provided and the dose calculations are based on empirical estimates of dust load in air. The occupancy for inhalation of dust is split into two components: one at low dust level (most of the year); and the other at a raised level associated with working/recreation on the contaminated soil. This second component is also associated with a higher breathing rate.

Contamination is assumed to enter the soil through the use of irrigation water applied continuously at a uniform rate for 1000 years. Precipitation could also affect the bulk water concentration; however any effects are considered small and would only serve to dilute the concentration in the bulk water. Thus, as a cautious approach precipitation effects were ignored in the model.

Evaporation of water during storage and distribution might give rise to a small increase in concentration of those radionuclides remaining in solution. However, total water losses via this route are considered unlikely to be significant in a temperate environment and the process is not included in the model.

Radionuclides can be lost from the surface soil compartment via infiltration into deeper soil, through crop harvesting, and by radioactive decay. These processes effectively result in loss of the contamination from the system as there is no return pathway modelled.

In calculating the dose to the critical group, where there was a choice of dose coefficients, the most pessimistic value was used.

2.1.4 Nirex

In the Nirex model, radionuclide concentrations in soil solids are computed as an average over the top 0.3 m. However, resuspension occurs only from a very thin surface layer. In practice, this is only an issue at the earliest times (~ 1 year) as arable agricultural soil subject to irrigation would normally be ploughed on a regular basis. Even if the concentration in the surface layer was enhanced by a factor of 100 in the first year, the concentration in resuspendable material would be no more than the concentration in bulk soil at 200 years. In view of these considerations, Pu-239 concentrations in air were computed using a mass loading approach and the calculated concentrations in bulk soil.

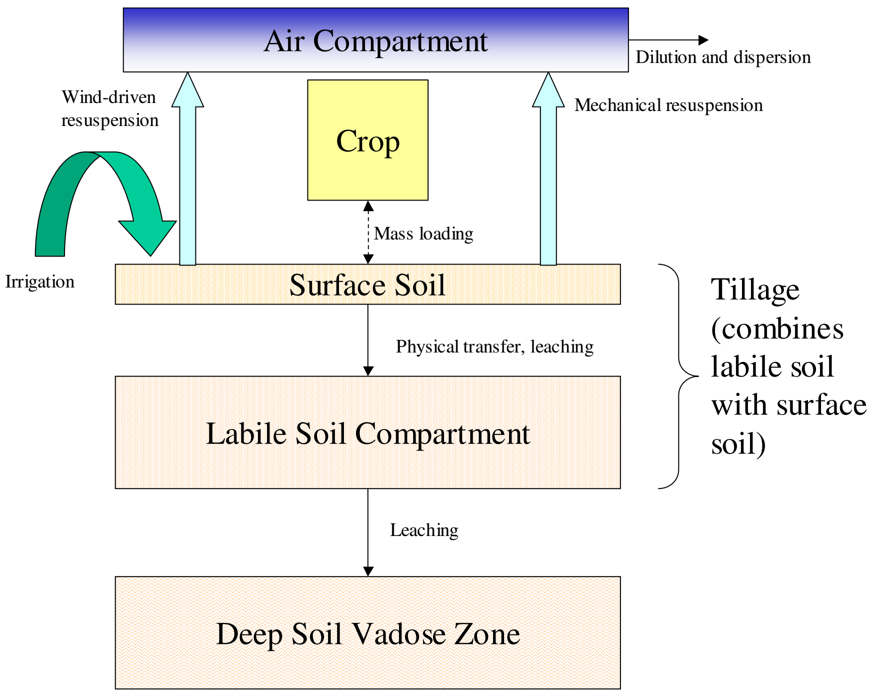
2.1.5 NUMO

Doses from inhalation were modelled in the H12 project [JNC, 2000], using a dose conversion factor, breathing rate, occupancy and dust concentration in air only. The radionuclide concentration in air is calculated using the retardation coefficient, soil porosity and grain density, the concentration in the soil compartment and the dust level in the air above the soil compartment. The radionuclide concentration in the atmosphere is assumed to reach equilibrium instantaneously with the concentration in surface soil [JNC, 2000]. Dust is assumed to enter the atmosphere as a result of farming practices (not including burning). Contamination in soil is as a result of irrigation and flooding. Infiltration takes place between the surface soil and subsoil, and erosion is also represented.

2.1.6 Risk Assessment Corporation

The model for transfer of plutonium in irrigation water to surface and labile soil compartments, and its subsequent resuspension via wind-driven and mechanical processes is illustrated in Figure 2.

Figure 2: Conceptual model for plutonium migration in soil and vegetation and subsequent resuspension and inhalation.



Plutonium accumulates in soil if irrigation with contaminated groundwater continues over many years. The radionuclide can be lost from the surface soil compartment by infiltration into deeper soil, through crop harvesting and by radioactive decay.

Plutonium attached to soil particulates enters the air as a result of wind-driven resuspension and mechanical disturbance of the soil. The magnitude of wind-driven resuspension depends on a number of factors including wind-speed, soil moisture content and vegetative cover. For fallow soils, the time since ploughing, soil moisture content and wind speed impact the amount of resuspension significantly in an arid temperate climate. The soils are more susceptible to wind-driven resuspension following ploughing in the spring and in the fall, when vegetative cover is minimal (before crop emergence and after harvest) and the soil-moisture content is low. Resuspension after crop emergence and during much of the growing season is minimal, because of vegetative cover and the higher soil moisture content that results from irrigation.

Plutonium is assumed to be present in the aqueous phase in the irrigation water. After reaching the soil, a fraction of the plutonium sorbs to soil particles with the remainder in aqueous solution. Aqueous-phase plutonium is subject to downward movement in infiltrating water. Partitioning between the aqueous and sorbed phases is described by the equilibrium partitioning coefficient or K_d. The amount of plutonium on soil particles is assumed to be proportional to the size of the resuspended soil particles.

The amount of plutonium inhaled is determined based on level of physical activity, age, gender and occupancy in the contaminated region. The plutonium inhalation dose coefficients (µGy/Bq) with uncertainties are taken from Grogan et al. [2000]. Plutonium is assumed to be plutonium oxide, and three particle size distributions (characterised by Activity Mean Aerodynamic Diameters (AMADs) of 1, 5 and 10 µm, each with a Geometric Standard Deviation (GSD) of 2.5) are considered.

2.1.7 STUDSVIK

Inhalation is modelled very simply and is based on an assumed mass loading in air. At present, Studsvik does not consider an enhanced concentration of elements in the small particles that may be present in air due to wind-driven resuspension or ploughing.

2.1.8 UKAEA

Soils and sediments can become resuspended in air by natural or mechanical disturbance, and then be inhaled. This pathway is only considered for man not animals, because animals ingest a large amount of soil directly. A simple model is applied to derive the concentration of contaminants in air, the dust-loading approach; a constant concentration of soil is assumed to be in suspension in air. The effective dose is calculated based on the occupancy and breathing rate of a person for each of the exposure materials considered.

The concentration of contamination in the resuspended soil is determined by the concentration in the soil compartment, which is determined by a number of processes, namely, interflow, infiltration, capillary rise and percolation. UKAEA also considers aerial transfers by erosion between the different soil compartments in the model. This process was not considered in the BIOPROTA test calculation; because it would have involved modelling many soil compartments, which would have been inconsistent with the specification of the case. Contamination was assumed to enter the soil as a result of application of irrigation water applied continuously for 1000 years.

2.1.9 Yucca Mountain Project (YMP)

Radionuclide concentrations in air resulting from soil resuspension are calculated in the YMP model as a product of radionuclide concentration in the soil, mass loading and an enhancement factor accounting for differences between the mass activity concentration in the surface soil and that of resuspended soil particles. The value of this enhancement factor is environment dependent (see the description of the environments below).

Radionuclide concentrations in surface soil are calculated in the model for the desired conditions of saturation. The source of radionuclides in the surface soil is contaminated irrigation water. Radionuclides can be removed from the surface soil by leaching into the deep soil, surface soil erosion, crop harvest removal and radioactive decay. Although crop harvesting is an important mechanism for radionuclide removal on cultivated lands, this mechanism was not considered in the biosphere model. This removal mechanism was omitted because it was considered to compensate for the possible reintroduction of radionuclides into the soil when contaminated cow manure was used as a fertilizer. The model also includes the build-up of decay products in the surface soil.

The mandated receptor for YMP is the reasonably maximally exposed individual (RMEI). With the exception of location and daily consumption of water, this receptor has to be based upon the characteristics of a population residing in the Amargosa Valley, a rural/farming community in the Yucca Mountain region.

Five environments associated with different human activities are considered in the model, four in the contaminated area: active outdoors ($n = 1$), inactive outdoors ($n = 2$), active indoors ($n = 3$), asleep indoors ($n = 4$), and one outside of the contaminated area ($n = 5$). These environments are associated with different levels of mass loading. Activity concentrations in the air outside the contaminated area are set to zero. These mutually exclusive environments represent behavioural and environmental combinations for which the receptor would receive a substantially different rate of exposure via inhalation or external exposure. For each of these environments, a specific value of the breathing rate is defined.

To account for variation and uncertainty in the amount of time the receptor would spend in environment n, four mutually exclusive population groups, m, are considered. These groups represented the range of behaviours that would most influence the amount of time that people were exposed to radionuclides via external exposure and inhalation. Variations between individuals for these exposure pathways are influenced primarily by the amount of time they spend indoors and outdoors within contaminated areas (and the amount of time they spend away from contaminated areas). For adults, variation amongst these time factors are primarily a function of occupational characteristics, as people working outside the contaminated area generally would experience less exposure than people who remained within the area, and people who work outdoors would be exposed at a different level than those who remain indoors. Therefore, the categories are based on work location and type of occupation.

Annual doses resulting from the inhalation of long-lived radionuclides include exposure to short-lived radionuclides in the decay chain. This is accomplished through the use of dose coefficients that include contributions from the short-lived decay products (half-life < 180 days), assumed to be in secular equilibrium with their parent radionuclides.

2.2 Mathematical Models

This section compares the mathematical models used by the different participants. Detailed mathematical descriptions of the models are provided in Appendix A.

2.2.1 Equations

Conceptually, the models used by the different organizations are similar; contaminated irrigation water accumulates in soil from where it is resuspended into the breathable atmosphere and inhaled. However the processes considered in representing accumulation in soil, resuspension and the calculation of the activity concentration in the atmosphere can be different. Accumulation of radionuclides in soil is also addressed in BIOPROTA Theme 2: Task 4 [BIOPROTA, 2005]; resuspension and the concentration of activity in the atmosphere are the main topics considered here. The mathematical representation of these processes can be different in the various models (inclusion/exclusion of processes, different parameter values). To explain the differences in the representation of these processes, equations used by each organisation are provided in Appendix A. Radionuclide concentrations in the surface soil are generally calculated with consideration of removal processes such as leaching and infiltration, although the mathematical expressions differ. Radionuclide concentrations in the atmosphere are calculated using either a mass-loading approach (based on the mass of airborne particulates per unit volume of air) or through the use of a resuspension factor. Some models included an enhancement factor to account for differences between the activity concentration in the surface soil and that of resuspended soil particles. The applicability of such a factor is discussed further in Section 5. Many models assume the concentration per unit mass of soil in the atmosphere is the same as that in top soil.

Receptor exposure is calculated by taking account of occupancy associated with the soil compartment and breathing rates. Occupancy in the soil compartment is usually described using a single parameter, but it may be partitioned into components to allow for different dust loads in air and breathing rates. For the YMP model, occupancy is described in terms of population groups and the environments these population groups are taken to occupy. Breathing rate is usually a single, annual-average. However it may be distinguished into components. If this is the case, a value is assigned to each component that depends upon the exercise/activity level of the receptor (asleep, normal activities, heavy exertion).

2.2.2 Processes

The processes affecting the radionuclide concentration in the soil compartment and the resuspension of contamination from the soil into the breathable atmosphere are listed in Table 2. Not all processes are considered by all organisations. The table also includes those processes that may influence inhalation exposure of the receptor.

Table 2: Processes Affecting Radionuclide Concentrations in Soil and in Resuspended Soil Particles, and Other Processes Affecting Inhalation Dose

Processes
Level of contamination in soil
Leaching
Radioactive decay
Soil erosion
Crop harvesting
Infiltration
Percolation
Capillary rise
Chemical retardation (in soil)
Chemical partition in solids
Level of contamination in air
Wind resuspension
Mechanical resuspension, e.g. ploughing
Enhancement factor of concentration of radionuclide in dust, compared with bulk soil
Seasonal factors (soil moisture content, vegetative cover)
Other processes affecting exposure of the receptor
Occupancy
Breathing rate
Respirability of soil particles

2.2.3 Parameters

Parameter values are detailed in Table 3 below. For element dependent parameters, Pu-239 is the radionuclide of interest. Risk Assessment Corporation parameter values have not been included since this model is still under development.

2.3 Key Model Differences

Various organisations use a typical mass loading in air of 1.0E-07 kg/m^3, though values ranging from 5.0E-09 to 5.0E-05 kg/m^3 have been used.

Some of the key model differences are the use of a resuspension factor (such as Studsvik and YMP) or a dust loading approach. Some models assume the activity concentration in the atmosphere is in equilibrium with that of the top soil and others do not. Dose coefficients from IAEA [1996] and ICRP [1996] are used. EPRI and NUMO use a retardation coefficient; other models assume equilibrium and reversible distribution coefficients and density and porosity assumptions to determine migration and accumulation in soil. Some organisations include several inputs to and losses from the soil compartment; others only represent those deemed to be the main contributors (typically irrigation and infiltration). In addition, some models only consider the top soil, whereas others consider two or more layers, e.g. the Nirex model, which distinguishes top soil and subsoil. Some models incorporate an enhancement factor for concentrations of radionuclides in resuspended material relative to concentrations in top soil, but other models neglect this effect.

