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2001:22 M.J. EGAN, P.R. MAUL, B.M. WATKINS AND A. VENTER

Work in Support of Biosphere Assessments for Solid Radioactive Waste Disposal

2. Biosphere FEP List and Biosphere Modelling

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

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TITLE/ TITEL: Work in Support of Biosphere Assessments for Solid Radioactive Waste Disposal.2. Biosphere FEP List and Biosphere Modelling/ Utvecklingsarbete av biosfärsanalyser vid slutförvaring av radioaktivt avfall. 2. Framtagande av FEP-lista för biosfären och biosfärsmodellering

SUMMARY: In order to assist SSI in its reappraisal of the SFR safety case, QuantiSci has been appointed to develop a systematic framework within which to conduct the review of SKB's post-closure performance assessment (PA). The biosphere FEP list presented here was developed for use as reference material in conducting the review.

SSI wishes to develop an independent PA capability for a time-dependent biosphere in preparation for the examination of the revised SFR safety case. This report documents the model development that has been undertaken by QuantiSci using the Amber computer code.

SAMMANFATTNING: Som ett stöd till SSI:s förestående granskning av SKB:s förnyade säkerhetsanalys för SFR har QuantiSci uppdragits att utveckla granskningssystematiken. För detta utarbetades bland annat en referensförteckning över relevanta förhållanden, händelser och processer (FEP, eng. features, events and processes).

Som en förberedelse inför den kommande granskningen har även SSI låtit utveckla ett datorverktyg som möjliggör tidsberoende modellering av biosfären baserat på programkoden Amber

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Förord

1988 fick Svensk Kärnbränslehantering AB (SKB) tillstånd till ett begränsat drifttagande av slutförvaret för radioaktivt driftavfall. Efter att SKB skickat in ett par kompletterande rapporter gav Statens strålskyddsinstitut (SSI) och Statens kärnkraftinspektion (SKI) sina slutliga driftmedgivanden 1992. Som villkor till de driftmedgivanden som SSI utfärdade både 1988 och 1992 anges att SKB ska inkomma med en uppdaterad säkerhetsredovisning vart tionde år. En sådan redovisning inkom till myndigheterna hösten 2001. Inför den förestående granskningen av denna rapport såg SSI att det fanns ett behov att uppdatera både modelleringsverktygen och granskningsstrategin inom området. (En bakomliggande orsak till detta behov är den precisering av kravbilden som erhållits genom utfärdandet av SSI:s föreskrifter (SSI FS 1998:1) om skyddet av hälsa och miljö vid slutförvaring av använt kärnbränsle och kärnavfall.) Med anledning av detta fick QuantiSci 1998 i uppdrag av SSI att:

- utveckla arbetsmetoderna för det kommande granskningsarbetet, dels utifrån SSI:s skyldigheter som landets strålskyddsmyndighet, dels utifrån ovan nämnda SSI-föreskrifter om skyddet av hälsa och miljö vid slutförvaring av använt kärnbränsle och kärnavfall
- utveckla grunderna för oberoende analyser och biosfärsmodelleringar, bland annat genom framtagande av modelleringsverktyg
- ge stöd i utvecklandet av en förteckning över vilka förhållanden, händelser och processer (FEP, från engelskans features, events and processes) som är av betydelse för biosfärsmodellering.

Delar av de modelleringsverktyg som tagits fram har integrerats med verktyg som SKI låtit utveckla i ett parallellt projekt, och kommer att utgöra en av grunderna i den myndighetsgemensamma granskningen av SKB:s uppdaterade säkerhetsanalys.

Projektet har mynnat ut i fem stycken QuantiSci-rapporter. Dessa är sammanställda i två SSI-rapporter, varav detta är den ena. I denna rapport diskuteras biosfärsmodellering och utvecklingen av en FEP-lista för biosfären. I SSI Rapport 2001:21 diskuteras säkerhetsanalys, krav och metodik samt kriterier för miljöskydd. Författarna svarar ensamma för rapportens innehåll, varför detta ej kan åberopas som Statens strålskyddsinstituts ståndpunkt.

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Biosphere FEP List

1 Introduction

In order to assist SSI in its reappraisal of the SFR safety case, QuantiSci has been appointed to develop a systematic framework within which to conduct the review of SKB's post-closure performance assessment (PA). The intention is that this framework should address the implications for PA of SSI's recent (September 1998) *Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste*. It is also intended that the recommended approach should take account of methods currently under development within the IAEA BIOMASS Theme 1 programme.

As part of this work, a biosphere FEP list has been developed for use by SSI as reference material in conducting the review. The list presented in this technical note has been developed by QuantiSci from the BIOMOVS II [1996] FEP list, taking account of recent work within BIOMASS, as well as other, more general, international FEP lists [NEA, 1998, ISAM, 1998]. Section 2 discusses the considerations that were taken into account in developing the FEP list, while Section 3 describes the structure adopted in organising and preparing entries for the list. The biosphere FEP list itself is presented in Annex 1.

2 General Considerations

Assumptions and simplifications are fundamental to PA studies, as a necessary response to the wide-ranging uncertainties associated with the long-term behaviour of a complex system. The use of a formal methodological framework is intended to expose to scrutiny the logic of these underlying assumptions, on which the evaluation of safety performance indicators is based.

Different approaches to post-closure performance assessment will address the management of uncertainties in different ways. There are different techniques for identifying and describing relationships between FEPs associated with the disposal system and its environment and alternative approaches for the management of uncertainties associated with environmental change. Nevertheless, the essence of any formal framework is that it should facilitate auditing to demonstrate how any specific issue has been addressed within the PA.

A basic aim is therefore that the PA should address as comprehensive as possible a list of FEPs and to prioritise and organise these based on best scientific judgment regarding their relevance to the assessment. The principal vehicle for demonstrating comprehensiveness is an independent FEP list, amenable to systematic screening based on arguments developed from the overall assessment context (site-specific considerations, assessment purpose, endpoints under consideration, etc [BIOMASS, 1998b]). Alternatively, reasoning may be developed to show that a FEP does not need to be explicitly included, not so much because of lack of relevance, but because its potential impact on the PA results is subsumed under assumptions adopted elsewhere.

It is useful for a reference FEP list to be based on a logical, hierarchical structure, since this facilitates systematic screening and more readily enables elaboration and augmentation, where necessary. Various systems for the development of such a structure are possible; ultimately, however, the primary requirement is that the logic should be consistent with the assessment approach and assist model development. Within a scenario-based approach to PA, a primary consideration is the requirement to distinguish between FEPs associated with the disposal system domain (the ‘Process System’) and those treated as external, or ‘scenario-generating’ FEPs. It is therefore normally considered helpful if distinctions can be drawn at a high level within the list between FEPs falling into the following categories:

- FEPs that relate to basic elements of the assessment context;
- FEPs that relate to system and landscape change, arising (for example) from future human actions, climate and geological events and processes;
- FEPs that relate to the characteristics of, and relationships between, components of the disposal system and its immediate environment;
- FEPs describing the behaviour and characteristics of radionuclides within the system and their role in contributing to radiation exposure.

Such a classification scheme – as adopted by the NEA [1998] and illustrated in Figure 1 – captures the hierarchy of dependencies that is implicit in radiological impact assessment.

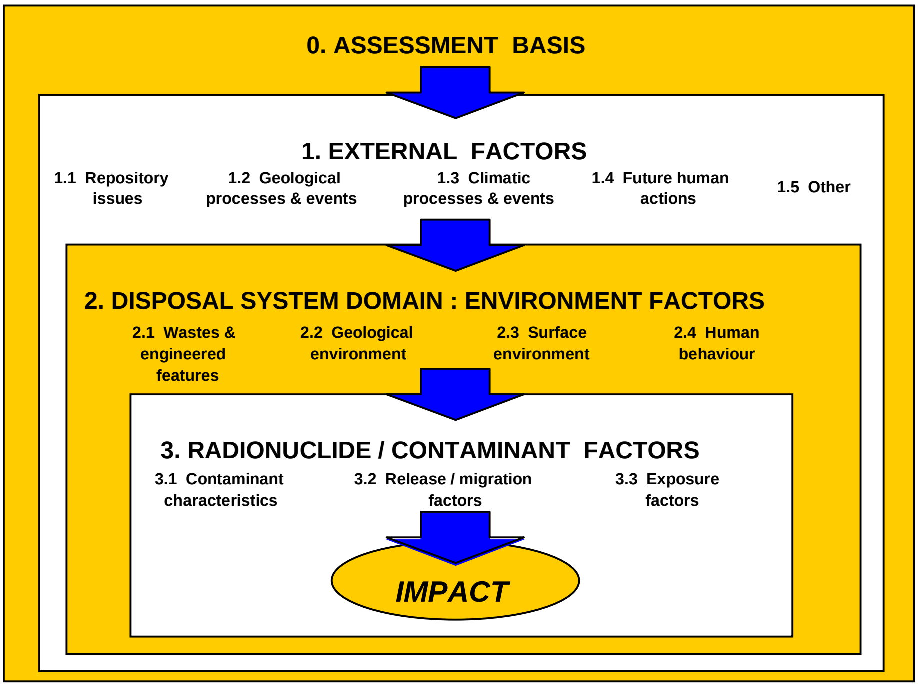

Figure 1
Classification Scheme Used in Deriving the International FEP List [NEA, 1998].

In practice, the boundaries between the different layers and categories in such a hierarchy will be subjective, depending on individual analysts' concepts and the corresponding extent of their models [ISAM, 1998]. Nevertheless, this should not preclude the self-consistent identification of FEPs within the list or a coherent mapping of project FEPs onto the list. Supporting documentation for each FEP is therefore important in guiding the interpretation and use of the list.

he extent to which increasing detail needs to be developed within a FEP list is largely a matter of judgment – for example, the BIOMOVS II list [BIOMOVS II, 1996] separately itemises more biosphere FEPs than does the NEA list [NEA, 1998]. It can be acceptable for specific examples of a higher level FEP to be incorporated as part of its definition, rather than pursuing the structure of the list to a lower level. This might be the case, for example, where there are a large number of potential members of a particular group (such as types of flora relevant to natural ecosystems), and there is no perceived need to identify all possible examples.

3 Development of the SSI Biosphere FEP List

A structured Biosphere FEP list, intended for application to the calculation of annual individual doses at an inland site from long-term releases of radionuclides in groundwater, was developed by the BIOMOVS II Reference Biospheres Working Group [BIOMOVS II, 1996]. The list did not include sufficient detail to be able to address all possible PA contexts of interest to biosphere assessment; nevertheless, it is considered a valid starting point in the context of reappraisal of the SFR safety case.

Since the original BIOMOVS II list was developed, renewed attention has been given within the IAEA BIOMASS programme and elsewhere to different aspects of the Reference Biosphere Methodology [BIOMASS, 1998a]. The changes in the organisation and contents of the FEP list presented here reflect the following developments:

- a clearer distinction between those elements of the list that correspond to the assessment context and those FEPs that are related to the biosphere system, radionuclide transport and radiation exposure;
- differentiation between 'biosphere system' FEPs, which relate solely to the properties of the system, and 'contaminant' FEPs (e.g. radionuclide migration and accumulation processes, and radiation exposures), which relate to the presence of radionuclides within the system;
- amplification and re-classification of FEPs based on experience gained from application of the Reference Biosphere Methodology since BIOMOVS II (see e.g., [EPRI, 1996]), including work in progress within BIOMASS Theme 1.

The proposed high-level structure of the SSI Biosphere FEP list is shown in Table 1; its full contents are presented in Annex 1.

A brief commentary on the hierarchy and main components of the list is merited here. Strictly speaking, 'Assessment Context' factors (Level 0) are not FEPs in the usually accepted sense, nor are most of them unique to the biosphere component of PA. Nevertheless, they are included here because a clear description of the basic premises of the assessment is considered important in identifying and justifying the various assumptions and simplifications that need to be made.

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Table 1
High-level Structure of the SSI Biosphere FEP List.

The distinction between ‘external’ and ‘system domain’ factors (i.e., Levels 1 and 2) depends critically on the overall approach taken to developing the PA and the corresponding scope of, and relationships between, the assessment models. In particular, it is relevant to understand the extent to which relevant climate change and geomorphological processes, such as isostatic uplift, will be treated as external ‘scenario-generating’ FEPs or explicitly simulated within the biosphere assessment. The assumptions implicit in the structure of the FEP list are not intended to represent a prejudice in favour of any particular assessment approach.

Biosphere ‘system domain’ FEPs (Level 2) have been further subdivided into (a) those that characterise the assumed components of the system (Environmental Features); and (b) those that describe phenomena (of natural or anthropogenic origin) within that system (Environmental Processes). This subdivision reflects the practical requirement first to identify and justify the biosphere system that is to be represented in the assessment, before moving on to develop a detailed description of that system suitable for model development.

It is recognised that, in practice, basic assessment considerations (summarised at Level 0) will tend to prescribe the assumptions adopted in describing the system. Nevertheless, contaminant behaviour within the biosphere system is addressed as a separate component of the FEP list (Level 3). The principle behind such a distinction is that it is helpful to distinguish those FEPs that relate to system behaviour and its evolution, independent of the presence of radionuclides, from those that relate specifically to the needs of radiological assessment. For example, whereas a description of the assumed human community is a necessary part of any biosphere system description; the characteristics of potential exposure groups are relevant only to the modelling of radiological exposure.

In completing the contents of the FEP list, the intention was not to provide an encyclopaedic description for each entry, backed up by exhaustive technical references. Nevertheless, a common format has been adopted in order to guide users in application of the list for assessment purposes. This format therefore consists of the following:

- FEP name and code;
- short definition;
- technical description and brief commentary on potential relevance to SFR;
- corresponding FEPs in the BIOMOVS II and NEA data bases.

There can be no absolute assurance of completeness in such a list. However, the fact that it is based on an extensive review of other work lends confidence to its use as a basis for biosphere modelling as part of the SFR safety case reappraisal. Meanwhile, the process of documenting how the list has been systematically screened at each stage of the assessment generates the necessary audit trail to provide a record of the comprehensiveness of the assessment.

4 References

BIOMASS (1998a). Long-term Releases from Solid Waste Disposal Facilities: The Reference Biosphere Concept. BIOMASS Theme 1, Working Document No.1, IAEA, Vienna.

BIOMASS (1998b). Alternative Assessment Contexts: Implications for Development of Reference Biospheres and Biosphere Modelling. BIOMASS Theme 1, Working Document No.2, IAEA, Vienna, April 1998.

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EPRI, (1996). Biosphere Modelling and Dose Assessment for Yucca Mountain. EPRI Technical Report, TR-107190, December 1996.

ICRP (1991). 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Annals of the ICRP, Vol 21, Nos.1-3.

ISAM (1998). Development of an Information System for Features, Events and Processes (FEPs) and Generic Scenarios for the Safety Assessment of Near-surface Radioactive Waste Disposal Facilities. Report of the Scenario Generation and Justification Working Group, ISAM Document SWG/0198, Version 0.1, June 1998.

NEA (1998). Safety Assessment of Radioactive Waste Repositories: An International Database of Features, Events and Processes. Nuclear Energy Agency, OECD, Paris. Draft report, January 1998.

Annex 1

SSI Biosphere FEP List

In what follows, the basic FEP list structure shown in Table 1 is expanded to provide definitions of each FEP (shown in the boxes). More detailed technical descriptions and comments (beneath each box) are also provided for each FEP, including notes on their potential role and relevance to the SFR safety case. Finally, cross-references are provided to the corresponding FEPs in the BIOMOVS II [1996] and NEA [1998] lists.

0 Assessment Context

The factors that need to be considered in determining the scope of the biosphere analysis, and which act as the primary reference point for any assumptions and simplifications that may be necessary.

The context in which a biosphere assessment is performed can have an important bearing on how the various environmental features, events and processes that are of potential importance are addressed within a specific assessment. A comprehensive discussion is provided in [BIOMASS, 1998b].

Corresponding FEPs:	NEA, 1998	Assessment basis (0)
	BIOMOVS II, 1996	Assessment context (1.1)

0.1 ASSESSMENT PURPOSE

The underlying reason for developing a biosphere model and/or carrying out a biosphere assessment. Example assessment purposes include:

- Demonstration of compliance with regulatory requirements for site licensing
- Formulation of regulatory guidance
- Contribution to confidence building
- Guide research priorities
- Proof of concept
- Guide to site screening, selection or approval
- System optimisation

Biosphere models are typically used as tools to determine the radiological significance of potential future discharges from waste disposal facilities. However, in any specific case, the purpose of developing and/or applying a model may vary from a simple calculation (e.g. to support concept development) to detailed site-specific performance assessment in support of a disposal licence application. Assessment assumptions and modelling simplifications that are appropriate to one type of calculation may not be so easily justified in different circumstances.

Corresponding FEPs:	NEA, 1998	Aims of the assessment (0.08)
	BIOMOVS II, 1996	Assessment purpose (1.1.1)

0.2 ASSESSMENT ENDPOINTS

The required format of the assessment results, expressed as a calculated radiological impact or in other terms. These may include both human health and environmental effects, or suitable indicators of – or surrogates for – such effects.

Examples include:

- – Annual individual dose/risk
- – Collective dose/risk
- – Modification of the radiation environment
- – Lifetime individual dose/risk
- – Impact on non-human biota and ecosystems
- – Non-radiological endpoints

The structure of an assessment model will tend to reflect the results that it is designed to evaluate. These, in turn, will largely depend on the criteria (regulatory or otherwise) that are adopted to judge the performance of the disposal system, of which the biosphere is a part. In calculating individual dose and/or risk, a clear description needs to be made of assumptions associated with defining representative members of hypothetical exposure groups. Modelling approaches may differ markedly according to whether the endpoint of an annual dose/risk calculation is interpreted as the maximum exposure in any year, or as an annualised lifetime exposure. Risk considerations also raise the question of how uncertainties in parameters affecting exposure should be interpreted in presenting the results of the assessment. SSI's regulations refer to an annual risk criterion of 10^{-6} for harmful effects from exposure, but provide no specific guidance regarding interpretation of the terms 'annual' or 'probability' (as a component of risk) in the context of biosphere assessment.

The calculation of collective dose (or risk) is critically related to the assumed size of the exposed population and the timescale over which integration is carried out, which should be defined as part of the basis of the calculation. It can be appropriate to limits to truncate both the timescale and the lower levels of individual exposure included in the evaluation of collective exposures. SSI's regulations require a calculation of collective dose, truncated at 10,000 years, for the exposures associated with releases during the first 1,000 years after repository closure.