Table 3: Parameters and their Values Used in Different Models

Parameter	ANDRA	CIEMAT (Conventional model	Ciemat (Particle Size M model)	EPRI	Nirex	NUMO	Studsvik	UKAEA	YMP
Grain density of soil (kg/m^3)	1.72E+03	2.65E+03	2.65E+03	2.65E+03	2.65E+03	2.65E+03 (or range 2.6E+03 - 2.7E+03)		2.65E+03	1.50E+03 kg/m^3 bulk density
Wet porosity of soil (unitless)		3.50E-01	3.50E-01	2.00E-01	3.50E-01	3.00E-01 (or range 6.00E-02 to 4.00E-01)		3.50E-01	2.30E-01
Total porosity of soil (unitless)	3.50E-01	3.50E-01 (top soil)	3.50E-01 (same value for all 3 compartments)	5.00E-01	3.50E-01	4.00E-01 or range 1.00E-01 – 7.00E-01		3.50E-01	
Precipitation and Irrigation			1.00E+00 m^3/y	2.00E-01 m^3/y	8.00E-01 m/ y			9.00E-01 m/y	
Evapotranspiration (m/y)					4.10E-01				
Baseflow losses from subsoil (m/y)				1.00E-01	3.90E-01			1.00E-01	
Percolation to substrate (m/y)			1.00E-01		6.40E-01				
Capillary Rise (m/y)					2.50E-01			1.08E-01	

Pu-239 sorption coefficient, of soil, K_d (m^3/kg)		5.40E-01	Clay: 3.40E-01 Silt: 1.40E-01 Sand: 6.0E-02 Total: 5.4E-01	5.40E-01 (dry wt)	5.40E-01	5.40E-01 (or range 1.00E-02 to 3.00E+02)		5.40E-01 (dry wt) (linear reversible sorption assumed)	Geometric mean = 1.20E+00
Concentration of dust in air above soil compartment (kg/m^3)		1.00E-07 normal activity, 5.00E-06 hard physical activity in dry conditions	1.00E-07 normal activity, 5.00E-06 hard physical activity in dry conditions	1.00E-07 normal activity, 5.00E-06 hard physical activity in dry conditions	1.00E-07 (agricultural and regional well)	2.00E-06 (or range 5.00E-09 to 5.00E-05)		1.00E-07 All scenarios	Environment-dependent ranging from 3.00E-08 for sleeping to 5.00E-06 for active outdoor
Occupancy rate	3.00E+00 h/d	4.00E+03 h/y normal activity, 4.50E+02 h/y hard physical activity in dry conditions	normal activity 4.00E+03 h/y hard physical activity in dry soil conditions 4.50E+02 h/y	Normal activity – 5.50E+03 h/y. hard physical activity – 6.10E+02 h/y	1.25E-02 fractional occupancy (couched in terms of typical total soil intake: 5.00E-04 kg/y)	8.00E+00 or range 2.00E+00 to 1.20E+01 h/d		0.00E+00 – 8.20E-01 (fractional occupancy of EM (varies according to land type, climate). 2.10E-01 used	Environment- and population group-specific
Breathing rate	1.20E+00 m^3/h	1.20E+00 m^3/h normal activity 1.70E+00 m^3/h hard physical activity in dry conditions	1.20E+00 m^3/h normal activity 1.70E+00 m^3/h hard physical activity in dry conditions	Normal activity – 1.20E+00 m^3/h. physical working in dry soil - 1.70E+00 m^3/h	6.5E+03 m^3/yr	1.80E+00 or range 1.20E+00 to 2.40E+00 m^3/h		Normal activity: 8.40E+03 m^3/y, 1.05E+04 m^3/y in work conditions	Environment – dependent, from 3.90E-01 m^3/h for sleeping to 1.57E+00 m^3/h for active outdoor
Inhalation dose coefficient for Pu-239 (Sv/Bq)		5.00E-05	5.00E-05	1.20E-04	5.00E-05	1.20E-04	age dependent	1.20E-04	1.16E-04

3. ASSESSMENT CONTEXT AND SYSTEM DESCRIPTION FOR MODEL TESTING CALCULATIONS

The inhalation test calculation used for the BIOPROTA modelling comparison task is based on BIOMASS [2003] Theme 1 Example Reference Biosphere 2A (see Table 4 and in more detail Appendix B), but with some modifications; see Table 5 for the specific changes and parameter values.

In practice, for a ‘real’ assessment, the principal consideration in justifying a particular choice of assessment approach and/or model is fitness for purpose. Hence, the overall assessment purpose is necessarily the main point of reference for developing a biosphere system description and assessment model. Other aspects of the assessment context (whether imposed or assumed) subsequently come into play by serving to circumscribe the scope of the assessment and the model development process [BIOMASS, 2003].

However, the requirements of the present exercise demand that the different examples studied in Theme 2 should be designed to focus attention on different assessment issues that are of particular practical interest. Consequently, the secondary, ‘constraining’ components are different for each of the examples studied.

Table 4: BIOMASS Assessment Context for ERB2A

Assessment Endpoint:	Annual individual effective dose.
Assessment Philosophy:	‘Equitable’ except with respect the critical group definition, which should invoke a ‘cautious’ approach.
Repository Type:	Deep repository for long-lived solid radioactive waste.
Site Context:	Generic inland repository, with aquifer at accessible depth. No biosphere change.
Geosphere/Biosphere Interface:	Well intruding into a plume within an aquifer, with abstraction at a rate consistent with domestic and agricultural use. Concentrations of radionuclides in the abstracted water (including relevant short-lived daughters) are provided by geosphere transport models.
Source Term:	Constant unit concentration maintained indefinitely for each radionuclide. Originally applied to Nb-94, Tc-99, I-129 and Np-237. These were chosen for consideration because they are representative of a range of physical and chemical behaviours and because of their importance in previous assessments. However, Pu-239 is addressed in this study.
Societal Assumptions:	Agricultural community, adopting modern practices (machinery and methods) for cultivation and animal husbandry. The resources available to the community are such that it is capable of producing locally a high proportion of the total diet of most foodstuffs.
Time Frame:	Up to 1 million years.

Table 5: BIOPROTA Inhalation Pathway Assessment Context

Assessment Endpoint:	Dose to the critical group from the specified source term.
Assessment Philosophy:	The same as ERB2A above.
Repository Type:	The same as ERB2A above.
Site Context:	Irrigation of agricultural land in Central Europe. No biosphere change.
Source Term:	1 $Bq/m^2/y$ of Pu-239 applied continuously to soil as a result of irrigation for 1000 years.
Exposure pathway:	The only exposure pathway considered will be inhalation of activity as a result of resuspended soil.
Geosphere/Biosphere Interface:	Of no importance to this calculation.
Societal Assumptions:	Agricultural community, adopting modern practices (machinery and methods) for cultivation and animal husbandry.
Time Frame:	Up to one thousand years.
Other factors (with values from Table 3) that are prescribed within this test calculation are:	
Top soil Depth:	0.3 m
Soil Porosity (Total):	0.35
Soil Porosity (Wet):	0.35
Grain Density:	2650 kg/m^3
Kd:	0.54 m^3/kg

The calculation comprises of four stages:

- Determination of Pu-239 concentration in soil
- Determination of Pu-239 concentration in air
- Determination of the activity of Pu-239 inhaled per year
- Determination of the committed effective dose due to inhalation of resuspended soil particulate.

Results were required after 1, 2, 5, 10, 20, 50, 100, 200, 500 and 1,000 years of irrigation.

The term critical group has been used to refer to the recipients of the dose for the BIOPROTA test calculations. The critical group is identified as the most exposed group out of a number of exposure groups considered in dose assessments associated with particular nuclear facilities.

The committed effective dose due to inhalation (referred to as inhalation dose) was provided by all participating organisations and results are given in Section 4. Pu-239 concentrations in soil and air and Pu-239 intakes, though calculated by all participants, are mentioned in varying degrees of detail.

4. RESULTS AND COMPARISON

4.1 Results for each modelling group

Seven organisations participated in the model inter-comparison exercise comprising ANDRA, CEIMAT, EPRI, Nirex, Numo, UKAEA and YMP. Results from each organisation are provided below at varying levels of detail.

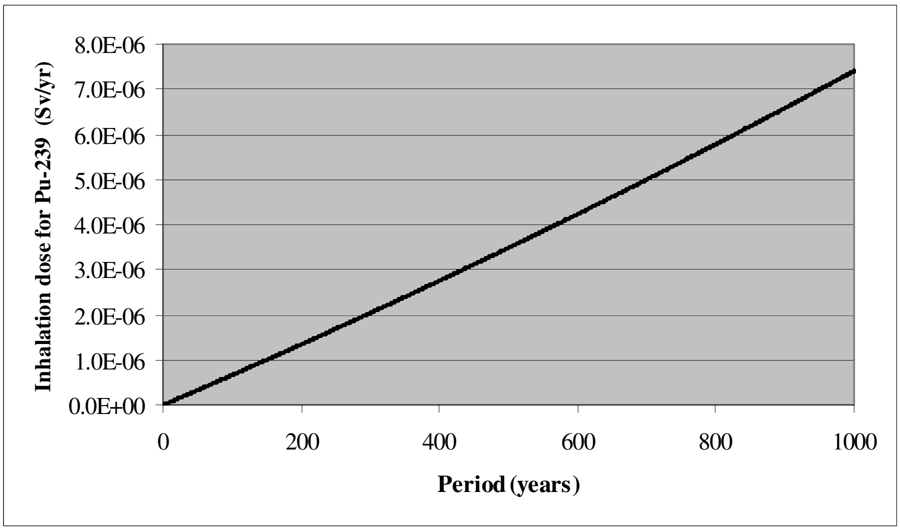
4.1.1 ANDRA

The ANDRA estimates of annual effective dose to the critical group via the inhalation pathway at the specified times are detailed in Table 6 and are also shown in Figure 3. The annual effective dose increases approximately linearly in time to 7.40E-06 Sv at the end of the continuous 1000 year irrigation period. The linear behaviour is due to the fact that the particle resuspension model employed by ANDRA (Appendix A) does not allow for Pu-239 depletion processes from the soil. Also, over 1000 years, radioactive decay of Pu-239 (half-life of 2.41E+04 y) is insignificant.

Table 6: ANDRA - Activity Concentration in the Soil and Inhalation Dose

Time (Years of Continuous Irrigation)	Activity concentration in the soil (Bq/kg dry weight)	Annual Inhalation dose (Sv)
1	1.94E-03	6.57E-09
2	3.87E-03	1.31E-08
5	9.68E-03	3.29E-08
10	1.94E-02	6.58E-08
20	3.88E-02	1.32E-07
50	9.73E-02	3.30E-07
100	1.96E-01	6.65E-07
200	3.96E-01	1.35E-06
500	1.03E+00	3.49E-06
1000	2.18E+00	7.40E-06

Figure 3: ANDRA - Annual Inhalation Dose



4.1.2 CIEMAT

The CIEMAT estimates of annual effective dose to the critical group at the specified times are given in Table 7. CIEMAT considered four variants based on combinations of different particle sizes, and different dust concentrations or loadings based on work activities (Appendix A). CIEMAT employ a dynamic compartment modelling approach to estimate soil concentrations.

Table 7: CIEMAT - Inhalation Dose for Normal and High Dust Concentrations

	Conventional Model		Particle Size M Model (considering inhalation of 17 % clay and 1 % silt)	
Time (Years of Continuous Irrigation)	Annual Effective Dose for Normal Dust Concentrations (Sv)	Annual Effective Dose for High Dust Concentrations (Sv)	Annual Effective Dose for Normal Dust Concentrations (Sv)	Annual Effective Dose for High Dust Concentrations (Sv)
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1	4.64E-11	3.69E-10	9.17E-11	7.31E-10
2	9.28E-11	7.39E-10	1.83E-10	1.46E-09
5	2.31E-10	1.84E-09	4.58E-10	3.65E-09
10	4.63E-10	3.69E-09	9.16E-10	7.30E-09
20	9.24E-10	7.37E-09	1.82E-09	1.46E-08
50	2.29E-09	1.83E-08	4.54E-09	3.62E-08
100	4.55E-09	3.62E-08	9.00E-09	7.17E-08
200	8.93E-09	7.12E-08	1.76E-08	1.41E-07
500	2.11E-08	1.68E-07	4.17E-08	3.33E-07
1000	3.84E-08	3.06E-07	7.61E-08	6.07E-07

Figures 4 and 5 provide soil and air concentrations, respectively. Figure 4 shows how the resuspendable particulate concentrates the Pu-239 more than the bulk soil, by about an order of magnitude. Figure 5 shows that there are large differences in Pu-239 concentrations in air associated with the two types of particles considered. The particle size M classification has a higher proportion of finer clay and silt than the standard soil type and, in consequence, gives rise to higher concentrations of Pu-239 in air.