There remains considerable uncertainty regarding how best to demonstrate compliance with safety principles requiring assurance of environmental protection. Nevertheless, SSI's regulations require that 'biological effects of ionising radiation in habitats and ecosystems concerned shall be described'. It is not unreasonable to consider that assessments of dose to a variety of species types might provide insight into the potential damage to the environment. Specific attention is focused in SSI's regulations on demonstrating protection for 'organisms worth protecting'.

Comparisons of predicted concentrations and/or distributions of repository-derived radionuclides in environmental media with, for example, natural background concentrations may represent a valid calculation endpoint, particularly at very long timescales. Such estimates are likely to be less dependent on seemingly arbitrary assumptions about human behaviour but correspondingly less indicative of the impact on human health. An important consideration is the assumed spatial extent over which the concentrations are evaluated – averaging approaches invoked in models designed to determine radiological exposure will not necessarily be appropriate to the determination of representative concentrations in environmental media. There is no explicit requirement in SSI's regulations to evaluate the future modification to the radiation environment. However, it may be possible to justify use of such an endpoint as a surrogate indicator of impact on non-human biota, as is widely practised in the context of environmental protection regulations for other contaminants.

Non-radiological endpoints may be important for certain categories of waste, in order to provide assurance of environmental protection from all contaminants that may be present. However, there is no explicit requirement to evaluate such endpoints in SSI's current regulations.

Corresponding FEPs:	NEA, 1998	Impacts of concern (0.02) Regulatory requirements and exclusions (0.09)
	BIOMOVS II, 1996	Assessment endpoints (1.1.2 et seq)

0.3 ASSESSMENT PHILOSOPHY

The underlying approach adopted towards the structuring of models and management of uncertainties within the assessment.

Even if the nature of the assessment endpoints may be clearly defined, the basic approach adopted in making assumptions within the assessment also needs to be made clear. An important example is the degree of pessimism introduced by assumptions necessary to determine radiological exposures for members of a hypothetical exposure group. Given that a hypothetical exposed individual is typically assumed to have access to resources from most contaminated parts of the environment, the question arises regarding the extent to which it is reasonable to add further pessimism in characterising their exposure (e.g. in respect of age). A related issue is the choice of dose-response function. If a uniformly pessimistic approach were adopted, it could be deemed appropriate to assume that the dose response function (for humans or other organisms) should be representative of the most sensitive individuals within a population, rather than the population average.

A distinction can be made [BIOMASS, 1998b] between the use of (a) a 'cautious' philosophy, designed to evaluate exposures for the potentially maximally-exposed individual at any time in the future; and (b) an 'equitable' approach, aimed at determining the typical exposure across a somewhat broader range of possible habits and/or locations. Where possible, consistency should be sought between the philosophy underlying the derivation of regulatory criteria (e.g., individual risk standards) and that adopted in calculations geared towards demonstrating compliance with such criteria.

SSI's regulations provide no specific guidance regarding the expected level of caution to be adopted in assumptions supporting the SFR post-closure performance assessment. However, they do indicate that dose-to-risk conversion factors (for members of potential exposure groups) should be those recommended by ICRP [1991].

Corresponding FEPs:	NEA, 1998	Spatial domain of concern (0.03) Future human behaviour assumptions (0.06) Dose response assumptions (0.07) Model and data issues (0.10) Adults, children, infants and other variations (2.4.02)

0.4 REPOSITORY SYSTEM

Assumptions made regarding the disposal facility to be addressed in the assessment calculation.

The description of the process system to be represented in a biosphere assessment model must be consistent with the known details of the disposal facility being considered, including the type of repository under consideration. For example, the type of repository (characterised by depth, waste type, host rock etc.), in conjunction with other aspects of the assessment context (such as the site context and evolution of future climate), can support identification of radionuclides of concern, or the geosphere/biosphere interface(s).

For SFR, the current status of the repository system and its local environment is well characterised. Repository-specific information can therefore be incorporated into the description of scenarios representative of future system evolution. In addition, however, it is important to recognise that assumptions regarding the operation, closure and subsequent administration of the repository may be significant in determining the ‘initial conditions’ at the start of the PA calculations.

Corresponding FEPs:	NEA, 1998	Repository assumptions (0.04)
	BIOMOVS II, 1996	Repository type (1.1.3)

0.5 SITE CONTEXT

A ‘broad-brush’ description of the physical features of the present-day biosphere in the general location where future releases may occur.

The overall spatial domain of interest to PA encompasses that associated with the recharge and discharge of the groundwater flow system passing through the repository at any time in the future. In addition, it needs to encompass all biosphere regions of potential importance to the determination of contaminant transport and radiological exposure. The surface environment in the region of interest can have an important influence on the likely transport pathways within the biosphere as well as the overall significance for the assessment of factors such as climate and geomorphological change. For example, a coastal location may provide a marine receptor for radionuclides released from the repository, whereas the assessment for an inland mountain location may not need to address marine FEPs. Alternatively, the topography at some sites may sustain the development of lake environments whereas others may not. The site context should therefore include a general description of the current topography and/or bathymetry in the vicinity of the site.

For SFR, current groundwater transport pathways from the repository lead to a marine receptor – however, isostatic uplift is considered likely to cause the coastline to reach the repository within a few thousand years. Groundwater flow rates and pathways through the repository may therefore change, and subsequent releases are likely to take place to a terrestrial environment.

Corresponding FEPs:	NEA, 1998	Spatial domain of concern (0.03)
	BIOMOVS II, 1996	Site context (1.1.4)

0.6 SOURCE TERM

The release of contamination into the biosphere from the repository system.

Biosphere assessment models are routinely decoupled, to a greater or lesser extent, from the models that are used to evaluate the release of radionuclides from the waste repository and transport through the geosphere. The link to the biosphere in such a system is described as the ‘source term’. In order to describe the source term relevant to biosphere modelling, it is necessary to describe the boundary interface across which the link between models is established (0.6.1), which in turn is partly dependent on the assumed release mechanism (0.6.2). In addition, the source term should describe the characteristics of the release itself, expressed in terms of its timing, content and other properties (0.6.3).

Corresponding FEPs:	BIOMOVS II, 1996	Source term (1.2)

0.6.1 Geosphere/Biosphere Interface

> The interface between biosphere and geosphere domains in a decoupled model of the process system.

The geosphere/biosphere interface defines the border of the biosphere model domain at its boundary with the geosphere. Definition of the interface is an intrinsic component of the conceptualisation of the disposal system and its environment, because the division of the repository environment into biosphere and geosphere domains is itself part of the overall conceptual approach. The interface should properly be located where decoupling of the models is most practicable, both in terms of their respective capability to represent relevant environmental features and processes and to ensure that recirculation of contaminants across the boundary is insignificant. Ideally, the domain of a biosphere model should be such that it can address various potential release mechanisms. In practice, an internally consistent identification of the interface will be obtained if both the biosphere and geosphere assessment models are informed by the same regional hydrological model. Except for simple well-water extraction scenarios, the detailed configuration and characteristics of the interface between the biosphere and geosphere is likely to be site specific and time dependent.

Corresponding FEPs:	BIOMOVS II, 1996	Geosphere/biosphere interface (1.2.1)

0.6.2 Release Mechanism

> The mechanism by which radionuclides (and any other contaminants of interest) are transferred from the geosphere to the biosphere. Example release mechanisms include:
> – Groundwater release to surface waters (fresh or marine) or land via natural aquifer discharge
> – Groundwater release via extraction of well water
> – Gaseous release
> – Release of contaminated solid materials as a result of human intrusion or natural erosion

Consideration of different potential mechanisms for releasing radionuclides to the biosphere is an integral part of the process of model definition. It is important in defining the spatial domain of concern to biosphere assessment models (including the geosphere/biosphere interface) as well as the physical and chemical form of the release.

Corresponding FEPs:	BIOMOVS II, 1996	Release mechanism (1.2.2 et seq)

0.6.3 Source Term Characteristics

> Basic attributes of the source term from the geosphere to the biosphere, including:
> – Radionuclide and other hazardous materials content
> – Physical and chemical properties of the release

Adequate characterisation of the source term is important in order to ensure that model definition properly addresses the specific properties of the release, for example in terms of the environmental behaviour of radiochemical elements and their radiological properties. If non-radiological endpoints are of potential concern, the source should include adequate description of possible future releases of such contaminants. Chemical properties of the associated transport medium, such as Eh and pH of groundwater, and any changes in such properties at the geosphere/biosphere interface, can be important in determining the transport and accumulation of particular contaminants in environmental media. In addition, the spatial and temporal characteristics of release to the biosphere (e.g. whether smooth or discontinuous) may be a significant consideration in biosphere assessment.

Corresponding FEPs:	BIOMOVS II, 1996	Source term characteristics (1.2.3 et seq)

0.7 TIME FRAMES

Identification of the time period(s) for which biosphere modelling is required, taking account of different assessment requirements (e.g. degree of detail) over different timescales.

The selection of a specific time frame can have considerable impact on considerations related to biosphere modelling, including the treatment of site evolution, critical radionuclides and geosphere/biosphere interfaces. SSI regulations identify two primary time periods for which results are to be presented. For the first 1,000 years after repository closure, the assessment is to be based on quantitative analysis of the impact on human health and the environment – this is also the period set for determination of collective dose (see 0.2 above). After the first 1,000 years, the assessment of safety performance is to be based on ‘possible sequences for the development of the repository’s properties, its environment and the biosphere’.