Figure 4: CIEMAT - Soil concentration, dry weight, for individual particles and total soil

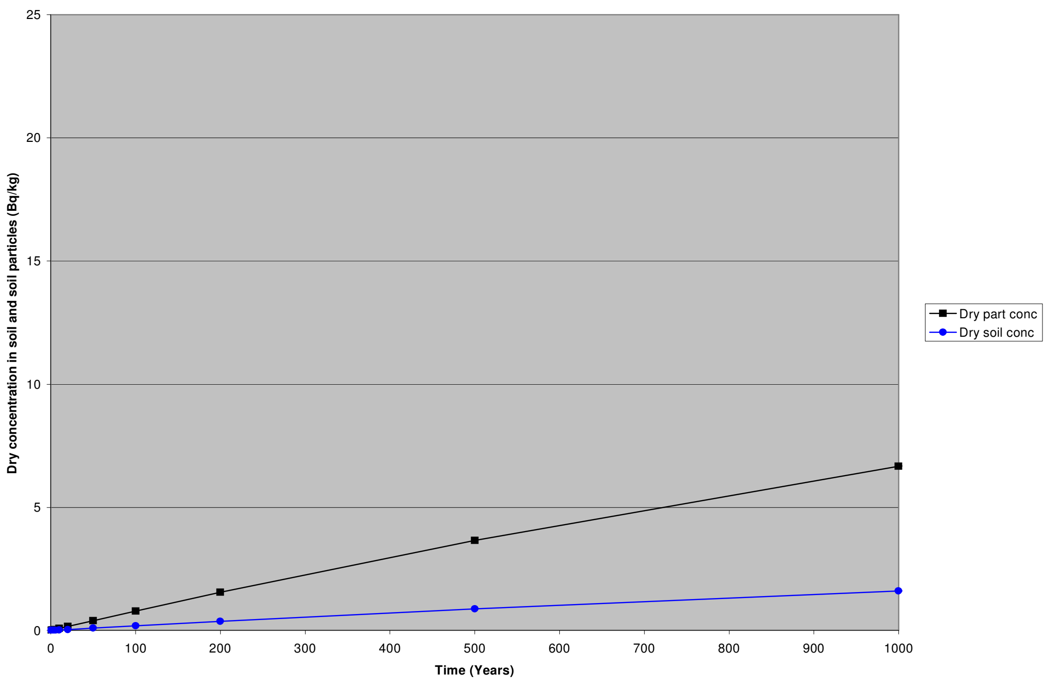
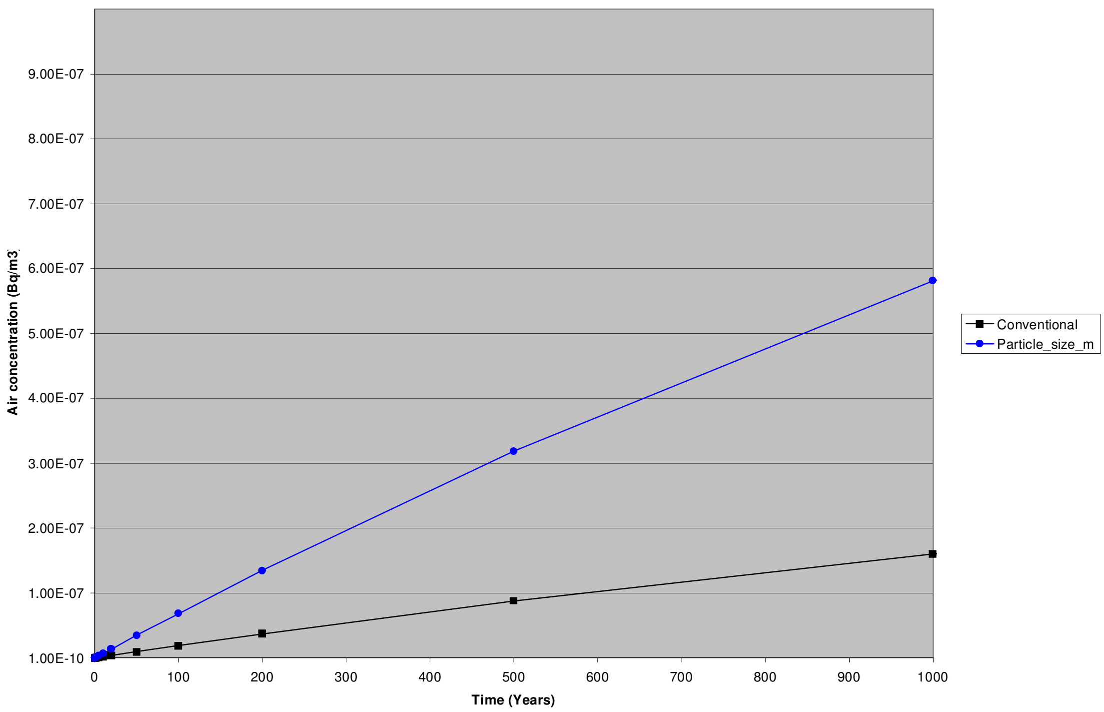


Figure 5: CIEMAT - Air concentration for the two particulate models.



Figures 6a and 6b show annual effective doses for two work-related scenarios relating to hard manual work (high physical activity) and normal work, respectively (Appendix A). Results are given out to 10,000 y. CIEMAT considered continued irrigation throughout this extended period and indications of approach towards a state of equilibrium are seen toward the end of the period. Annual effective doses for the hard work scenario are around a factor of eight higher than for the normal work scenario, irrespective of particle size. The various graphs have similar shapes, reflecting similar timescales for build up to equilibrium concentrations in soil.

Figure 6a: CIEMAT - Dose results calculated until 10,000 years for hard physical work scenario

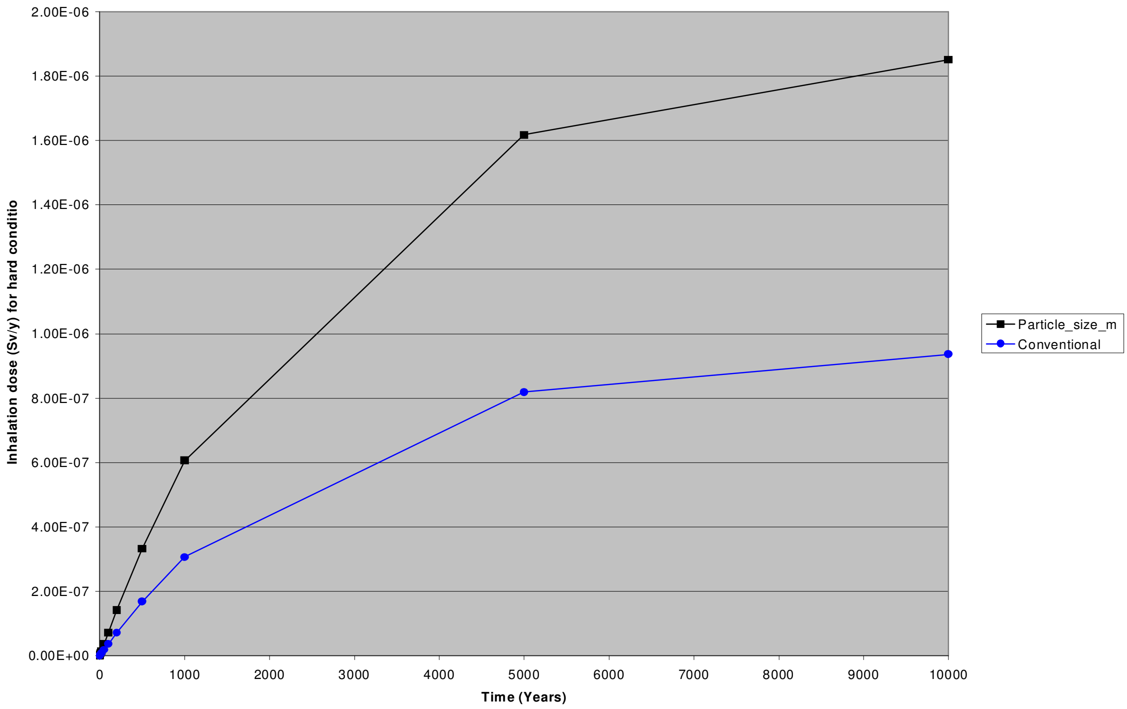
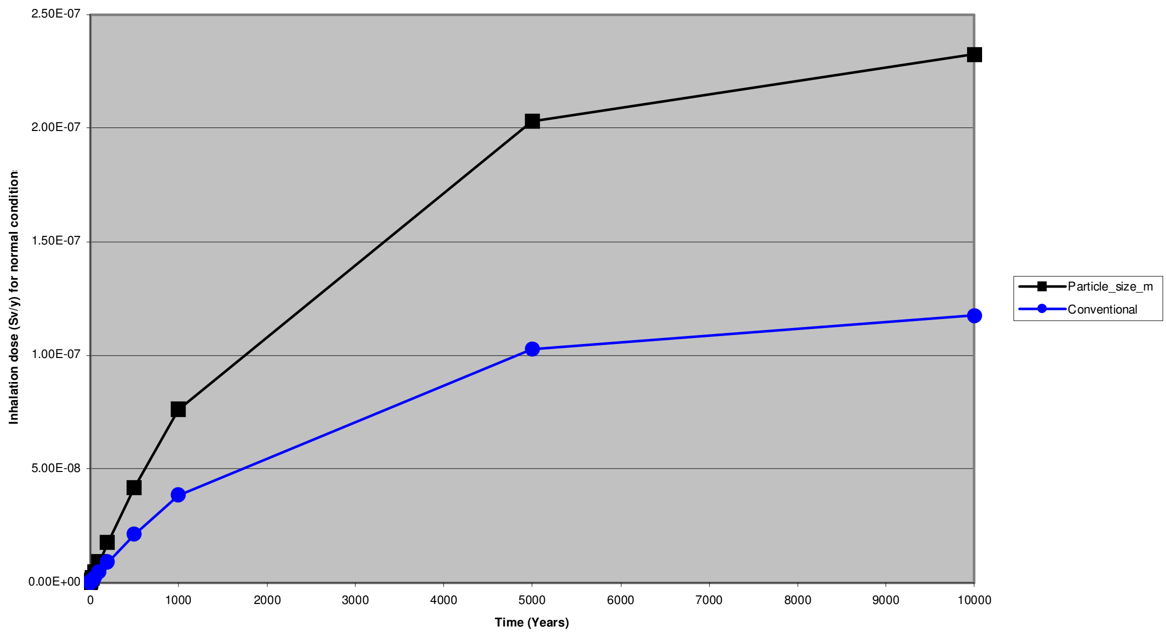


Figure 6b: CIEMAT - Dose results calculated until 10,000 years for normal work scenario



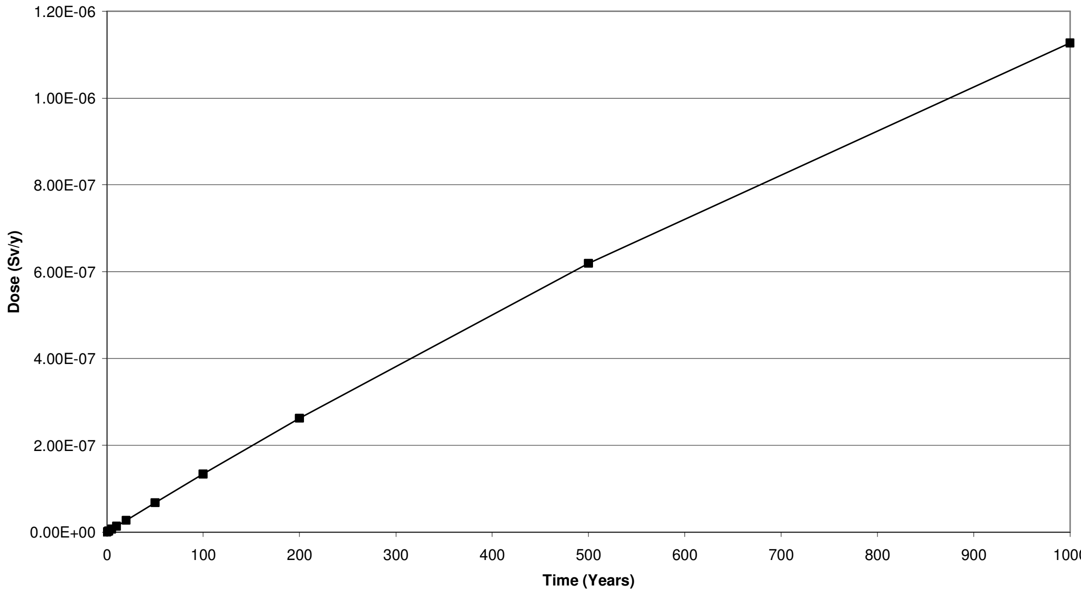
4.1.3 EPRI

Table 8 and Figure 7 present the modelled doses to the critical group. In-growth of Pu-239 decay products has not been considered, as this would not be significant on the time-frame considered here. The annual effective dose received by the critical group increases almost linearly with time. This is as a result of accumulation in the soil with very limited losses over this period.

Table 8: EPRI - Pu-239 Inhalation Dose

Time (Years of Continuous Irrigation)	Annual Effective Dose (Sv)
1	1.36E-09
2	2.73E-09
5	6.82E-09
10	1.36E-08
20	2.72E-08
50	6.76E-08
100	1.34E-07
200	2.62E-07
500	6.19E-07
1000	1.13E-06

Figure 7: EPRI - Inhalation Dose



4.1.4 Nirex

The amount of activity inhaled per year is directly proportional to the integral over a year of the product of the activity concentration in air and the breathing rate. Agricultural workers could be present in irrigated fields for a large part of the working year. Therefore, a reasonable but cautious occupancy is 2000 hours with a respiration rate for light activity of 1.2 m^3/h. With a mass loading of 1.0E-07 kg/m^3, this gives an annual inhalation of soil of 2.4E-04 kg. Alternatively, measured mass loadings behind a tractor [NCRP, 1999] had a median of 1.5E-5 kg/m^3 and a range of from 3.0E-07 to 2.0E-04 kg/m^3, so only ten hours ploughing could give an intake of 1.8E-04 kg (range 3.6E-06 to 2.4E-03).

In addition, it should be recognized that contaminated soil can be transported home on shoes and clothing. When this soil has dried, it may become resuspended indoors. In this case, a mass loading of no more than 1.0E-07 kg/m^3 seems reasonable. However, this should be combined with a total air volume inhaled of about 6500 m^3/y for an adult. This gives a total annual soil inhalation of 6.5E-04 kg.

These various lines of argument indicate that the total soil intake by inhalation can reasonably be set at about 5.0E-04 kg for an adult, but that values up to an order of magnitude larger are possible. As results of the calculations are directly proportional to the total annual soil intake by inhalation, a single reference value of 5.0E-04 kg is adopted here.

Annual intakes of Pu-239 at the times of interest were derived using the calculated activity concentrations in soil. Results are presented in Table 9. These values are applicable to adults. Except for translocation of activity to domestic premises, as discussed above, adults are the age group that are likely to be most exposed.

Table 9: Nirex - Adult Annual Intake of Pu-239

Time (y)	Annual intake (Bq) by an adult inhaling 5.0E-04 kg of contaminated soil
1	9.66E-07
2	1.93E-06
5	4.81E-06
10	9.56E-06
20	1.89E-05
50	4.57E-05
100	8.64E-05
200	1.55E-04
500	2.90E-04
1000	3.92E-04

As the annual intakes are estimated for adults, it is also appropriate to use Committed Effective Dose per unit intake values for adults. Standard practice is to use the values given in ICRP Publication 72 [ICRP, 1996]. For Pu-239, the values listed in Table A.2 of that publication are 1.2E-04, 5.0E-05 and 1.6E-05 Sv/Bq for Class F, M and S compounds, respectively. A cautious but prudent assignment of Pu-239 is to Class M. Thus, the reference value adopted herein is 5.0E-05 Sv/Bq. Results based on this value are presented in Table 10.