Corresponding FEPs:	NEA, 1998	Timescales of concern (0.02) Regulatory requirements and exclusions (0.09)

0.8 SOCIETAL ASSUMPTIONS

Basic assessment premises relating to the way in which representative future biospheres are presumed to be affected by human activity.

Human activities have a major influence on the status of the environment. The definition of future biosphere systems will therefore involve implicit or explicit hypotheses concerning social-economic structures (e.g. industrial, agrarian), land use, technological development, etc. Such hypotheses will influence both the definition of the biosphere system and the assumed behaviour of potential exposure groups.

Corresponding FEPs:	NEA, 1998	Future human action assumptions (0.05) Future human behaviour assumptions (0.06) Regulatory requirements and exclusions (0.09)

1 Biosphere System External Factors

The identification of FEPs with causes or origin outside the biosphere system domain, which need to be taken into account in describing the future environmental conditions at the site(s) of interest.

In scenario-based approaches to performance assessment, the decision is often made to separate the modelling of the 'process system', within which radionuclide migration, accumulation and exposure pathways will be evaluated, from consideration of the future evolution of the system. In practice, the boundary between 'external' and 'process system' FEPs will be subjective, depending on individual analysts' concepts and their modelling capabilities. The division made here is not intended to be definitive, but simply to provide guidance based on an interpretation of SSI regulatory requirements. Primary factors affecting landform change and biosphere evolution are considered to be: geological processes and their effects; climate processes and their effects; future human actions.

Corresponding FEPs:	NEA, 1998	External factors (1)

1.1 GEOMORPHOLOGICAL PROCESSES AND EFFECTS

Process system change within the biosphere caused by geological processes and events. Potentially relevant mechanisms on the timescales of interest to biosphere assessment include:

– Inundation by tidal wave generated by a seismic event
– Changes in topography/coastline associated with large-scale erosion processes
– Changes in topography/coastline in response to isostatic depression and rebound
– Soil conversion

A variety of processes of geological origin may have an impact on the future evolution of the process system relevant to a radioactive waste disposal. Many of these are relevant primarily to the description of the geological environment and the potential effect on groundwater flow rates, release from the near-field and contaminant transport pathways. However, certain processes may be responsible for landform change to the extent that they directly influence the characterisation of the biosphere within a PA. Particularly important at a coastal site (such as SFR) are those geological processes that may affect the position of the coastline and, thereby, the receptor for future releases from the repository.

Of the examples listed above, only the tsunami event falls readily into this classification. By contrast, erosion processes will occur on a wide range of spatial and temporal timescales. Consequently, it can be difficult to make a clear distinction between those effects of erosion that are better considered as an intrinsic part of a dynamic process system and those that are more readily treated as 'scenario-generating' effects. Coastline erosion may be particularly significant for sites (such as SFR) that are located close to the coast and therefore needs to be considered in developing an understanding of the future evolution of the site and its environment. The possibility of accelerated coastal erosion is routinely considered in the context of sea-level rise. However, the erosion of seabed sediments that become subjected to high-energy coastal processes as a result of sea level fall can also be an important consideration in the context of long-term assessment. This is a particularly relevant issue if such sediments were considered to have been previously contaminated as a result of contaminant releases to the marine environment.

Topographic change from down-cutting of river beds in response to change of sea-level is also a large-scale, long-term phenomenon, but is perhaps less directly relevant to describing the biosphere relevant to SFR. More localised FEPs, such as river bank erosion and landslides, occur on smaller temporal and spatial scales and consideration of their effects is therefore usually confined to the process system description (see 2.2.1).

Isostatic depression and rebound is, strictly, a geomorphological response to the climate-driven processes of global and regional sea-level change and ice-loading, rather than a geological process per se. Nevertheless, it is clearly a relevant consideration on Sweden's Baltic coast and therefore included here. On much longer timescales, tectonic and orogenic processes within the lithosphere may more accurately be considered as geological factors responsible for topographic change. However, such factors are likely to be only of limited importance to biosphere assessment on the timescales of interest to the SFR safety case.

Finally, it is important to recognise that soil conversion is a continuous geomorphological process of direct relevance to providing a description of the terrestrial biosphere. Typically, soil conversion is not represented explicitly within a dynamic system model; however, it is important to ensure that the characterisation of soil/sediments types within the biosphere system description (see 2.1.4) is consistent with other assessment assumptions. In the context of performance assessment, soil conversion is perhaps most important as a consideration associated with responses to climate and ecological change or climate-driven effects, such as sea-level change.

Corresponding FEPs:	NEA, 1998	Geological processes and effects (1.2) Tectonic movements and orogeny (1.2.01) Deformation (1.2.02) Seismicity (1.2.03) Isostatic sea level change (1.3.03) Erosion and sedimentation (1.2.07)
	BIOMOVS II, 1996	General biosphere system description (1.3.2) Environmental evolution (2.1.1) Physical changes (2.1.1.1.3 et seq)

1.2 CLIMATE CHANGE PROCESSES AND EFFECTS

Process system change within the biosphere may be caused by climate change. Potentially relevant mechanisms on the timescales of interest to biosphere assessment include:

- Change of global climate (with associated eustatic sea level change)
- Change of local and regional climate characteristics (with associated ecosystem, hydrological and human community responses)
- Ice sheet development and its effects
- Geomorphological response to specific climate effects

The treatment of climate in characterising the future biosphere systems may range from the assumption of constant present-day conditions to a full simulation of continuously-varying climate successions. The choices made in respect of modelling climate (and its effects on the biosphere system) can have a strong influence on the overall structure and composition of the biosphere model. There is no direct guidance in SSI regulations regarding the treatment of climate change, although they do require that the assessment includes a hypothetical case in which the biosphere conditions existing at the time of licence application do not change.

For the period after the first 1,000 years, it is expected that the performance assessment will be based on 'various possible sequences for the development of … the biosphere'. One option would be to model the release of contaminants into any one of a variety of time-invariant biosphere systems, each of which is consistent with a selected representative climate state. A more sophisticated approach would involve consideration of the transition between climate states; however, there is substantial scientific uncertainty concerning the timing of future sequences of climate development, especially in relation to the effects of global warming. Moreover, the temporal relationship between climate change and landform or ecological transition would also need to be considered in the context of such a 'dynamic' approach. The approach taken in practice will depend, in part, on the overall assessment philosophy with respect to the management of uncertainty (see 0.3).

Corresponding FEPs:	NEA, 1998	Climate processes and effects (1.3)
	BIOMOVS II, 1996	General climate description (1.3.1) Description of climate change (1.3.1.2)

1.2.1 Change of Global Climate

Possible future changes in global climate and their effects on the biosphere process system.

The Quaternary period has been characterised by climate cycling on a global scale between glacial and interglacial periods. Such global changes are understood to be caused by long-term changes in the seasonal and latitudinal distribution of solar insolation, due to periodic variations in the Earth's orbit around the Sun. These direct effects are modulated by feedback via albedo and atmospheric composition. Global climate change on a shorter timescale (and generally to a less significant degree) is also influenced by shifts in ocean circulation (e.g. the 'El Niño' effect) and sunspot activity. The interaction between anthropogenic greenhouse gas emissions and other factors affecting global climate is not yet well understood; however, it is thought that global warming may delay the onset of the next global ice age for several tens of thousands of years. The principal effects of global climate change in the context of biosphere assessment for geological disposal are (a) its impact on local and regional climate characteristics at particular locations (see 2.2.2), and (b) changes in eustatic sea level as a result of thermal expansion and contraction and the growth and decay of ice sheets.

Corresponding FEPs:	NEA, 1998	Climate change, global (1.3.01) Eustatic sea level change (1.3.03) Human influences on global climate (1.4.01)
	BIOMOVS II, 1996	Description of climate change (1.3.1.2)

1.2.2 Change of Regional and Local Climate

Possible future changes in local and regional climate and their effects on the biosphere process system.

Climate is characterised by a range of factors, including temperature, precipitation and pressure and their seasonal variations (see 2.1.1). Broad climate categories, based on classification schemes for present-day biomes across the globe, are typically distinguished in PAs in order to characterise potential future conditions at the site of interest. Downscaling from simulations of future global climate to regional and local conditions can involve additional uncertainties regarding the detailed climate characteristics and the sequence of particular changes. The situation is further complicated by the possibility of fluctuations on timescales of a few decades or less. Limited guidance is provided in SSI's regulations regarding the treatment of local and regional climate change in post-closure assessments (see discussion under 2.2). A clear description of the approach to be adopted is therefore necessary as part of the basic premises of the biosphere assessment.

The identification and definition of future biomes should be based on a coherent scheme, taking account of the overall assessment context. Identification of a particular climate analogue will involve consideration of the latitude, longitude, altitude and aspect of the region of interest, taking account of best understanding of the relevant factors determining global climate. Characterisation of climate states would be expected to rely predominantly on accepted classification schemes, including diurnal, seasonal and other variations in the primary climate parameters.