Table 10: Nirex - Inhalation Dose

Time (y)	Annual Committed Effective Dose (Sv) to an adult inhaling 5.0E-04 kg/y of contaminated soil
1	4.83E-11
2	9.65E-11
5	2.40E-10
10	4.78E-10
20	9.45E-10
50	2.28E-09
100	4.32E-09
200	7.75E-09
500	1.45E-08
1000	1.96E-08

It should be recalled that the value in the first few years may be underestimated by as much as a factor of 100 because the plutonium will not have been redistributed in the soil by ploughing. In all years, values up to one order of magnitude larger than the calculated value are possible because of different assumptions on dust loading in air. There is also the possibility of an enhanced concentration of plutonium in the resuspended dust relative to bulk soil. This has not been taken into account. Effects of alternative hydrological assumptions are small compared with the above uncertainties. Overall, the following reference and cautious estimates of doses are obtained (Table 11), assuming ploughing after the first year of irrigation.

Table 11: Nirex Annual Inhalation Dose

Time (y)	Annual Committed Effective Dose (Sv)	
	Reference	Cautious Estimate
1	4.83E-11	4.83E-08
2	9.65E-11	9.65E-10
5	2.40E-10	2.40E-09
10	4.78E-10	4.78E-09
20	9.45E-10	9.45E-09
50	2.28E-09	2.28E-08
100	4.32E-09	4.32E-08
200	7.75E-09	7.75E-08
500	1.45E-08	1.45E-07
1000	1.96E-08	1.96E-07

4.1.5 NUMO

Results in Table 12 show the contributions to dose made up from the different work related activities throughout the year. Results from the H12 assessment are also shown for comparison [JNC, 2000] and are quite similar to the combined results from the BIOPROTA test calculations. NUMO employs a dynamic compartment modelling approach to represent irrigation and the loss of Pu-239 from the soil through processes such as infiltration. However, the approximately linear increase in annual effective doses from 100 years to 1000 years demonstrates the limited significance of these loss processes over a period of irrigation of 1000 years.

Table 12: NUMO – Annual Effective Inhalation Dose

Time [y]	H12 [JNC,2000] (Sv)	BIOPROTA Scenario, normal activity (Sv)	BIOPROTA Scenario, physical work (Sv)	BIOPROTA Scenario, total (Sv)
0	0.0E+00	0.0E+00	0.0E+00	0.0E+00
100	5.7E-09	5.8E-10	4.6E-09	5.2E-09
200	1.1E-08	1.1E-09	9.1E-09	1.0E-08
300	1.6E-08	1.7E-09	1.3E-08	1.5E-08
400	2.1E-08	2.2E-09	1.8E-08	2.0E-08
500	2.6E-08	2.7E-09	2.2E-08	2.4E-08
600	3.1E-08	3.2E-09	2.5E-08	2.9E-08
700	3.6E-08	3.6E-09	2.9E-08	3.3E-08
800	4.0E-08	4.1E-09	3.3E-08	3.7E-08
900	4.4E-08	4.5E-09	3.6E-08	4.1E-08
1000	4.8E-08	4.9E-09	3.9E-08	4.4E-08

4.1.6 UKAEA

Results for annual effective dose at the specified times are provided in Table 13, using a modelling approach that allows for irrigation, and a range of processes including interflow, infiltration, capillary rise, percolation and erosion between soil compartments. The inhalation dose results in Table 13 appear to be quite linear in time up to around 50 years, after which there is some decrease in the rate of accumulation. Nevertheless, in common with the other models, losses from soil are only of very limited significance out to 1000 years.

Table 13: UKAEA - Inhalation dose

Time (years)	Annual Effective Dose (Sv)
0	0.00E+00
1	5.88E-11
2	1.17E-10
5	2.93E-10
10	5.84E-10
20	1.16E-09
50	2.83E-09
100	5.46E-09
200	1.02E-08
500	2.07E-08
1000	3.08E-08

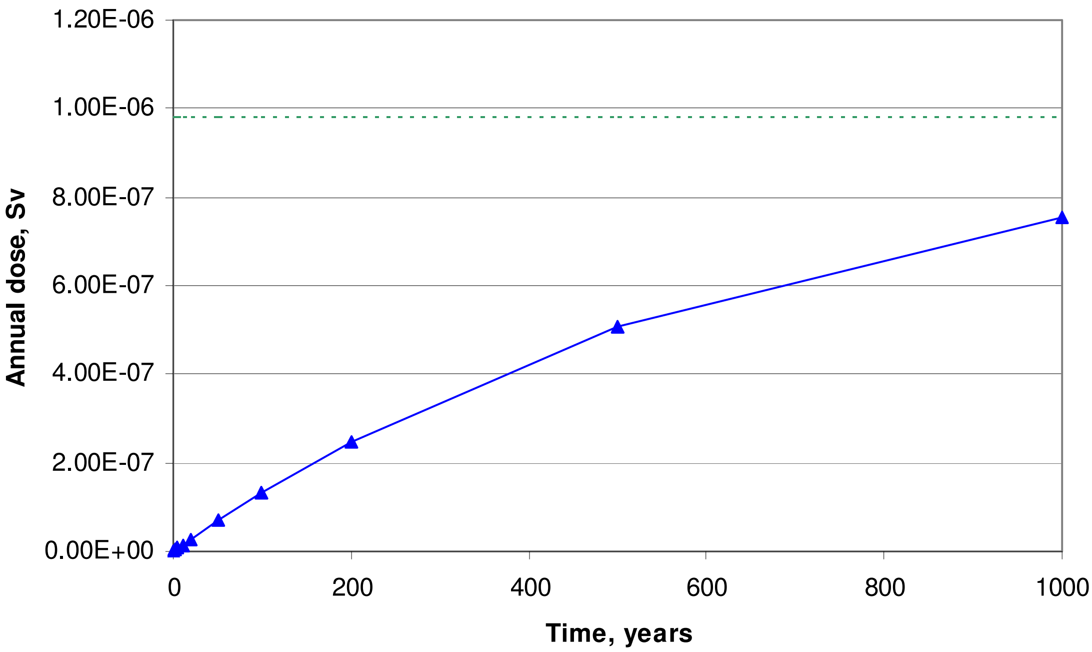
4.1.7 YMP

The activity concentration of Pu-239 in soil and the annual effective dose to the receptor arising from inhalation of resuspended soil particles are presented in Table 14. The YMP used a dynamic modelling approach to model the irrigation input and loss processes from the soil. The annual effective dose as a function of time is shown in Figure 8, which also shows the annual effective dose that would be realised if irrigation was protracted indefinitely.

Table 14: YMP - Activity Concentration in Surface Soil and Inhalation Dose

Time(Years)	Concentration in Surface Soil (Bq/kg)	Annual Effective Dose (Sv)
1	2.22E-03	1.42E-09
2	4.44E-03	2.84E-09
5	1.11E-02	7.08E-09
10	2.21E-02	1.41E-08
20	4.38E-02	2.80E-08
50	1.07E-01	6.86E-08
100	2.07E-01	1.32E-07
200	3.86E-01	2.47E-07
500	7.92E-01	5.07E-07
1000	1.18E+00	7.53E-07
∞	1.54E+00	9.86E-07

Figure 8: YMP - Inhalation dose



4.2 Comparison

A comparison of inhalation doses obtained by the different participating organisations is presented Table 15, where it can be observed that CIEMAT, Nirex, NUMO and UKAEA estimated comparable doses that are smaller than those from ANDRA, EPRI and YMP. This situation arises from the different combinations of assumptions concerning processes such as radionuclide enhancement in the resuspended dust, dust loading in air, breathing rate, occupancy and inhalation dose factor.

Basing a comparison of annual effective dose results at 1000 y, ANDRA calculated the highest annual effective dose of 7.40E-06 Sv. This was partly because they used a simple linear model to accumulate Pu-239 in the soil from irrigation. Their model does not appear to allow for removal processes such as leaching. Over the 1000 y timescale, radioactive decay of Pu-239 is insignificant as a removal process.

From Table 15 in descending order, EPRI produced the second largest annual effective dose of 1.13E-06 Sv. Although they used a soil compartment approach, there is no evidence of significant depletion of the accumulating soil inventory over the irrigation period.

The YMP's approach involved the use of the ERMYN biosphere model which when modelling soil irrigation allows for losses through leaching and erosion as well as radioactive decay. Examining the parameters in Table 3, the YMP uses a larger geometric mean K_d value of 1.2, as opposed to 0.54 m^3/kg, which could explain why they obtain the third highest inhalation dose with more Pu-239 adsorbing to the soil. However, as losses from soil are generally insignificant with a K_d value of 0.54 m^3/kg, this is not thought to be a very important consideration. The YMP also used an enhancement factor in deriving radionuclide concentrations in air from soil concentrations. As this is effectively a linear scaling factor, it is considered much more important than the increased K_d in enhancing the inhalation dose.

In comparison to the YMP annual effective doses, the results from the other organisations are more than an order of magnitude lower at around (2.0 – 5.0)E-08 Sv at 1000 y. These organisations deploy compartmental modelling approaches in which they allow for various loss processes from the soil. However, as the annual effective doses increase approximately linearly or only slightly sub-linearly with time over the 1000 year irrigation period, loss processes from soil are not a major determinant of the relative magnitude of the various model results at 1000 years.

For NUMO, the annual effective dose of 4.8E-08 Sv reflects a combination of normal and physically strenuous work practices. For CIEMAT, the value of 3.84E-08 Sv reflects a surface soil compartment model that distinguishes between three grain sizes. This value is the lowest inhalation dose value from their four scenario variants and represents normal sized particles and normal working conditions. For M particles and hard manual working conditions, their largest value of 6.07E-07 Sv is comparable with the YMP value at 1000 y in Table 15.

UKAEA and Nirex produced the lowest annual effective dose values of 3.08E-08 and 1.96E-08 Sv, respectively, at 1000 y. However, Nirex commented that their annual effective dose would be one order of magnitude larger in a more cautious calculation. Besides irrigation, the UKAEA modelling approach allows for a range of processes involving surface and sub-surface compartments that includes interflow, infiltration, capillary rise, percolation and erosion between soil compartments. With the exception of erosion, the Nirex model has all of these attributes in a water-balance approach. The use of lower breathing rates and inhalation dose coefficients (Table 3) are contributing factors as to why the Nirex model inhalation doses are lower than the UKAEA doses.

Some further observations made during model comparison are that:

- Ploughing and wind erosion are the primary factors that result in resuspension of dust from top soil - the process of ploughing is not modelled explicitly and is effectively considered by having 0.3 m deep soil compartments that are taken to be uniformly mixed in compartmental modelling;

- Most participating models used a dust-loading approach, only ANDRA used a resuspension factor approach;

- Activity concentrations in the air are substantially higher when the soil is being mechanically disturbed;

- The breathing rate used by most participants was 1.2 m^3/h for normal activity, however this value can vary depending on the activity level and the environment;

- Neither the soil density nor soil porosity appear to vary significantly and results are not highly sensitive to these parameters;

- The depth of soil and when ploughing takes place in relation to the irrigation event is important, but only at early times in the scenario; the longer term quasi-equilibrium reached is not very sensitive to the ploughing assumptions; and,

- Soil structure, including cohesiveness, as determined by climate, water content, grain density, soil type *etc.* is important since it affects the resuspendability of contaminants.

Table 15: Comparison of annual effective doses (Sv)

Time (Years)	ANDRA	CIEMAT (Conventional model and normal dust loading)	EPRI	Nirex / MTA	NUMO	UKAEA	YMP
1	6.57E-09	4.64E-11	1.36E-09	4.83E-11		5.88E-11	1.42E-09
2	1.31E-08	9.28E-11	2.73E-09	9.65E-11		1.17E-10	2.84E-09
5	3.29E-08	2.31E-10	6.82E-09	2.40E-10		2.93E-10	7.08E-09
10	6.58E-08	4.63E-10	1.36E-08	4.78E-10		5.84E-10	1.41E-08
20	1.32E-07	9.24E-10	2.72E-08	9.45E-10		1.16E-09	2.80E-08
50	3.30E-07	2.29E-09	6.76E-08	2.28E-09		2.83E-09	6.86E-08
100	6.65E-07	4.55E-09	1.34E-07	4.32E-09	5.2E-09	5.46E-09	1.32E-07
200	1.35E-06	8.93E-09	2.62E-07	7.75E-09	1.0E-08	1.02E-08	2.47E-07
500	3.49E-06	2.11E-08	6.19E-07	1.45E-08	2.4E-08	2.07E-08	5.07E-07
1000	7.40E-06	3.84E-08	1.13E-06	1.96E-08	4.4E-08	3.08E-08	7.53E-07

4.3 Model Limitations

Most participants model the inhalation pathway in a very similar way, using an assumed dust loading in air above the soil compartment that arises from contaminated soil resuspension caused by, for example, wind or mechanical processes, such as ploughing. A member of the critical group breathes in this contaminated dust thereby receiving an intake and hence a radiation dose. The degree to which each participating organisation justifies particular assumptions or correlates resuspension mechanisms with occupancy and dust loading varies.

A number of potential sensitivities were also identified, such as whether the concentration of contaminants in dust derived from soil is identical to the concentration in the bulk soil. Various arguments suggest that this assumption may not be cautious because:

- airborne dust is more likely to be composed of smaller than average soil particles whose specific surface area (and hence specific sorption capacity) is likely to be greater than the bulk soil average; and,

- smaller particles are likely to remain resuspended for longer, travel further, and once inhaled are more likely to penetrate into the deep lung.

Most models are not sensitive to the amount of activity attached to small particles, although this is important for the YMP who have incorporated an enhancement factor in their approach.

Other issues relating to the test calculation are:

- whether the soil thickness modelled was appropriate or justifiable (30 cm corresponds to the likely ploughing depth, thereby suggesting a reasonable homogeneous compartment). Clearly such an approach would not be appropriate for a short-term input into the soil compartment, but for a long-term continual release this simplification seems appropriate;

- redox-sensitive elements (e.g. Tc) could accumulate in sub-surface horizons, if reduced to less soluble forms - under such circumstances, bioturbation or erosion might lead to enhanced loadings in dust at some stage in the future;

- the difficulties of modelling erosion versus deposition, and the net effect over long periods, bearing in mind that the higher doses are assessed to arise only after a considerable accumulation period; and,

- explicit consideration of the effects of wind speed and lateral transport by wind, though this might be avoided on the basis that resuspension doses are dominated by the contribution by other physical disturbances, such as ploughing.

5. DISCUSSION

Resuspension of Particles

From past assessments, inhalation of dust can be an important pathway for exposure to actinides such as uranium, neptunium and plutonium. To a large degree this arises because these actinides are highly excluded from biota, so foodchain pathways are of little significance. Also, they are only taken up from the gastrointestinal tract to a very limited degree, so limiting the significance of ingestion in drinking water. The other consideration, well illustrated by the results reported here, is that these actinides, notably plutonium, are highly adsorbed to particulate matter in soil. This means that, for chronic uniform inputs, soil concentrations increase almost linearly with time over very long timescales (hundreds to thousands of years). Thus, the duration of persistence of the practice giving rise to the contamination is likely to be a more important consideration than the exact way that retention in the soil is modelled.

Adsorption to particles affects retention in soil, as noted above. However, in the present context, an equally important consideration is the variation of adsorption with particle size (see Sheppard [1995] and Arimoto et al. [2002]). Small particles have a higher surface to volume ratio than large particles. Indeed, this ratio increases in inverse proportion to the linear dimensions of the particle. Particle-reactive contaminants, such as environmentally dispersed plutonium, can, therefore, be preferentially associated with small particles [Arimoto et al., 2002] Thus, preferential resuspension of small particles will give an enhanced concentration of radionuclides in solids in air relative to bulk soil. Rautenstrauch et al. [2003] give a range of enhancement factors of from 2.2 to 6.5. Enhancement factors have been used in Contaminated Land Exposure Assessments [CLEA, 2002]. Values adopted were 6 for sandy soil, 3 for loam, 1.5 for clay soil and 1.0 for organic soil. On the basis of these values, the enhancement factor is significant, but does not dominate over other uncertainties, such as the choice of mass-loading and occupancy factors.

Resuspension Processes

Resuspension of contaminated dust is likely to occur due to the action of wind, disturbance by animals or disturbance by man. The last is especially relevant because it implies the presence of an individual who can inhale the dust. In all cases, resuspension is likely to be greater from dry surfaces than from wet surfaces, and is likely to be enhanced where vegetation cover is sparse or non-existent.

Although not addressed in this comparison study, combustion of contaminated biomass may also give rise to significant activity levels in air in some circumstances [Grebenkov et al., 1998; Levesque et al., 2001]. In particular, combustion of contaminated peat may require specific consideration.

Intake of Resuspended Dust and Dose Assessment

The annual intake of resuspended dust is commonly assessed on the basis of:

- an assumed respirable dust loading (g/m^3);
- an assumed breathing rate (m^3/h); and,
- an annual occupancy (h/y).

The annual committed effective dose is the product of these three parameters, and:

- the concentration of activity in the resuspended dust (Bq/g); and,

- the dose coefficient (Sv/Bq).

Each of these factors is considered below in terms of implications for dose assessment.

Dust Loading

There can be large variations in observed dust loading according to different situations. This contributes to wide ranges in inhalation dose estimates even for the same level of radionuclide accumulation in soil (See BIOMOVS [1990]).

Normal ambient levels in agricultural environments may be around 1.0E-04 g/m^3. Very high levels can arise as a result of mechanical ploughing of dry soils. However, it would be unusual for humans to be exposed to such dust levels for long periods. Also, a significant proportion of the dust produced in those circumstances could exceed a few microns in diameter and might, therefore, be of limited respirability. However, set against this, under conditions of heavy activity, inhalation may be more by mouth than nose breathing, reducing the discrimination against particles of large diameter. An overall dust loading of 5.0E-02 g/m^3 represents a possible upper limit for relatively extended exposure, being the level above which nuisance is observed in terms of disturbance of breathing [BIOMOVS, 1990].

As to particle size, there is some information for environmentally dispersed thorium in Leifer et al. [2002]. These data relate to a contaminated site under remediation and suggest an average AMAD of about 6 microns, but with significant seasonal variations.

In considering dust loading, it is important to take into account the relationship and/or correlation between dust loading and assumptions about breathing rates and occupancy.

Breathing Rate

Breathing rates are about 50% higher during vigorous work activity compared with the rate in normal activities, and a factor of two higher than in resting conditions [IAEA, 2003]. It is appropriate to take this factor into account in determining an appropriate breathing rate for the assumed cause of resuspension of the dust.

Occupancy

Continuous occupancy or occupancy for long periods in high dust levels is unlikely. A 50% occupancy under normal activities (at low dust level and low breathing rate) and 10% occupancy during vigorous work associated with soil disturbance (at high dust level and high breathing rate) is suggested here as an example of a reasonable combination. On this basis, and all other things being equal, the high dust level situation would provide the largest contribution to total dust inhalation.

Dose Coefficients

Dose coefficients vary with chemical form and with particle size, as indicated above. So far as possible, these factors should be taken into account in selection of model parameter values. This may include making assumptions about proportions of resuspended dusts in different size and solubility categories.

It is noted here that the uncertainties in the cancer risks associated with particular components of effective dose for inhaled alpha activity can be considerable, leading to a factor of 25 uncertainty in radiological implications [Grogan et al., 2001].

Uncertainties in cancer risk associated with defined radionuclide intakes are not normally taken into account in post-closure assessments. However, such uncertainties are not negligible and they provide a perspective on the significance of uncertainties in other parts of the overall assessment.

Enhancement Factor

Enhancement (or enrichment) factors are used in modelling to account for the smaller mean diameter size of particles in the atmosphere than in soil. These enhancement factors account for small particles being more easily resuspended and having a longer residence time in the atmosphere once resuspended. Also, fine particles are more readily inhaled. Enhancement factors tend to be higher for sandy soils, since they have a smaller proportion of silt and clay. Thus, if the silt and clay fraction is resuspended, concentration effects are more pronounced in sandy soils.

Choice of Layer Thickness for Resuspension

The activity concentration in respirable dust is related to the concentration in the soil from which it is derived, though modified by an enhancement factor, as discussed above. The BIOMASS project [IAEA, 2003] considered the significance for concentrations of contaminants in air assuming that resuspension occurs only from a thin surface layer of thickness 1 cm, and, as an alternative, from a 30 cm top soil layer. As might be expected, explicit representation of a thin surface layer results in inhalation doses for particle-reactive radionuclides being higher by about a factor of 30 during the first year or so. However, if additions to soil continue over about 30 years, then, allowing for soil mixing processes and accumulation, the inhalation dose is about the same in the long-term. A similar result may be expected if the source of contamination arises from below, except that assuming a single thick (30 cm) soil compartment results in an initial overestimate of dose rather than an underestimate. Therefore, for determining the annual effective dose for long-term releases, there does not appear to be a need to consider a thin surface soil layer. Similar remarks were made in the Nirex contribution to this study.

6. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Significant information has been presented on how different groups address the assessment of doses via dust inhalation of long-lived alpha activity, represented by Pu-239, taking account of their assessment and project specific contexts. This provides a detailed consideration of potentially relevant features, events and processes. In addition, details of the mathematical model representation of the processes have been provided.

Calculations have been made and results presented for a generically defined inhalation dose assessment. The results are purely illustrative and are not representative of specific assessment projects on-going within national programmes.

The results have been compared and the implications of different assumptions have been considered. The spread of results spans two orders of magnitude.

The spread arises to some extent because of the different treatments of processes in the models, but mainly because of different parameter value assumptions. An important conclusion is that for the highly particle-reactive radionuclides reaching the soil in irrigation waters, which is the context in which resuspension has the potential to be the most important pathway of exposure, details of the approach to modelling radionuclide retention in soil have little impact on the results obtained. This arises because such radionuclides are retained in top soil for long periods, but are relatively rapidly redistributed through it by processes such as ploughing and bioturbation.

Differences in model results were found to relate significantly to:

- the degree to which human disturbance results in high dust levels;
- the degree of enrichment in radionuclide content of the resuspended dust;
- the occupancy period for which high dust levels were assumed to persist.

There is no simple approach to justifying assumptions on these issues, which relate largely to human behaviour.

Also important is the period over which it is reasonable to assume continuous accumulation of activity in a soil due to continued irrigation. All the participants made the same assumption of 1000 years, since this was given in the calculation specification, but the models generally indicated that prolonging input beyond 1000 years would lead to significant further accumulation.

The model input data requirements are indicative of the types of site characterisation information that may be needed in order to describe a site for the purposes of such an evaluation. For example, resuspension of soil dust can be soil-type dependent as well as climate dependent.

Some evidence exists which suggests that contaminant concentrations in resuspended dusts may be higher than those in the bulk soil from which they are derived. It would be useful to have more information on such enhancement, not least because it is one of the few areas in which current assessment assumptions may not be conservative.

Further consideration might also be given to the appropriate assumptions for dose coefficients relevant to the chemical forms and particle size of the dusts concerned. Consideration might also be given to the distribution of activity among particles of different size and the implications that this would have for the selection of appropriate dose coefficients.

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APPENDIX A: MODEL EQUATIONS

A.1 ANDRA

Inhalation dose is calculated as:

$$D_{inh} = FD_{inh}\ C_{soil}\ Susp\ Air_{inh}\ \rho_{cult}\ Depth\ Conv_{yr\_d}$$

where:

D_{inh}	=	Effective dose rate acquired through inhalation of air carrying contaminated soil, Sv/y
FD_{inh}	=	Inhalation dose factor, Sv/Bq
C_{soil}	=	Activity concentration in surface soil, Bq/kg_{dry}
$Susp$	=	Resuspension factor, 1/m
Air_{inhal}	=	Daily air intake, m^3/d
ρ_{cult}	=	Dry density of cultivated soil, kg_{dry}/m^3
$Depth$	=	Depth of ploughing = depth of root zone, m
$Conv_{yr\_d}$	=	Days per year, d/y

Activity concentration in the air from resuspension of soil particulates in air is generally calculated as:

$$C_{air} = ADL\ C_{soil}$$

where:

C_{air}	=	Activity concentration in air, Bq/m^3
ADL	=	Atmospheric dust load ($kg_{dry\ soil}/m^3_{\ air}$)

Note that a resuspension factor approach is used for dose estimation and that an occupancy factor is not explicitly included, but that a dust loading approach is used for estimating air concentrations. With this latter approach, the radionuclide transfer to man from inhaling contaminated air is given by the following equation, which explicitly includes an occupancy factor:

$$Tman_{air} = C_{air}\ I_{air}\ O$$

where:

$Tman_{air}$	=	Daily activity intake by inhalation, Bq/d
C_{air}	=	Activity concentration in air, Bq/m^3 $C_{air} = C_{air\_tp} + C_{air\_ap}$
I_{air}	=	Human inhalation rate, m^3/d
O	=	Occupancy time, or fraction of the time the individual occupies the local area (unitless)

A.2 Risk Assessment Corporation

Material balance in each of the compartments illustrated in Figure 2 of the main text is described in terms of ordinary differential equations. Solutions to these equations can be approximated using a Runge-Kutta numerical algorithm with adaptive step-size control or analytical solutions.

Surface Soil (Qss)

$$\frac{dQss}{dt} = Ir(t)C_{Ir}\ fp - kpQss - \lambda Qss \text{ (Growing seasons)}$$

$$\frac{dQss}{dt} = -kpQss - \lambda Qss \text{ (Fallow seasons)}$$

where *Ir* is the irrigation rate (m^3/d), *kp* = physical movement and/or aqueous-phase leaching rate constant (1/d), *fp* = fraction of plutonium in irrigation water that remains in surface soil, C_{Ir} = concentration of plutonium in irrigation water (Bq/m^3), λ = radioactive decay constant (1/d). Resuspension onto the plant surface and weathering is combined into an equilibrium mass-loading process that relates the activity on the plant to surface soil activity (*fp*). The amount of activity that is on the plant at harvest is removed from the model. Activity taken into the plant tissue by root uptake and translocation is not considered. Losses from wind-driven resuspension and mechanical resuspension from the surface soil compartment are also not considered. Tillage in the spring homogenizes radionuclide concentrations between the surface soil and labile soil compartments.

Labile Soil (*Qls*)

$$\frac{dQls}{dt} = kpQss - kl(t)Qls - \lambda Qls$$

where *kl*(*t*) is the leaching rate constant which is time dependent. The leaching rate constant is given by

$$kl(t) = \frac{q(t)}{\theta(t)\, T\left(1 + \frac{K_d\, \rho}{\theta(t)}\right)}$$

where *q*(*t*) is the net infiltration rate (m/d), $\theta(t)$ is the volumetric water content, K_d is the equilibrium partitioning coefficient (mL/g), and ρ is the bulk density (g/mL). The infiltration rate and moisture content are related by the moisture characteristic curve. These are available for various soil types.

Air Compartment (*Qa*)

$$\frac{dQa}{dt} = Rw + Rm - kaQa$$

where *Rw* is the resuspension source term from wind-driven resuspension (Bq/d), *Rm* is the resuspension source term from mechanical resuspension (Bq/d) and *ka* is the removal rate constant (1/d). The removal rate constant is given by

$$ka = \frac{u}{H}$$

where *u* is the mean wind speed (m/d) and *H* is the height of the mixing cell (m). The wind-driven resuspension term is given by

$$Rw = kr\,Qss$$

where *kr* is the resuspension rate constant (1/d). Mechanical resuspension is based on empirical mass-loading data for agriculture activities.