Certain climate categories will be associated with specific geomorphological processes (see 1.2.3–1.2.5). In addition, however, it is important to take into account within an assessment the more general responses associated with changes of intensity in temperature, precipitation and the like. These may affect the near-surface hydrological regime, such as changes in evapotranspiration, infiltration, soil water balance and surface runoff (which will also be modified by vegetation and human actions). Ecological responses to climate change on a regional and/or local scale include changes to soil types (see 1.1) and modifications to the equilibrium between plant and animal species, resulting in the development of new ecosystems. Human responses may include changes to the control over natural resources (e.g. storage of water), use of irrigation systems and modifications to farming methods (e.g. use of glasshouses).

Corresponding FEPs:	NEA, 1998	Climate change, regional and local (1.3.02)
		Hydrological response to climate change (1.3.07)
		Ecological response to climate change (1.3.08)
		Human response to climate change (1.3.09)
	BIOMOVS II, 1996	Differentiation of climate categories (1.3.1.1)
		Description of climate change (1.3.1.2)
		General biosphere system description (1.3.2)

1.2.3 Effects of Ice Sheet Development

Geomorphological effects associated with the development of local ice sheets.

Local glacial ice and regional ice sheets are expected to impact on SFR on a timescale of approximately 10^5 years. Ultimately, erosion by ice is likely to serve as a natural ‘cut off’ to the timescale over which any assessment of safety performance can be made. Such an episode therefore effectively dictates the timescale of interest for detailed post-closure performance assessment of SFR. Isostatic depression and rebound effects associated with ice loading and unloading effects have already been discussed above (1.1). As far as the biosphere component of the assessment is concerned, perhaps the most important considerations linked to local ice sheets are pro-glacial effects on surface hydrological features associated with meltwaters and outwash.

Corresponding FEPs:	NEA, 1998	Glacial and ice sheet effects, local (1.3.05)

1.2.4 Cold Climate Effects

Biosphere processes linked specifically to cold climate conditions.

Physical processes in cold, but ice-free, environments include the potential for large-scale water movements associated with seasonal thaws. Permafrost will restrict such movements to the surface environment, while potentially serving to isolate deep (contaminated) groundwater from the surface hydrological regime. Regional groundwater flow may become focused at localised unfrozen zones, under lakes, large rivers or at regions of groundwater discharge. Cold region processes could become of considerable significance at SFR in climate cooling episodes prior to the next glaciation.

Corresponding FEPs	NEA, 1998	Periglacial effects (1.3.04)
	BIOMOVS II, 1996	Differentiation of climate categories (1.3.1.1)

1.2.5 Warm Climate Effects

Biosphere processes linked specifically to warm climate conditions.

Regions with a tropical climate may experience extreme weather patterns (monsoon, typhoon), associated with flooding, storm surge, etc. These, in turn may have implications for local hydrological and erosional processes. High temperatures and humidity can also result in rapid biological degradation, causing tropical soils to be thin. In hot arid climates, total rainfall, erosion and recharge may be dominated by infrequent storm events. However, it seems unlikely that warm conditions as extreme as those encompassed by this FEP will occur at SFR prior to the next glaciation.

Corresponding FEPs:	NEA, 1998	Warm climate effects (tropical and desert) (1.3.06)
	BIOMOVS II, 1996	Differentiation of climate categories (1.3.1.1)

1.3 FUTURE HUMAN ACTIONS AND EFFECTS

This FEP corresponds to a description of the assumed role of human actions in defining the biosphere system. Principal features of human society relevant to the description of the biosphere system include:

- Land management systems that describe the level of human influence on the environment (e.g. through industry, agriculture, urbanisation)
- Specific resource exploitation practices associated with the management of water resources, land, flora and fauna, and the extent of import and export of resources to/from the domain of the biosphere system

The description of the biosphere system domain (see 2, below) needs to take into account basic assumptions related to the effects of human activities on the environment. A coherent description of human society should therefore be adopted, consistent with other assumptions regarding climate, landscape and (where appropriate) ecology, and taking account of the overall socio-economic context assumed as a basis for assessment. For the biosphere component of PA, however, there is no particular interest in identifying those human actions that might alter the performance of the engineered and/or geological barriers. It is assumed that human influences on global climate are addressed elsewhere (1.2.1).

Corresponding FEPs:	NEA, 1998	Surface environment, human activities (1.4.06)
	BIOMOVS II, 1996	Environments (1.3.2.1 et seq)
		Chemical changes by human action (2.2.1)
		Physical changes by human action (2.2.2)

1.3.1 Land Use Systems

The identification of different types of land use and their effect in defining the type of biosphere system.

Over the long periods of time generally associated with safety assessments for the disposal of solid wastes, the range of possible future land uses is very wide. Because of this, and the wide-ranging uncertainties associated with future human actions, biosphere systems adopted for the purpose of assessing potential radiological impact are best considered as contributing to representative indicators of performance, rather than as definitive predictions of future environmental conditions. The main features of the biosphere system are typically described in terms of large-scale environment 'types', within which specific ecosystems are identified. The intervention of man can dramatically influence the natural progression of ecosystems, for example through agricultural and land development practices. Relevant classifications include: natural and semi-natural environments, agricultural environments, urban and industrial environments.

It is possible to identify natural and semi-natural environments where humans have access but within which the natural biogeochemical cycles are largely unaltered. Such environments might include, for example, undeveloped marshland, natural forest, heather moorland and alpine meadows, as well as the marine fisheries. In the context of biosphere assessment, the primary distinctions between these and other classes of environment are therefore: (i) human influences are small; and (ii) exposure pathways for humans will tend to be based on the exploitation of natural resources. Some low-intensity farming practices may involve the use of semi-natural ecosystems as grazing land. In addition, it may be important to consider processes rated to radionuclide distribution within natural ecosystems if the endpoints to be addressed include the demonstration of adequate protection of the environment.

Agricultural and aquacultural ecosystems are associated with the intensive exploitation of land and water resources for the production of food. The intensity of land and water use will be constrained by primary productivity (i.e. a function of climate), and will be affected by the introduction of cultivation methods and nutrients that alter the natural biogeochemical cycle. Different levels of intensification can be identified for contemporary food production practice in different climate conditions around the world; these will typically form the basis for assumptions regarding the definition of an agricultural environment appropriate to the site under consideration.

The degree of industrialisation in a society has a marked effect on the extent to which humans have an influence on their environment, rather than allowing natural processes to determine the dynamic evolution of the biosphere. There may be a limited measure of self-sufficiency in urban environments (gardens etc.), but a major element of such 'systems' is the extent to which foodstuffs and other materials are transported from distant regions.

Corresponding FEPs:	NEA, 1998	Social and institutional developments (1.4.08) Technological developments (1.4.09) Community characteristics (2.4.08)
	BIOMOVS II, 1996	Environments (1.3.2.1 et seq) General human society description (1.3.3)

1.3.2 Resource Exploitation Practices

> The description of specific resource exploitation practices and their effect on natural cycles within the biosphere system.

Within a given environment, the particular resource exploitation practices followed by the community can have an important impact on the way in which bulk materials and contaminants are distributed and/or give rise to radiological exposures. Important considerations are the way in which terrestrial and aquatic resources are used and the extent to which human actions influence natural hydrological and biogeochemical cycles. More detailed consideration of specific processes associated with particular types of land use are considered as part of the system description (see 2.2.2).

In the natural and seminatural environments (including the marine environment), effects of human actions are, by definition, limited to the hunting/gathering of food and water, with limited disturbance of natural processes. One exception to this, perhaps, is upland farming, where grazing may significantly alter the natural ecosystem, although it would normally still be described as a semi-natural system.

Agricultural practices involve a variety of activities that may significantly influence the turnover and distribution of bulk materials and associated contaminants. These include the possible import and export of materials such as fertilisers and other nutrients, irrigation and land use rotation.

The industrialised exploitation of natural resources (e.g., mining and processing of minerals, pumping of groundwater, use of reservoirs) can have a marked effect on natural hydrological and biogeochemical cycles. Construction activities might lead to the large-scale redistribution of contaminated materials, and may be associated with exposure groups linked to ‘specialist’ activities (e.g. the handling of contaminated materials over extensive periods) that would not be a feature within other biosphere systems. Industrial activities on a regional scale may influence local air quality (and thereby local climate) or water quality. Human activity in urban and industrial environments can also lead to major changes to the natural topography (e.g. via land reclamation or levelling) and hydrological cycles (e.g. through artificial drainage).

Corresponding FEPs:	NEA, 1998	Water management (wells, reservoirs, dams) (1.4.07)
		Wild and natural land and water use (2.4.08)
		Rural and agricultural land and water use (2.4.09)
		Urban and industrial land and water use (2.4.10)
	BIOMOVS II, 1996	Environments (1.3.2.1 et seq)
		Chemical changes by human action (2.2.1 et seq)
		Physical changes by human action (2.2.2 et seq)

2 Biosphere System Domain Factors

A comprehensive description of the biosphere system(s) assumed to be representative of future environmental conditions at the site(s) of interest.

The development of conceptualised description of future biosphere systems involves characterising all the FEPs deemed relevant to the assessment context, consistent with assumptions made in respect of land use, as well as climatological and landform change. Potentially relevant considerations are described under items 2.1 and 2.2 below.

Corresponding FEPs:	NEA, 1998	Disposal system domain: environmental factors (2)
	BIOMOVS II, 1996	Basic system description (1.3)

2.1 ENVIRONMENTAL FEATURES

Potentially relevant characteristics of the biosphere system domain are identified under the following general headings:

– Climate characteristics
– Near-surface hydrogeology
– Surface waters (fresh and marine)
– Atmosphere
– Topography and morphology
– Soils and sediments
– Ecological Systems
– Human community characteristics

A comprehensive description of the biosphere system of interest to performance assessment begins with the identification of relevant features and classification of their important characteristics.