A.3 CIEMAT

The mathematical representation of the intercompartment transfer processes takes the form of a matrix of transfer coefficients which allows the compartmental inventories to be calculated using a set of first-order linear differential equations. For the *i*th compartment, the rate at which the compartment inventory changes with time is given by:

$$\frac{dN_i}{dt} = \left(\sum_{j\neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t)\right) - \left(\sum_{j\neq i} \lambda_{ij} N_i + \lambda_N N_i\right)$$

where:

N_i	=	activity of radionuclide *N* in biosphere compartment *i*, Bq
N_j	=	activity of radionuclide *N* in biosphere compartment *j*, Bq
M_i	=	amount of radionuclide *M* in biosphere compartment *i* (*M* is the precursor radionuclide of *N* in a decay chain), Bq
$S_i(t)$	=	external source term of radionuclide *N* to compartment *i*, Bq/y

Process representation

Irrigation water (irrigation source term) in the conventional model of one soil compartment is assumed to be applied to cultivated soil at a rate V_{irr} of 1 m^3/y. This volume rate is that applied to 1 m^2 of soil, i.e. the irrigation rate is 1 m/y. Although a fraction of irrigation water is intercepted by crops, all the activity in the water is assumed to enter the soil immediately. The relatively minor delay before weathering removes intercepted activity to the soil is ignored so far as the concentration in soil calculation is concerned. The proportion of intercepted activity which is absorbed by the crop is also ignored so far as calculation of this concentration is concerned. Changes in concentrations from well head to the point of irrigation are also ignored. Thus, the source term to the soil due to irrigation, S, Bq/y, is given by:

$$S = V_{irr} C_w$$

where:

C_w	=	radionuclide concentration in the well water, Bq/m^3
V_{irr}	=	irrigation rate, m^3/y

Infiltration (and other downward losses) from cultivated soil transfer rate from top to deep soil (Sink3) due to infiltration of water (1/y) is represented by:

$$\lambda_{\inf} = \frac{Adv_{flow}}{D_{top} R}$$

The R term is calculated using the following equation:

$$R = 1 + \frac{(1-\theta_t)\rho}{\theta} K_d$$

where:

θ_t	=	total porosity of the cultivated soil compartment
ρ	=	grain density of the cultivated soil compartment, kg/m^3
Kd	=	sorption coefficient of the cultivated soil compartment, m^3/kg
θ	=	wet porosity of the cultivated soil compartment

For the Particle Size M mathematical model, there are three soil compartments, which represent the 3 grain sizes. Spatially these all occupy the same area to a depth that is 0.3 m multiplied by the percentage of total bulk soil that comprises that compartment. The percentages selected for each component are:

Clay: 17 %; Silt: 20 %; Sand: 63 %

Process representation

The three compartments are contaminated by irrigation water (0.33 $Bq/m^2/y$ for each compartment) and there is a loss to deeper layers represented as in the previous case. No erosion is considered and infiltration is defined as before.

The total distribution coefficient of the soil (Kd) value of 0.54 m^3/kg, was shared between the three particle sizes. The procedure to share has been performed following [Arimoto et al., 2002], around 85 % of activity is linked to PM10, so:

- sand compartment Kd: 0.06 m^3/kg (15 % of total Kd value provided)
- silt compartment Kd: 0.14 m^3/kg
- clay compartment Kd: 0.34 m^3/kg

Clay may have a higher value Kd value than silt, and the share between silt and clay was based on judgment.

Doses

Inhalation dose of dust

The annual individual dose to humans from the inhalation of dust is given by:

$$D_{dust} = DC_{inh} BR\ O_s C_{airs}$$

where:

D_{dust} is the individual dose from the inhalation of dust, Sv/y,

DC_{inh} is the dose coefficient for inhalation for Plutonium 239, Sv/Bq,

BR is the breathing rate of the human in the soil compartment, m^3/h.

O_s is the individual occupancy in the soil compartment, h/y,

C_{airs} is the radionuclide concentration in the air above soil (formed by resuspension from the three compartments, Bq/m^3.

$$C_{airs} = \frac{Csoil}{(1-\theta_t)\rho} \frac{R-1}{R} dust_{lev}$$

The inhalation dose is computed considering the concentration in air above two compartments. Clay particles (a total of 17 %) and silt particles (a total of 20 %) are resuspended due to ploughing and wind resuspension into the atmosphere. No resuspension of sand particles (a total of 63 %) is considered.

Inhalation is considered for particle sizes below 10 µm aerodynamic diameter, this means an assumption that only 1 % (from the total 20 %) of silt can be inhaled. As in the previous case, consideration has been given to different occupation and breathing rates and different dust level values in air (one at low dust level (most of the year) and one at high dust level (associated with working)).

The dose conversion factor was set to 5.0E-05 Sv/Bq for all cases, in order to separate out the effect due to the particle-size distribution in soil and the associated Kd values.

A.4 EPRI

The radionuclide concentration is the air is calculated as:

$$C_{air} = \frac{C_s}{(1-\theta_t)\rho}\frac{(R-1)}{R} dust_s$$

and the annual effective dose to the receptor arising from inhalation of resuspended soil particles is calculated as:

$$D_{dust} = DC_{inh}\ BR\ O_s C_{air} \quad .$$

where:

C_{air}	=	radionuclide concentration in the air above the cultivated soil compartment (Bq/m^3)
C_s	=	concentration of radionuclide in the bulk cultivated soil compartment (Bq/m^3)
ρ	=	grain density of the cultivated soil compartment (kg/m^3)
θ_t	=	total porosity of the cultivated soil compartment (-)
R	=	retardation coefficient for the cultivated soil compartment given by $1+\frac{(1-\theta_t)\rho K_d}{\theta}$, where θ is the water-filled porosity of the cultivated soil compartment; and K_d is the linear reversible sorption coefficient of the cultivated soil compartment (m^3/kg)
$dust_s$	=	soil derived dust level in the air above the cultivated soil compartment (Bq/m^3)
D_{dust}	=	individual dose from the inhalation of dust (mrem/y)
DC_{inh}	=	dose coefficient for inhalation (mrem/Bq)
BR	=	breathing rate of the human in the soil compartment (m^3/h), split into two levels
O_s	=	individual occupancy in the soil compartment (h/y), split into two levels

A.5 NIREX

Computation of the Pu-239 concentration in soil

The modelling approach adopted for estimating radionuclide concentrations in soil at equilibrium has been set out in a report to Nirex[1].

Water balance in the soil system:

1 Thorne, M C (2003). A Guide to the Spreadsheet Calculations for the Generic Performance Assessment, Mike Thorne and Associates Limited Report MTA/P0011D/2002-2; Issue 2, June 2003.

$$I_1 + E_2 - I_2 - E_1 - S_{out} = 0 \quad (1)$$

$$G + I_2 - E_2 - B_{out} = 0 \quad (2)$$

Radionuclide transport in the soil system:

$$E_2(C_2/K_2) - (S_{out} + I_2)(C_1/K_1) - \lambda d_1 C_1 + \lambda d_1 C_{1,parent} + F_1 = 0 \quad (3)$$

$$I_2(C_1/K_1) - (E_2 + B_{out})(C_2/K_2) - \lambda d_2 C_2 + \lambda d_2 C_{2,parent} + F_2 = 0 \quad (4)$$

$$K_1 = \phi_1 + \rho_1 Kd_1 \quad (5)$$

$$K_2 = \phi_2 + \rho_2 Kd_2 \quad (6)$$

In these equations, the variables are as defined in Table A1.

Table A1: Equation variables

Quantity	Units	Description
I_1	m/y	Precipitation plus irrigation
I_2	m/y	Percolation to substrate
E_1	m/y	Evapotranspiration
E_2	m/y	Capillary rise to replenish soil moisture deficit
S_{out}	m/y	Through-flow losses from surface soil
B_{out}	m/y	Base-flow losses from subsoil
G	m/y	Groundwater discharge to subsoil
C_1	Bq/m^3	Concentration of the radionuclide of interest in surface soil
C_2	Bq/m^3	Concentration of the radionuclide of interest in subsoil
λ	1/y	Decay constant of the radionuclide of interest
d_1	m	Depth of the surface soil layer
d_2	m	Depth of the subsoil layer
$C_{1,parent}$	Bq/m^3	Concentration of the immediate parent of the radionuclide of interest in surface soil
$C_{2,parent}$	Bq/m^3	Concentration of the immediate parent of the radionuclide of interest in subsoil
F_1	$Bq/m^2/y$	Flux of the radionuclide of interest into surface soil
F_2	$Bq/m^2/y$	Flux of the radionuclide of interest into subsoil
ϕ_1	-	Water-filled porosity of surface soil
ρ_1	Kg/m	Dry bulk density of surface soil
Kd_1	m^3/kg	Distribution coefficient for the radionuclide of interest in surface soil
ϕ_2	-	Water-filled porosity of subsoil
ρ_2	Kg/m^3	Dry bulk density of subsoil
Kd_2	m^3/kg	Distribution coefficient for the radionuclide of interest in subsoil

For natural groundwater discharge, F_1 = 0 and F_2 is taken as a constant. For well abstraction, F_2 = 0 and $F_1 = I_{irr}C_w$, where I_{irr} (m/y) is the irrigation rate and C_w (Bq/m) is the concentration of the radionuclide of interest in the abstracted well water.

In evaluating the equilibrium radionuclide transport equations, it is convenient to define the following supplementary quantities:

$$T_1 = F_1 + \lambda d_1 C_{1,\mathrm{parent}} \tag{7}$$

$$T_2 = F_2 + \lambda d_2 C_{2,\mathrm{parent}} \tag{8}$$

$$\alpha_1 = E_2/K_2 \tag{9}$$

$$\alpha_2 = (E_2 + B_{\mathrm{out}})/K_2 + \lambda d_2 \tag{10}$$

$$\beta_1 = (S_{\mathrm{out}} + I_2)/K_1 + \lambda d_1 \tag{11}$$

$$\beta_2 = I_2/K_1 \tag{12}$$

With these definitions, the equilibrium solutions to the transport equations become:

$$\beta_1 C_1 - \alpha_1 C_2 = T_1 \tag{13}$$

$$-\beta_2 C_1 + \alpha_2 C_2 = T_2 \tag{14}$$

These are readily solved to give:

$$C_1 = (\alpha_1 T_2 + \alpha_2 T_1)/(\alpha_2\beta_1 - \alpha_1\beta_2) \tag{15}$$

$$C_2 = (\beta_1 T_2 + \beta_2 T_1)/(\alpha_2\beta_1 - \alpha_1\beta_2) \tag{16}$$

C_1 and C_2 are the total concentrations in soil, expressed on a volumetric basis. They are converted to a dry mass basis (Bq/kg) using:

$$CT_1 = C_1/\rho_1 \text{ and } CT_2 = C_2/\rho_2 \tag{17}$$

Also, the concentrations on soil solids and in soil solution are required separately. Concentrations in soil solids (Bq/kg) are given by:

$$CS_1 = CT_1\rho_1 Kd_1/(\phi_1 + \rho_1 Kd_1) \text{ and } CS_2 = CT_2\rho_2 Kd_2/(\phi_2 + \rho_2 Kd_2) \tag{18}$$

Concentrations in soil solution (Bq/m^3) are given by:

$$CL_1 = C_1/(\phi_1 + \rho_1 Kd_1) \text{ and } CL_2 = C_2/(\phi_2 + \rho_2 Kd_2) \tag{19}$$

However, for the calculations required in the test case, it is necessary to compute the build up of radionuclides in soil with time. For this it is necessary to use the kinetic equations that underpin the equilibrium solutions given above. These are as equations (3) and (4), but with the zeros on the right-hand side replaced with $d_1 \mathrm{d}C_1/\mathrm{d}t$ in (3) and $d_2 \mathrm{d}C_2/\mathrm{d}t$ in (4). Making the appropriate substitutions from equations (7) to (12), this yields:

$$d_1 \mathrm{d}C_1/\mathrm{d}t = T_1 + \alpha_1 C_2 - \beta_1 C_1 \quad (20)$$

$$d_2 \mathrm{d}C_2/\mathrm{d}t = T_2 + \beta_2 C_1 - \alpha_2 C_2 \quad (21)$$

However, we can define the total activity in each layer as A_1 and A_2, respectively. We can also redefine:

$$\alpha_1 = E_2/K_2 d_2 \quad (22)$$

$$\alpha_2 = (E_2 + B_{\mathrm{out}})/K_2 d_2 + \lambda \quad (23)$$

$$\beta_1 = (S_{\mathrm{out}} + I_2)/K_1 d_1 + \lambda \quad (24)$$

$$\beta_2 = I_2/K_1 d_1 \quad (25)$$

This leads to the equations:

$$\mathrm{d}A_1/\mathrm{d}t = T_1 + \alpha_1 A_2 - \beta_1 A_1 \quad (26)$$

$$\mathrm{d}A_2/\mathrm{d}t = T_2 + \beta_2 A_1 - \alpha_2 A_2 \quad (27)$$

To address the cases of interest, we consider a unit spike input at t = 0 into the compartment of interest. Solutions for any other case can be obtained from these unit spike input cases by convolution of the solutions with the appropriate time-dependent input rates.

For the unit spike input cases, $T_1 = T_2 = 0$.

Thus:

$$\mathrm{d}A_1/\mathrm{d}t = \alpha_1 A_2 - \beta_1 A_1 \quad (28)$$

$$\mathrm{d}A_2/\mathrm{d}t = \beta_2 A_1 - \alpha_2 A_2 \quad (29)$$

The general solution for two equations of this form is:

$$A_1(t) = a \exp(-k_1 t) + b \exp(-k_2 t) \quad (30)$$

$$A_2(t) = c \exp(-k_1 t) + d \exp(-k_2 t) \quad (31)$$

In the case of irrigation, the spike input is into compartment 1, so we impose the specific constraints that:

$$a + b = 1 \quad (32)$$

$$c + d = 0 \quad (33)$$

By substituting equations (30) and (31) into equations (28) and (29), and equating terms in $\exp(-k_1t)$ and $\exp(-k_2t)$ we obtain the following four relationships:

$$-ak_1 = \alpha_1 c - \beta_1 a \quad (34)$$

$$-bk_2 = \alpha_1 d - \beta_1 b \quad (35)$$

$$-ck_1 = \beta_2 a - \alpha_2 c \quad (36)$$

$$-dk_2 = \beta_2 b - \alpha_2 d \quad (37)$$

Equations (32) to (37) constitute a set of six simultaneous equations in six unknowns. By some rather tedious algebra, these can be solved to yield:

$$a = 0.5 + (\alpha_2 - \beta_1)/2f \quad (38)$$

$$b = 0.5 - (\alpha_2 - \beta_1)/2f \quad (39)$$

$$c = \beta_2/f \quad (40)$$

$$d = -\beta_2/f \quad (41)$$

$$k_1 = 0.5\ (\alpha_2 + \beta_1 - f) \quad (42)$$

$$k_1 = 0.5\ (\alpha_2 + \beta_1 + f) \quad (43)$$

$$f = [4\alpha_1\beta_2 + (\alpha_2 - \beta_1)^2]^{1/2} \quad (44)$$

Having obtained this solution, equations (30) and (31) can be integrated from time zero to yield the following values for unit input rate into compartment 1:

$$A_1(t) = a[1-\exp(-k_1t)]/k_1 + b[1-\exp(-k_2t)]/k_2 \quad (45)$$

$$A_2(t) = c[1-\exp(-k_1t)]/k_1 + d[1-\exp(-k_2t)]/k_2 \quad (46)$$

It is noted that a similar analysis can be undertaken for the case in which the system is contaminated radionuclides present in upwelling groundwater. In that case, $a + b = 0$, $c + d = 1$ and the approach follows the same line of argument. Equations (38) to (44) have a different form[2], but equations (45) and (46) are as given above.