2.1.1 Climate Characteristics

A description of climate characteristics relevant to the climate state(s) addressed within the assessment.

Potentially relevant climate characteristics include the following:

- temperature;
- precipitation (rainfall, snowfall, occult deposition);
- pressure;
- windspeed and direction;
- solar radiation.

Seasonal variability of certain climate characteristics may be an important controlling factor on processes affecting the time-averaged concentrations of contaminants in environmental media and, hence, potential exposures. Longer-term variability and extremes (e.g. drought, storm events) may be important in assessing the possible sensitivity of annualised assessment endpoints to such uncertainties.

Of the above, however, precipitation is the only characteristic likely to be used directly within an assessment model, as a contribution to the overall water balance. Average windspeed may play a role in determining atmospheric concentrations of radionuclides released in gaseous form; however, it seems unlikely that climate-dependent windspeeds (rather than default values) would be used in practice within an assessment model.

Temperature is important in so far as the characterisation and importance of specific processes (e.g. freeze-thaw phenomena, vegetation growth, evapotranspiration) and practices (e.g. animal husbandry, water consumption) will tend to be a function of seasonal temperatures. Likewise, average windspeed and solar radiation levels may play a part in determining potential evapotranspiration rates, atmospheric dust levels and crop growing seasons, but otherwise have limited direct importance as biosphere parameters. Atmospheric pressure might be relevant in determining gaseous release rates but is very unlikely to play a direct role in the biosphere assessment itself.

Corresponding FEPs:	NEA, 1998	Meteorology (2.3.10)
	BIOMOVS II, 1996	General climate description (1.3.1) Seasonality (2.1.1.1.1) Rainfall (2.1.3.2.3) Snowfall (2.1.3.2.7)

2.1.2 Topography and Morphology

A description of relief and shape of the surface environment.

This FEP relates to local landform characteristics, including the coastline, plains, plateaus, hills and valleys, etc., within the domain of interest to biosphere modelling. An understanding of relief is clearly relevant to determining groundwater recharge and flow on a regional scale; on the local scale, there may be topographic effects on surface drainage that are relevant to describing near-surface hydrological pathways. However, it is unlikely that a description of topography would be incorporated directly within a biosphere assessment model; instead, its influence will normally be incorporated into the parameterisation of specific processes, such as interflow. Nevertheless, knowledge regarding present-day site relief (including bathymetry) is clearly relevant to developing an understanding of potential geomorphological change and future surface drainage patterns.

Important components of the topographical and morphological description of the biosphere system domain include those features that relate to the ‘margins’ between major environmental features. In particular, a time-dependent description of the margin between land areas and surface waters (eg the sea coast, meandering of rivers, evolution of lakes) is fundamental to any description of the long-term dynamics of the process system.

Corresponding FEPs:	NEA, 1998	Topography and morphology (2.3.01) Coastal features (2.3.05)
	BIOMOVS II, 1996	General biosphere system description (1.3.2)

2.1.3 Near-surface Hydrogeology

A description of the characteristics of the variably saturated and saturated zones on a catchment scale, typically within a few metres of the land surface.

This FEP relates to the attributes and properties of consolidated and unconsolidated geology within the domain of the biosphere system. The presence of aquifers and other underground water bearing features will be determined by geological, hydrological and climate factors. The extent to which such features need explicitly to be incorporated within the biosphere system domain depends on how the geosphere/biosphere interface (0.6.1) is defined. For example, if water extraction from a particular aquifer is to be explicitly represented within the biosphere model, the characteristics of that aquifer (its permeability, porosity, mineralogy, driving head, etc.) need to be defined in order to evaluate properly the contaminant concentration in the well water. Alternatively, if the aquifer is simply assumed to act either as a source of water at a fixed contaminant concentration (provided by the geosphere model), or as a 'sink' for percolating meteoric water, the specific properties of that aquifer are not directly relevant.

Knowledge of the lithostratigraphy and groundwater flow systems underlying the biosphere system domain can be particularly important in determining the partitioning of discharge from the regional groundwater system between direct leakage into surface water courses and release via surface soil. Hence, although detailed information may not be used explicitly within the assessment model, it can be directly relevant to determining the distribution of the source term (0.6) between different biosphere receptors.

Understanding of the characteristics of solid and unconsolidated geological features underlying the domain of the biosphere system (such as their erodability) is also clearly relevant to developing an understanding of potential long-term geomorphological change.

Corresponding FEPs:	NEA, 1998	Aquifers and water-bearing features, near surface (2.3.03)
		Hydrogeological regime, near surface (2.3.11)
	BIOMOVS II, 1996	Environmental components (1.3.2.3)

2.1.4 Soils and Sediments

A description of the characteristics of soils and sediments within the domain of the biosphere system.

Different soils and sediment types (characterised by their texture, mineralogy and organic content) will exhibit different properties with respect to drainage, sorption of contaminants, erosion and deposition, etc. Given these properties, together with assumptions relating to climate, topography and near-surface hydrogeology, it should also be possible to characterise the seasonal fluctuation of soil water content. An accurate definition of the precise characteristics of soils and sediments at a particular site long into the future is not practicable. However, by giving attention to soil conversion processes (see 1.1), alongside assumptions related to climate change and land use, it may be possible to reduce the uncertainties associated with parameterisation of relevant properties.

In order to characterise adequately the biosphere system, it may be necessary to identify different soil horizons, with different characteristics, as well as possible variations over the spatial domain of the system. The extent to which such descriptions are required as a basis for assessment modelling will depend on the geosphere/biosphere interface and other basic assumptions regarding potential pathways of environmental contamination. For example, if releases can occur at the margin between the marine and terrestrial environment, particular attention may need to be given to characterising the properties of coastal soils and intertidal sediments.

Corresponding FEPs:	NEA, 1998	Soil and sediment (2.3.02)
	BIOMOVS II, 1996	Environmental components (1.3.2.3)

2.1.5 Surface Waters (Fresh and Marine)

A description of the characteristics of surface water bodies within the biosphere system domain.

The importance of transport pathways mediated by water flow means that the identification and characterisation of surface water features can represent important elements of radiological impact assessment. This is not necessarily always the case, as certain contamination routes (e.g. irrigation by water abstracted via a well) may mean that the prime function of surface waters is to act as an effective ‘sink’ for radionuclides within the assessment model. However, it is also possible that exposure pathways associated with aquatic features can represent an important consideration in other assessment contexts, particularly if it is possible for contaminants to be concentrated in aquatic organisms or sediments.

It is customary to include the characterisation of suspended sediment within the description of the surface water bodies themselves. Relevant characteristics of surface water bodies therefore include their shape (see also 2.1.2), hydrochemistry, flow characteristics, suspended sediment composition, suspended sediment load, and sedimentation rate.

Corresponding FEPs:	NEA, 1998	Lakes, rivers, streams and springs (2.3.04) Marine features (2.3.06)
	BIOMOVS II, 1996	Environmental components (1.3.2.3)

2.1.6 Ecological Communities

A description of the characteristics of ecological communities within the biosphere system domain.

The identification and description of the characteristics of plants, animals and other organisms that are assumed to be present within the biosphere is a critical element of the overall system description. The objective is to be able to represent transfer pathways sufficiently well so that the endpoints of the assessment calculations are judged sufficiently representative of the potential effects of a future release. Where the overall objective includes an assessment of potential exposures of non-human species (0.2), the ecosystems included need to incorporate those specific organisms deemed particularly important. Where exposures of humans are being considered, sufficient detail needs to be provided to enable all potentially relevant exposure pathways to be evaluated with a sufficient level of caution.

The degree of heterogeneity within the biosphere system domain is an important characteristic of the description of plant and animal communities. The overall foodchain/foodweb structure, based on links between identified community components is also part of the ecological community description. For example, if agricultural biospheres or gardens are being considered, plant and animal communities can be represented a comparatively simple systems, rather than as complex foodwebs and nutrient cycles. Nevertheless, it may be necessary to show that foodstuffs and other resources derived from native plants and animals do not represent significant sources of potential exposure.

Potentially relevant components of terrestrial communities include:

- agricultural and native plants (trees, lianas, shrubs, herbs, epiphytes and thallophytes);
- domesticated and native animals (herbivores, carnivores, omnivores and detrivores);
- other organisms (fungi, algae, microbes).

For each of these, potentially relevant characteristics include:

- net primary and secondary productivity;
- biomass/standing crop per unit area;
- cropping;

- population dynamics;
- vegetation canopy, root structure and nutrient absorption characteristics;
- animal diets and behavioural characteristics;
- chemical composition and chemical cycles;
- metabolism.

A similar list of components and characteristics can be identified for aquatic ecosystems, viz:

- cultivated and native aquatic plants (emergent and submerged attached plants, phytoplankton);
- cultivated and native aquatic animals (herbivores, carnivores, omnivores and detrivores);
- other aquatic organisms (microbes).

Potentially relevant characteristics in each case include:

- net primary and secondary productivity;
- biomass/standing crop per unit area;
- cropping;
- population dynamics;
- vegetation root structure and nutrient absorption characteristics;
- animal diets and behavioural characteristics;
- chemical composition and chemical cycles;
- metabolism.

It is highly unlikely that all the issues identified here as being potentially relevant to a comprehensive description of ecological communities would be explicitly incorporated as part of a biosphere assessment model. In practice, for assessment purposes, a 'representative' ecological system will be identified, for which justification needs to be provided – compared with alternative approaches that could be taken – in respect of its 'fitness for purpose' in the context of the assessment. Part of the justification involves reference to the overall context of the assessment, with particular attention to scientific understanding of the relative importance of different ecological pathways to the assessment purpose and endpoints. Also important is an understanding of the potential ecological response to future climate change at a particular site (1.2) and assumptions made regarding the influence of human communities (1.3).

Corresponding FEPs:	NEA, 1998	Vegetation (2.3.08) Animal populations (2.3.09)
	BIOMOVS II, 1996	Environmental components (1.3.2.3) Resource usage (2.3.1.1)

2.1.7 Atmosphere

A description of the characteristics of the atmosphere within the biosphere system domain.

The local atmosphere within the biosphere system domain may be the receptor for gaseous and vapour releases. It may also act as a medium for aerosol transport. The primary characteristic of the atmosphere relevant to evaluation of dispersion and aerosol transport is near-surface wind speed (see also 2.1.1). In addition, atmospheric stability (which is itself a function of meteorological properties, such as insolation and wind speed) can be relevant. However, it seems unlikely that detailed representation of atmospheric properties will be a significant factor in biosphere assessment for waste disposal. Simple models for the effects of aerosol and gaseous transport, supported by appropriate sensitivity calculations, should normally suffice. It may be appropriate to draw a distinction between indoor and outdoor atmospheres if it is considered possible that contamination could be released directly into a building.

Corresponding FEPs	NEA, 1998	Atmosphere (2.3.07)
	BIOMOVS II, 1996	Environmental components (1.3.2.3)

2.1.8 Human Community Characteristics

> A description of the characteristics of the human community within the biosphere system domain, with particular attention to the role of human actions in defining the local biosphere.

Relevant characteristics include the population size and the degree of self-sufficiency of the local community with respect to the use made of local biosphere resources (including water). The extent to which a particular biosphere is able to sustain population resource requirements will determine the extent to which contamination is effectively diluted in terms of its effect on human exposure. If the biosphere system is assumed to support a resident population, the existence of homes and other domestic facilities may influence the approach taken to representing certain pathways of exposure. See also (1.3) et seq.

Corresponding FEPs:	NEA, 1998	Community characteristics (2.4.05) Dwellings (2.4.07)
	BIOMOVS II, 1996	General human society description (1.3.3)

2.2 ENVIRONMENTAL PROCESSES

> Phenomena, whether natural and artificial, that may influence the dynamics of the biosphere system or the behaviour of trace materials within the biosphere.

Environmental processes are sub-divided here into two main groups according to whether they are of natural or human origin. It is not considered necessary to distinguish between events and processes; generally, events are regarded as short-term and processes as continuous. In practice, however, it is not unknown for events (such as rainfall or erosion) to be represented within assessment models as processes, and processes (such as environmental change) to be modelled as events. In addition, as noted previously (1), the boundary between 'external' and 'process system' phenomena is somewhat subjective – the FEPs listed here relate principally to system dynamics operating on relatively short timescales within a typical region of interest to biosphere assessment.

Corresponding FEPs:	NEA, 1998	Surface environment (2.3)
	BIOMOVS II, 1996	Events and processes (2)

2.2.1 Natural Cycling and Distribution of Materials

> Natural phenomena giving rise to the movement of materials within the biosphere system.

Redistribution of environmental materials occurs continuously as a result of the cycling of materials in a biosphere system. Recycling processes mediated by living components of ecosystems include bulk movements of solids and liquids by flora and fauna, as well as metabolic processing of nutrients and other materials. Recycling processes mediated by non-living components of ecosystems include movements of solids, liquids and gases in the atmosphere, waters bodies, soils and sediments.

Corresponding FEPs:	NEA, 1998	Surface environment (2.3)
	BIOMOVS II, 1996	Natural events and processes (2.1)

2.2.1.1 Atmospheric Transport Phenomena

Natural processes related to materials transport within the atmosphere.

Various processes linked to the atmosphere contribute to the natural movement of materials within the biosphere system. These include:

- evaporation;
- gas transport by convection and diffusion in the atmosphere;
- aerosol formation and transport;
- sea spray formation and transport;
- precipitation;
- washout and wet deposition;
- dry deposition;
- wind-driven erosion (see also 2.2.1.3).

Corresponding FEPs:	NEA, 1998	Atmosphere (2.3.07) Atmospheric transport of contaminants (3.2.10)
	BIOMOVS II, 1996	Atmospheric transport processes (2.1.2.1)

2.2.1.2 Water-borne Transport Phenomena

Natural processes related to materials transport within the biosphere mediated by water.

A variety of processes associated with the hydrosphere may contribute to the natural movement of materials within the biosphere system. Mass transport processes cover the water itself, as well as suspended materials, associated gases and liquids, and trace materials in solution. These include:

- infiltration of water into soil;
- surface run-off;
- percolation of water through soils and sediments under the influence of gravity;
- capillary rise;
- groundwater recharge and discharge;
- saturated zone groundwater transport;
- multiphase flow;
- advection and diffusion (water and suspended sediment) in stream flow;
- advection and diffusion (water and suspended sediment) by tidal and marine currents;
- erosion of solid materials by waters (see also 2.2.1.3);
- aerosol generation by wave and wind action.

Corresponding FEPs:	NEA, 1998	Lakes, rivers, streams and springs (2.3.04) Coastal features (2.3.05) Marine features (2.3.06) Hydrological regime and water balance (2.3.11) Erosion and deposition (2.3.12) Water-mediated transport of contaminants (3.2.07)
	BIOMOVS II, 1996	Surface water aqueous transport processes (2.1.2.2) Porous media aqueous transport processes (2.1.2.3)

2.2.1.3 Solid-phase Transport Phenomena

> Natural processes related to the exchange of solid materials within and between environmental media.

Various processes may contribute to the movement of solid materials within terrestrial and aquatic environments. These include:

- settling of suspended sediments within water bodies;
- erosion and suspension of bed sediments by wave action and turbulence;
- coastal erosion;
- deposition of sediment during flooding;
- localised transport of soil material by rain splash;
- wind-driven aerosol generation;
- aerosol generation by fire;
- land slip.

Corresponding FEPs:	NEA, 1998	Coastal features (2.3.05) Erosion and deposition (2.3.12) Solid-mediated transport of contaminants (3.2.08)
	BIOMOVS II, 1996	Solid phase transport (2.1.2.5)

2.2.1.4 Transport Mediated by Flora and Fauna

> The movement of materials within the environment associated with biological processes and organisms.

Potentially relevant phenomena include:

- root uptake of water and nutrients from soil solution;
- plant respiration;
- plant transpiration;
- translocation of materials within plants;
- consumption of soils, sediments and foods by animals;
- inhalation of aerosols by animals;
- metabolism of materials within animal body tissue;
- interception of rainfall, aerosol or suspended sediment by plants and animal surfaces;
- weathering and/or volatilisation of materials from plant and animal surfaces;
- redistribution and mixing of soils or sediments by the activities of plants or burrowing animals (bioturbation);
- recycling associated with death and decay of organisms or parts of organisms.

Corresponding FEPs:	NEA, 1998	Vegetation (2.3.08) Animal populations (2.3.09) Ecological/biological/microbial systems (2.3.13) Animal, plant and microbe mediated transport (3.2.10)
	BIOMOVS II, 1996	Natural events and processes (2.1)

2.2.2 Cycling and Distribution of Materials by Human Activity

Human activities that contribute to the cycling of materials within the biosphere system.

Phenomena related to human activity can be an important feature of cycling of bulk and trace materials within the biosphere system. These include actions that modify the natural physical and chemical equilibrium within the biosphere, as well as processes that augment the movement of materials in the solid and liquid phase.

Corresponding FEPs:	NEA, 1998	Human behaviour (2.4) Human action mediated transport (3.2.12)
	BIOMOVS II, 1996	Events and processes related to human activity (2.2)

2.2.2.1 Changes to Natural Phenomena Associated with Human Actions

Changes to natural physical and biogeochemical cycles associated with human practices and activities.

Certain practices and activities undertaken by the local community may modify significantly the natural dynamics of cycling and distribution of materials within the biosphere system. These include:

- modification of plant and animal communities by agricultural practices;
- physical and chemical changes from the use of imported materials for soil improvement;
- chemical changes associated with pollution by industrial activities;
- alteration of natural water potentials by the pumped extraction (or recharge) of water from (or to) aquifers;
- modification of natural infiltration and drainage systems by construction activities;
- artificial mixing of water bodies;
- fire prevention and response measures in forest systems;
- drainage and reclamation of wetland and aquatic systems.

Corresponding FEPs:	NEA, 1998	Human behaviour (2.4)
	BIOMOVS II, 1996	Chemical changes by human action (2.2.1) Physical changes by human action (2.2.2) Transport mediated by human action (2.2.4)

2.2.2.2 Bulk Material Transport Phenomena linked to Human Actions

Human activities that augment the movement of bulk materials within the biosphere over and above the cycling associated with natural processes.