Both the irrigation case and the upwelling groundwater case have been implemented as simple spreadsheets.

In the test case of irrigation with Pu-239 the input rate is taken as 1 $Bq/m^2/y$ from the task specification.

In the initial study values of E_2, I_2, S_{out} and B_{out} were taken for a well-drained soil with the water table at a depth of more than 2 m; such soils are suitable for intensive arable agriculture that requires irrigation in temperate conditions. The values used were $E_2 = 0.25$, $I_2 = 0.64$, $S_{out} = 0$ and $B_{out} = 0.39$. The value of B_{out} was selected as $I_2 - E_2$ to simulate a system in which $G = 0$, i.e. neither

2 For contamination of soil from below, the equations become: $a = \alpha_1/f$; $b = -\alpha_1/f$; $c = 0.5 + (\beta_1 - \alpha_2)/2f$; $d = 0.5 - (\beta_1 - \alpha_2)/2f$; $k_1 = 0.5(\beta_1 + \alpha_2 - f)$; $k_2 = 0.5(\beta_1 + \alpha_2 + f)$. The form of f is unchanged.

groundwater discharge nor recharge (see (2)). These values were taken from a report to Nirex on generic biosphere modelling[3].

Values of Kd_1 and Kd_2 were taken as 0.54 from the task specification (strictly the value for subsoil is not specified in the task, but it seems plausible to take a value identical to that of surface soil for a deep well-drained soil). Values of ϕ_1 and ϕ_2 were both taken as 0.35 from the task specification. Values of ρ_1 and ρ_2 were computed as 1722.5 from the total porosity and grain density given in the task specification. This dry bulk density is almost certainly too high to be realistic for surface soils. A value ~ 1000 would be more realistic, reflecting mainly a higher porosity, but also with some effects of organic matter content.

The value of d_1 is given in the task specification as 0.3. The value of d_2 is of only secondary importance. Bearing in mind that a deep, well-drained soil is being considered, a nominal value of 2 is adopted.

The decay constant of Pu-239, λ, is taken as 2.88E-05.

A.6 NUMO

Irrigation (source term) is calculated as:

$$S = V_{irr} C_w$$

where:

S	=	source flux to surfaces soil, Bq/y
V_{irr}	=	irrigation rate, m^3/y
C_w	=	radionuclide concentration in the irrigation water, Bq/m^3

Infiltration is calculated as:

$$F_{\inf} = \frac{I}{R_{sed}\theta_{sed}d_{sed}} \cdot N_{ss}$$

where:

F_{inf}	=	flux by infiltration from surface soil to deeper soil, Bq/y
I	=	infiltration rate, m/y
R_{sed}	=	radionuclide retardation coefficient for the surface soil
θ_{sed}	=	total porosity of the surface soil
d_{sed}	=	depth of the surface soil, m
N_{ss}	=	activity of the radionuclide in surface soil, Bq

3 Stansby, S J and Thorne, M C, (2000) Generic Biosphere Modelling: Final Report, AEA Technology Report AEAT/R/ENV/0296 to United Kingdom Nirex Limited.

The R_{sed} term is calculated using the following equation:

$$R_{sed} = 1 + \frac{(1-\theta_{sed})\rho_{gsed}}{\theta_{sedw}} Kd_{sed}$$

where:

θ_{sedw}	=	water filled porosity of the soil compartment
ρ_{gsed}	=	grain density of the surface soil, kg/m^3
Kd_{sed}	=	sorption coefficient of the soil compartment, m^3/kg

The radionuclide concentration in the air above the surface soil compartment C_{air} is represented by:

$$C_{air} = \frac{C_{sed}}{(1-\theta_{sed})\,\rho_{gsed}} \frac{(R_{sed}-1)}{R_{sed}} dust_{sed}$$

where:

C_{sed}	=	radionuclide concentration in the soil compartment, Bq/m^3
θ_{sed}	=	total porosity of the soil compartment
ρ_{gsed}	=	grain density of the soil compartment, kg/m^3
R_{sed}	=	retardation coefficient for the soil compartment
$dust_{sed}$	=	dust level in the air above the soil compartment, kg/m^3

The annual individual dose to humans from the inhalation of dust is given by:

$$D_{dust} = D_{inh}\, BR_{sed}\, O_{sed}\, C_{air}$$

where:

D_{dust}	=	individual dose from the inhalation of dust, Sv/y
D_{inh}	=	activity to dose conversion factor for inhalation, Sv/Bq
BR_{sed}	=	breathing rate of the human in the sediment or soil compartment, m^3/h
O_{sed}	=	individual occupancy in the sediment or soil compartment, h/y
C_{air}	=	radionuclide concentration in the air above the sediment or soil compartment, Bq/m^3

A.7 STUDSVIK

The annual internal dose due to inhalation of soil particles (D_{inh}) is described by:

$$D_{inh} = t_{exp}\ Inh\ c_{dust}\ c_{ts}\ DC_{inh}$$

where:

t_{exp}	=	time spent on contaminated ground (h/a)
Inh	=	inhalation rate (age-dependent, m^3/h)
c_{dust}	=	concentration of dust in air due to resuspension when cultivating (kg/m^3),
c_{ts}	=	radionuclide activity concentration in topsoil (Bq/kg)
DC_{inh}	=	age-dependent and nuclide-dependent dose coefficient for inhalation (Sv/Bq)

A.8 UKAEA

$$E_{InhDust} = \sum_{EM} C_s\ O\ C_{Aero}\ B\ DC_{In}$$

$$C_S = K_d\ C_L$$

$$C_L = \frac{I}{\kappa}$$

$$I = V\ [\varepsilon\theta_{flow} C_L + \varepsilon\beta\rho(1-\theta_{total})C_S + \varepsilon\theta_{flow} S\, C_S].$$

$$\kappa = \kappa_L + \kappa_S + \kappa_c$$

$$\kappa_L = V\varepsilon\theta_{flow}$$

$$\kappa_S = V\varepsilon\beta\rho(1-\theta_{total})K_d$$

$$\kappa_c = V\varepsilon\theta_{flow} K_d\ S$$

where:

C_{Aero}	=	concentration of dust in air over the soil compartment (kg/m^3)
B	=	person's average breathing rate whilst over the soil compartment (m^3/y)
O	=	occupancy of humans on the soil compartment (-)
DC_{In}	=	dose coefficient for inhalation (Sv/Bq)
C_s	=	concentration of radionuclide in the solid phase (Bq/kg)
K_d	=	soil distribution coefficient, (m^3/kg)
C_l	=	contaminant concentration in the liquid phase (Bq/m^3)
I	=	total inventory in the compartment (Bq)

κ	=	capacity of each compartment for contaminants (m^3)
V	=	volume of soil (m^3)
ε	=	degree of saturation (dimensionless)
θ_{flow}	=	wet soil porosity (dimensionless)
β	=	fraction of solid in contact with flowing liquid (dimensionless)
ρ	=	soil grain density (kg/m^3)
θ_{total}	=	total soil porosity (dimensionless)
S	=	concentration of resuspended solids and colloids in the liquid phase (kg/m^3)

A.9 YMP

Annual dose from inhalation of a long-lived radionuclide is calculated as:

$$D_{inh} = EDCF_{inh}\left[\sum_n Ca_n\ BR_n \sum_m \left(PP_m\ t_{n,m}\right)\ \right]$$

where:

D_{inh}	=	annual dose from inhalation exposure to a long-lived radionuclide in re-suspended particles (Sv/yr)
$EDCF_{inh,l}$	=	effective dose conversion factor for inhalation of a long-lived radionuclide (Sv/Bq). Effective dose conversion factor includes contributions of the short-lived decay products (half-life less than 180 days) weighted according to the branching fractions. Short-lived radionuclides are assumed to be in secular equilibrium with their parents.
n	=	environment index; n = 1 for active outdoors, 2 for inactive outdoors, 3 for active indoors, 4 for asleep indoors, and 5 for away from the contaminated area
$Ca_{,n}$	=	activity concentration of a long-lived radionuclide in air for environment n (Bq/m^3) Note: these activity concentrations apply only to human exposures; different values are used for deposition on crops.
BR_n	=	breathing rate for environment n (m^3/h)
m	=	population group index; m = 1 for commuters, 2 for local outdoor workers, 3 for local indoor workers, and 4 for non-workers
PP_m	=	fraction of the total population in population group m (population proportion) (dimensionless)
$t_{n,m}$	=	annual amount of time that population group m spends in environment n (exposure time) (h/yr).

In the Environmental Radiation Model for Yucca Mountain, Nevada (ERMYN) biosphere model, the dose from inhalation of a long-lived radionuclide in resuspended particulates also includes contributions from the long-lived decay products produced in the soil by the decay of long-lived parent radionuclides. However, to simplify the mathematical expression, these contributions were not included for the purpose of this comparison/exercise.

The effective inhalation dose conversion factors can be expressed as:

$$EDCF_{inh} = \sum_{s} DCF_{inh,s} \times BN_s$$

where:

$DCF_{inh,s}$	=	dose conversion factor for inhalation for a short-lived radionuclide *s* in a decay chain of a long-lived radionuclide (Sv/Bq)
s	=	index of short-lived radionuclide in a decay chain of a long-lived radionuclide
BN_s	=	breaching fraction for a short-lived radionuclide *s* in a decay chain of a long-lived radionuclide (dimensionless)

Radionuclide concentrations in the air were calculated as:

$$Ca_n = f_{enhance,n}\ Cs_m\ S_n = f_{enhance,n}\ \frac{Cs}{\rho_s}\ S_n$$

where:

Ca_n	=	activity concentration of radionuclide in the air from soil resuspension of soil particles for the assessment of human inhalation exposure in environment *n* (Bq/m^3)
$f_{enhance,n}$	=	enhancement factor for the activity concentration of re-suspended particulates in environments *n* (dimensionless). This parameter accounts for possible differences in mass activity concentration of airborne particulates as compared to that of surface soil.
S_n	=	concentration of total resuspended particulates (mass loading) for evaluation of inhalation exposure for environment *n* (kg/m^3). In ERMYN this parameter value is taken from filed experiments (literature review).
Cs_m	=	activity concentration of radionuclide in the surface soil per unit mass (Bq/kg); saturation activity concentration is used in the ERMYN model.
Cs	=	activity concentration of radionuclide in the surface soil per unit area (Bq/m^2)
ρ_s	=	a real density of surface soil (kg/m^2)

Radionuclide concentration in the surface soil, assuming constant values of activity concentration the water the crop irrigation rate, was expressed as:

$$Cs\ (t) = \frac{Cw_i\ IR}{\lambda_d + \lambda_l + \lambda_e}\left[1 - e^{-(\lambda_d + \lambda_l + \lambda_e)\,t}\right] = \frac{Cw\ \ IR}{\lambda_{eff}}\left(1 - e^{-\lambda_{eff}\ t}\right)$$

where:

$Cs(t)$	=	activity concentration of radionuclide in surface soil per unit area at time *t* (Bq/m^2)
t	=	time variable (y)

$Cw(t)$	=	activity concentration of radionuclide in the groundwater at time *t* (Bq/m^3)
$IR(t)$	=	annual average irrigation rate on land (annual irrigation rate) (m/y)
λ_d	=	radioactive decay constant for radionuclide (/y)
λ_l	=	average annual leaching removal constant for radionuclide (/y)
λ_e	=	average annual surface soil erosion removal constant (/y)
λ_{eff}	=	effective removal constant for radionuclide (/y)

Note λ_l is a function of the annual over-watering rate and soil properties of bulk density, thickness, partition coefficient, and water content at field capacity.

When radionuclide concentrations in the surface soil reach the saturation concentration, the concentration in the soil, *Cs*, can be expressed as the ratio of the radionuclide addition rate to the removal rate:

$$Cs = \frac{Cw \ IR}{\lambda_{eff}}$$

To limit speculation regarding the historic irrigation practices and land use, it was assumed that the saturation concentration in surface soil exists at all times.

The activity concentration of a radionuclide in surface soil described above is given in units of activity per unit area (Bq/m^2). It can be converted to activity concentration in Bq per unit mass of surface soil using

$$Cs_m = \frac{Cs}{\rho_s}$$

where:

Cs_m	=	saturation activity concentration of radionuclide *i* in surface soil per unit mass (Bq/kg)
Cs	=	saturation activity concentration of radionuclide *i* in surface soil per unit area (Bq/m^2)
ρ_s	=	areal density of surface soil (kg/m^2)

The surface soil density was calculated using:

$$\rho_s = \rho \times d$$

where:

ρ	bulk density of surface soil (kg/m^3)
d	depth of surface soil (m)

As previously noted, radionuclide decay and ingrowth in the surface soil due to introduction of primary radionuclides in irrigation water were considered in the model. At saturation for the parent long-lived radionuclides and its long-lived decay products, that is, $\frac{dCs_l(t)}{dt} = 0$, the saturation activity concentration of decay product *l* was calculated as:

$$Cs_l = \frac{\lambda_{d,l}}{\lambda_{d,l} + \lambda_{l,l} + \lambda_e} Cs_{l-1} = \frac{\lambda_{d,l}}{\lambda_{eff,l}} Cs_{l-1}$$

where:

Cs_l	=	saturation activity concentration of a decay product *l* in surface soil (Bq/m^2)
Cs_{l-1}	=	saturation activity concentration of a primary radionuclide if *l* = 1, or a decay product (*l*-1) in surface soil (Bq/m^2)
$\lambda_{d,l}$	=	radioactive decay constant for long-lived decay product *l* (/y)
$\lambda_{l,l}$	=	average annual leaching removal constant for long-lived decay product *l* (/y)
$\lambda_{eff,l}$	=	effective removal constant for the l^{th} decay product (/y)

APPENDIX B: BIOSPHERE SYSTEM DESCRIPTION

BIOMASS Theme 1 Example Reference Biosphere 2A Biosphere System Description.

The first step of the biosphere description procedure is to identify those characteristics and properties of each component of the biosphere system that are relevant to providing an assessment-oriented description of the system. This is achieved by working through a checklist of common general characteristics, descriptive of potentially relevant features for each system component and selecting specific items for their relevance to the overall assessment objective according to the assessment context and any additional assumptions invoked in the preceding system identification.

The following discussion summarises the screening arguments considered in respect of the different components of the biosphere system.

Climate Characteristics

Consideration of climate characteristics contributes to providing a coherent overall description of the biosphere system, especially in so far as precipitation is an important contribution to the availability and quality of local surface resources (and hence demands on aquifer use). Other components of climate are important in determining the growth regime of plants, animal husbandry practices, water demand, *etc*. Table B1 summarises the screening arguments that have been deployed in respect of the climate characteristics of the biosphere system.

Table B1: CLIMATE CHARACTERISTICS

Biosphere System Component	Characteristic	Relevant ?	Comments
CII Climate characteristics	Temperature Precipitation Pressure Wind speed/direction Solar radiation	Y Y N N N	Temperature and precipitation determine basic productivity and need for irrigation Pressure not relevant (no gas release) Wind speed ruled out on basis of low importance (can determine evapotranspiration without it) Effects covered in temperature
CII Temporal variability of climate	Diurnal Seasonal Interannual Decadal	Y Y N N	Probably not represented explicitly in models Seasonal because it determines the growing season and need for irrigation Longer term variations ruled out on basis of low relevance to lifetime average exposure
CII Spatial variability of climate	Latitude Longitude Altitude Aspect	N N N N	Spatial extent too small for climatic variation No significant variation in a plains area Aspect not relevant for a plains area

The assessment context for ERB2A specifies no biosphere change. Nevertheless, relatively short-term variability may be relevant to the radiological assessment, in so far as the use of water will be influenced by climate fluctuations over diurnal and seasonal timescales. Inter-annual and decadal variabilities have limited relevance to the determination of lifetime average exposures, and it is assumed that they will be addressed through the selection of appropriate annual-average parameter values based on measurements over decades.

The geographical extent of the biosphere system is restricted to the region within which agricultural practices involving the use of well water are carried out by the local community. There is unlikely to be any significant spatial variability in climate over the domain of the biosphere system, particularly as it is assumed that the site is situated on a plain. This factor can therefore be considered irrelevant to the system description.

Geology, Soil and Topography Characteristics

As the geosphere/biosphere interface is restricted to abstraction of water via a well, the only function of the saturated zone is to act as a sink for percolating water. Detailed characteristics of the underlying geology are, therefore, largely irrelevant, except in so far as they influence the properties of the soil and variably saturated zone. Soil characteristics are relevant to providing a description of the structure and composition of the substrate within which crops are grown. Table B2 summarises the screening arguments deployed in respect of these aspects of the biosphere system.

The topography does not have a major influence on the overall system description, although its characteristics may be relevant to considerations such as the description of field drainage. Table B2 summarises the screening arguments deployed in respect of this component of the biosphere system description.

Table B2: GEOLOGY, SOIL AND TOPOGRAPHY CHARACTERISTICS

Biosphere System Component	Characteristic	Relevant?	Comments
GII Consolidated/ Solid Geology	Lithostratigraphy Fracture systems Degree of weathering Erodability Mineralogy	Y Y Y Y Y	Only relevant insofar as it affects the past development and present type of soil.
GII Unconsolidated/ Drift Geology	Lithostratigraphy Fracture systems Degree of weathering Erodability Deposition rates Mineralogy	Y Y Y Y Y Y	Only relevant insofar as it affects the type of soil and as a host for the variably saturated zone. An unspecified transmissivity is required to allow sufficient water movement.

Table B2 (Continued): GEOLOGY, SOIL AND TOPOGRAPHY CHARACTERISTICS

Biosphere System Component	Characteristic	Relevant?	Comments
SII Soil	Stratification (e.g. soil horizons) Composition (organic content, mineralogy) Texture Areal variation	Y Y Y Y	≥60 cm, organic rich, A-horizon. Sub soil consistent with sedimentary geology. Apart from breaking up any possible iron pan by ploughing and cultivation effects on humus content, the properties of the cultivated soil will be largely those of unmodified chernozems. Potentially relevant to extensive agricultural region.
TII Topography	Altitude Slope Erodability Deposition Rate	Y Y N N	Low enough to permit agriculture. 0-5% according to plain topography. Limited significance in region of low relief with no surface water courses. Assessment context requires that biosphere system should be constant.

Hydrology Characteristics

Identified water bodies present within the biosphere system include a well, variably saturated zone and saturated zone. There is also the possibility of including consideration of a small reservoir, or pond, to distribute water for irrigation and animal watering. Table B3 summarise the screening arguments deployed in respect of these aspects of the biosphere system.

It can be inferred from the assessment context that technological development is sufficient to allow for abstraction of water to take place. The actual level of technology required would depend on the specific situation in which abstraction takes place. Simple excavation into a shallow aquifer requires less technology than pumping from a borehole drilled into a deep, relatively impermeable, formation.

Although not strictly part of the system description for this example, consideration of local community structures may be implicit in other basic assumptions adopted regarding the biosphere system and/or exposure groups. For example, a small, remote (or even temporary) community may be less likely to invoke complex water storage and distribution systems prior to use, whereas industrialised abstraction for a larger population might involve more sophisticated technologies.

Although consideration of population size does not necessarily influence the biosphere system description, it may be important in applying and interpreting the results. For example, the size should be consistent with the underlying geosphere characteristics, in so far as radionuclide concentrations in well water are assumed to be unaffected by withdrawal rates, or variations in withdrawal rates. It might also be inferred from the assessment context that, if water abstraction is to be sustainable over an indefinite period, population size should be compatible with the capacity of the aquifer. Moreover, the overall community context (combined with local lithostratigraphy) may affect the type of well that is constructed, and hence the potential (as well as the realised) abstraction rates in any given situation. Specification of a particular abstraction rate (necessary to guide the geosphere calculations) will constrain the type of well that can be used.

Table B3: HYDROLOGY CHARACTERISTICS

Biosphere System Component	Characteristic	Relevant?	Comments
WII Well	Geometry	N	Excluded by assessment context
	Flow Rate	N	
	Suspended Sediment	Y	
	Freeze/Thaw Phenomena	N	Excluded by assessment context
	Hydrochemistry	Y	Composition and load, pH, Eh
WII Variably Saturated Zone	Geometry	Y	Seasonal variation
	Level and Basal Flow Rate	N	Not relevant to irrigation
	Freeze/Thaw Phenomena	N	Not relevant given source term in assessment context
	Ground Freezing	Y	Influence of snowpack development
	Water Body Freezing	N	Not relevant
	Hydrochemistry	Y	Potential influence on sorption
WII Saturated Zone	Geometry	N	Only role of saturated zone within conceptualised system is as a sink for infiltrating water. Characteristics are irrelevant to assessment context.
	Flow Rate	N	
	Freeze/Thaw Phenomena	N	
	Hydrochemistry	N	

APPENDIX C: NIREX / MTA SUPPLEMENTARY INFORMATION

Results of the reference calculations on subsoil and topsoil concentrations are tabulated below.

Time (y)	Subsoil Concentration (Bq/m^3)	Topsoil Concentration (Bq/m^3)
1	5.73E-04	3.33E+00
2	2.29E-03	6.65E+00
5	1.43E-02	1.66E+01
10	5.68E-02	3.29E+01
20	2.25E-01	6.51E+01
50	1.37E+00	1.57E+02
100	5.25E+00	2.98E+02
200	1.93E+01	5.34E+02
500	9.49E+01	9.98E+02
1000	2.68E+02	1.35E+03
10000	1.82E+03	2.13E+03
100000	2.06E+03	2.23E+03
1000000	2.06E+03	2.23E+03

These results are readily understood. At early times, all the activity remains in the topsoil. Thus, at ten years, the total activity in the topsoil is the concentration of 32.9 Bq/m^3 multiplied by the depth 0.3 m to give 9.87 Bq compared with a cumulative input of 10 Bq. By 1000 years, the topsoil contains 405 Bq and the subsoil 536 Bq. The total in the system is 941 Bq. The remaining 59 Bq has been lost by leaching and decay, but explicit calculations show that this loss is mainly by leaching. At 1.00E+06 years, the system has come into equilibrium. There are 2230 Bq in the topsoil and 2060 Bq in the subsoil. If radioactive decay was the only loss process, we would expect 34720 Bq in the system at this time. Thus leaching is of substantial significance in the long term.

As a confirmatory check, equilibrium equations (15) and (16) from Appendix A were solved. These gave concentrations in topsoil and subsoil of 2229 and 2057 Bq/m^3, respectively.

The concentrations in soil on a dry mass basis were calculated using equation (17) and the concentrations in soil solids from equation (18) of Appendix A. Only the values for topsoil are relevant in the current context. These are given in the following table.

Time (y)	Total Soil Concentration (Bq/kg)	Soil Solids Concentration (Bq/kg)
1	1.93E-03	1.93E-03
2	3.86E-03	3.86E-03
5	9.62E-03	9.62E-03
10	1.91E-02	1.91E-02
20	3.78E-02	3.78E-02
50	9.14E-02	9.13E-02
100	1.73E-01	1.73E-01
200	3.10E-01	3.10E-01
500	5.79E-01	5.79E-01
1000	7.84E-01	7.84E-01
10000	1.24E+00	1.24E+00
100000	1.30E+00	1.29E+00
1000000	1.30E+00	1.29E+00

There is almost no difference between the results, because of the appropriately high *Kd* value adopted.

Two alternative scenarios were investigated. These are summarized below.

In other calculations, an infiltration rate of 0.1 m/y has been proposed. This was achieved by setting I_1 = 0.8, E_1 = 0.7, I_2 = 0.35, E_2 = 0.25, S_{out} = 0, B_{out} = 0.1 and G = 0.

Results of this calculation are summarized in the table below, which compares soil calculations with the reference case.

As expected, the reduced infiltration results in rather higher concentrations in topsoil in the variant case. Up to 1000 years, the increased retention in topsoil results in lower concentrations in subsoil. However, on longer timescales, the lower baseflow in the variant case means that subsoil concentrations are higher than in the reference case.

Time (y)	Subsoil Concentration (Bq/m^3)		Topsoil Concentration (Bq/m^3)	
	Reference Case	Variant	Reference Case	Variant
1	5.73E-04	3.13E-04	3.33E+00	3.33E+00
2	2.29E-03	1.25E-03	6.65E+00	6.66E+00
5	1.43E-02	7.82E-03	1.66E+01	1.66E+01
10	5.68E-02	3.12E-02	3.29E+01	3.31E+01
20	2.25E-01	1.24E-01	6.51E+01	6.58E+01
50	1.37E+00	7.64E-01	1.57E+02	1.61E+02
100	5.25E+00	2.98E+00	2.98E+02	3.13E+02
200	1.93E+01	1.14E+01	5.34E+02	5.89E+02
500	9.49E+01	6.18E+01	9.98E+02	1.24E+03
1000	2.68E+02	2.00E+02	1.35E+03	1.93E+03
10000	1.82E+03	2.92E+03	2.13E+03	4.51E+03
100000	2.06E+03	5.71E+03	2.23E+03	6.59E+03
1000000	2.06E+03	5.71E+03	2.23E+03	6.59E+03

Although soils in the upper 0.3 m of agricultural land are likely to become well-mixed after a period of a few years, it was thought to be of interest to consider a system in which the soil was distinguished into an upper 0.01 m layer and an underlying 0.29 m. For this system, the following parameters were adopted: d_1 = 0.01; d_2 = 0.29; I_1 = 0.8; E_1 = 0.41; I_2 = 0.7; E_2 = 0.31; S_{out} = 0; B_{out} = 0.39 and G = 0. This is similar to the reference case, but with baseflow from the top 0.3 m rather than from deeper. Results from this case, relative to the reference case, are summarized in the following table.

Time (y)	Subsoil Concentration (Bq/m^3)		Topsoil Concentration (Bq/m^3)	
	Reference Case	Variant	Reference Case	Variant
1	5.73E-04	1.26E-01	3.33E+00	9.63E+01
2	2.29E-03	4.93E-01	6.65E+00	1.86E+02
5	1.43E-02	2.86E+00	1.66E+01	4.17E+02
10	5.68E-02	1.02E+01	3.29E+01	7.04E+02
20	2.25E-01	3.27E+01	6.51E+01	1.04E+03
50	1.37E+00	1.23E+02	1.57E+02	1.34E+03
100	5.25E+00	2.77E+02	2.98E+02	1.43E+03
200	1.93E+01	5.55E+02	5.34E+02	1.56E+03
500	9.49E+01	1.18E+03	9.98E+02	1.84E+03
1000	2.68E+02	1.78E+03	1.35E+03	2.11E+03
10000	1.82E+03	2.34E+03	2.13E+03	2.36E+03
100000	2.06E+03	2.34E+03	2.23E+03	2.36E+03
1000000	2.06E+03	2.34E+03	2.23E+03	2.36E+03

At early times, the concentration in the top 0.01 m is a factor of 30 higher than the concentration in the top 30 cm. However, with only a 0.01 m thick upper layer, transport in groundwater alone distributes the plutonium to depth on a timescale of a few decades. Inclusion of bioturbation in the model would increase the rapidity of this process.

APPENDIX D: CHLORINE-36

The test calculation discussed in the main body of the report focused on plutonium deposition, resuspension and inhalation. However, Cl-36 behaves differently to plutonium, and is of particular interest at marine locations and sites where there is a surface water body near by.

In the ANDRA model, Cl-36 transfers from river water to air, from soils and plants to air and from the atmosphere to humans via inhalation. The special equation used for transfer from river water to air is discussed below.

Transfer from River Water to Air

Bursting of bubbles and wind action will release aerosols from the surface of the river and will eject Cl-36 in water droplets to the local atmosphere. As the water droplets evaporate, dry aerosols are left suspended. An assumption that is made here is that all of the particles suspended initially are small enough to remain suspended in the air. For aquatic particulate resuspension, a mass-loading concept is appropriate and the concentration of Cl-36 in the air from aquatic particulate, Cair_cl36_ap, in Bq/m^3, is defined as:

$$Cair\_cl36\_ap = AADL \bullet Cw\_cl36\_rwater \bullet CnvLtom3$$

Where:

AADL	the aquatic atmospheric aerosol load (m^3 water/m^3 air)
Cw_cl36_rwater	the Cl-36 concentration in the river water (Bq/L water)
CnvLtom3	the conversion from L to m^3

This mass-loading approach is assumed to account for all the possible aquatic particulate resuspension mechanisms. The Cl-36 from this pathway is used to compute air concentrations for inhalation and immersion, and for deposition onto plants.