Human activities can result in the movement of environmental materials within the biosphere system – if people are assumed to be present, there possible contribution to the dynamics of the system should be considered. Potentially relevant phenomena include:

- gross movement of material by construction activity (excavation, ground levelling etc.);
- ploughing;
- abstraction of well water;
- abstraction of water from surface water bodies;
- irrigation of gardens and/or agricultural crops;
- recycling of crop residues, manure, ash or sewage sludge;
- removal of sediments for lakes, rivers, estuaries etc., by dredging;
- transfer of dredged sediments to land;
- controlled ventilation of buildings.

Corresponding FEPs:	NEA, 1998	Human behaviour (2.4)
	BIOMOVS II, 1996	Recycling and mixing by human action (2.2.3) Transport mediated by human action (2.2.4)

2.2.2.3 Trace Material Distribution Phenomena linked to Human Actions

Human activities that alter the natural physical and chemical composition of biosphere materials.

Certain human activities are deliberately intended to modify the natural distribution of trace materials in environmental media (irrespective of the possible presence of radionuclide contamination). Potentially relevant phenomena include:

- water treatment (filtering, chemical treatment, storage);
- air filtration;
- food processing.

Corresponding FEPs:	NEA, 1998	Food and water processing and preparation (2.4.06)
	BIOMOVS II, 1996	Air, water and food processing (2.3.1.3)

3 Radionuclide Contaminant Factors

Phenomena related to the behaviour of contaminants within the biosphere system and their impact on radiological exposure.

The development of an biosphere model for radiological assessment involves consideration of FEPs that directly affect the physicochemical behaviour of radionuclides and other contaminants, their concentration in environmental media, and associated pathways of radiological exposure. Relevant considerations include FEPs related to the physical and chemical properties of the contaminants (3.1), factors affecting migration and accumulation in the biosphere (3.2), and FEPs determining potential exposure (3.3).

Corresponding FEPs:	NEA, 1998	Radionuclide contaminant factors (3)
	BIOMOVS II, 1996	Processes affecting radionuclide concentrations (2.1.3) Events and processes related to human exposure (2.3)

3.1 CONTAMINANT CHARACTERISTICS

Potentially relevant physical and chemical characteristics of radionuclides and other toxic species that may be relevant to post-closure safety assessment are identified under the following general headings:

- Radioactive decay and ingrowth
- Volatility and volatilisation
- Chemical/organic toxin stability
- Organic materials formation

A comprehensive description of the behaviour of radionuclides and other contaminants of interest within the biosphere system begins with the identification of those FEPs that describe the basic physical and chemical characteristics of the materials involved.

Corresponding FEPs:	NEA, 1998	Contaminant characteristics (3.1)

3.1.1 Radionuclide Decay and Ingrowth

Spontaneous disintegration of unstable atomic nuclei, resulting in the emission of subatomic particles and the transformation of the original isotope to its daughter.

The treatment of radionuclide decay and ingrowth within the biosphere can be particularly important for those radionuclides that may accumulate in environmental media over substantial periods of time.

3.1.2 Chemical/Organic Toxin Stability

The chemical stability of chemotoxic species exposed to environmental processes.

Consideration of chemical stability within the biosphere can be particularly important for those chemotoxic species that may accumulate in environmental media.

3.1.3 Volatility and Volatilisation

FEPs related to the physical stability of radiochemical and other toxic species in the solid or liquid phase.

Some radionuclides may be naturally gaseous elements (e.g. the noble gases) or may form volatile compounds within the environment (e.g. iodine). These characteristics will be relevant to the way in which such radionuclides are treated within the assessment model.

3.1.4 Organic Materials Formation

FEPs related to the characteristics of radiochemical and other toxic species that have the potential to form organic materials in environmental conditions.

Certain chemical elements and species are capable of forming organic complexes when they come into contact with environmental materials. The subsequent behaviour of such materials may be substantially different from that of the inorganic form.

3.2 MIGRATION AND ACCUMULATION FACTORS

FEPs that directly affect the migration of radionuclides subject to recycling and distribution within the biosphere system domain. These are subdivided into the following:

– Dissolution and precipitation
– Speciation and solubility
– Sorption/desorption processes
– Interaction and transport with colloids
– Foodchain transfer

In order to model the behaviour of radionuclides and other contaminants of interest, it is necessary to take account of those FEPs that affect their migration and accumulation within environmental media.

Corresponding FEPs:	NEA, 1998	Contaminant release/migration factors (3.2)
	BIOMOVS II, 1996	Chemical reactions (2.1.3.1)

3.2.1 Dissolution and Precipitation

FEPs related to the dissolution, precipitation and crystallisation of radionuclides and other contaminants within the biosphere system.

Precipitation occurs when chemical species in solution react to produce an insoluble solid. The most likely potential causes of precipitation within the biosphere are chemical changes linked to speciation change at redox fronts. Chemical changes leading to precipitation or dissolution may also occur at the interface between fresh and saline water. Chemical changes introduced by human actions (e.g. in water treatment, or as a result of other chemical processing) may induce dissolution or precipitation processes.

Corresponding FEPs:	NEA, 1998	Dissolution, precipitation and crystallisation (3.2.01)
	BIOMOVS II, 1996	Dissolution/precipitation (2.1.3.1.1)

3.2.2 Speciation and Solubility

FEPs related to chemical speciation and solubility of radionuclides and other contaminants within the biosphere system.

The chemical form and speciation of a substance in aqueous solution is affected by temperature, pH and redox conditions; these, in turn, affect its solubility. The speciation in groundwater may be affected by chemical changes between the geosphere and biosphere – chemical speciation should therefore be indicated as part of the source term description (0.6.3).

Corresponding FEPs:	NEA, 1998	Speciation and solubility (3.2.02)

3.2.3 Sorption/Desorption Processes

FEPs related to the sorption and desorption of radionuclides and other contaminants within the biosphere system.

Sorption describes the physicochemical interaction (e.g. as a result of ion-exchange, complexation and matrix diffusion) of dissolved species with a solid phase. Such processes can be very important in determining the rate of transport and accumulation of contaminants in environmental media. Description via a simple partition coefficient (K_d) involves the assumption that sorption is reversible, that equilibrium is achieved rapidly, and that it is independent of changes in water chemistry or mineralogy, solid-water concentration ratio, or the presence of other species.

Corresponding FEPs:	NEA, 1998	Sorption/desorption processes (3.2.03)
	BIOMOVS II, 1996	Adsorption/desorption (2.1.3.1.2)

3.2.4 Interaction and Transport with Colloids

FEPs related to the transport of colloids and interaction of radionuclides and other contaminants with colloids in the biosphere system.

Colloids are naturally present in groundwater and may also be produced during degradation of the wastes or engineered barrier materials. Colloids may serve to enhance or retard contaminant transport, and can potentially influence the availability of contaminants for biotic uptake. The possible presence of colloids should be indicated as part of the source term description (0.6.3).

Corresponding FEPs:	NEA, 1998	Colloids, contaminant interactions and transport (3.2.04)
	BIOMOVS II, 1996	Transport of colloids (2.1.2.3.6.2)

3.2.5 Foodchain Transfer

FEPs related to the incorporation of radionuclides and other contaminants into plants and animal species that form part of the foodchain to humans or other target organisms.

Plants may become contaminated either as a result of the direct deposition of radionuclides onto their surfaces or via uptake from contaminated soils and water through the roots. Animals may become contaminated with radionuclides as a result of ingesting contaminated plants, soils, water and other animals, or via the inhalation of contaminated aerosols and gases. Changes in radionuclide content (e.g. through radioactive decay) may arise as a result of the storage of foods and other biosphere products before use or consumption.

Corresponding FEPs:	NEA, 1998	Uptake of contaminants in food chains (3.2.13)
	BIOMOVS II, 1996	Root uptake (2.1.2.7.1)
		Intake by animals (2.1.2.7.3)
		Radionuclide translocation and metabolism (2.1.4)
		Storage of products (2.3.1.2)

3.3 EXPOSURE FACTORS

FEPs that directly affect the exposure determined for members of hypothetical exposure groups and other organisms (where appropriate), given the calculated concentrations in environmental media. These are subdivided into the following:

– Human characteristics
– Human Habits
– Non-food products
– Dosimetry
– Non-radiological effects
– Exposure modes
– Drinking water and foodstuffs
– Other environmental media
– Radiological effects

Identification of potential exposure pathways needs to be consistent with the assumed characteristics of the biosphere system (climate, water resources, etc.), together with the underlying assumptions about human society.

Corresponding FEPs:	NEA, 1998	Human behaviour (2.4)
		Exposure factors (3.3)
	BIOMOVS II, 1996	Events and processes related to human exposure (2.3)

3.3.1 Human Characteristics

FEPs related to the characteristics of potentially exposed individuals.

Factors relevant to the determination of exposure include physiology and metabolism. Both of these are influenced by age, sex and occupation, as well as other genetic factors. It is necessary to decide whether exposures will be determined for adults only (based on standard ICRP dose factors) or if they are to incorporate calculations for other age groups. Detailed physiological and metabolic characteristics are not usually represented explicitly in assessment models, but assumptions influence the choice of data used to characterise exposure pathways and dosimetry.

Corresponding FEPs:	NEA, 1998	Human characteristics (2.4.01)
		Adults, children, infants and other variations (2.4.02)

3.3.2 Exposure Modes

FEPs related to the exposure of man or other organisms to radionuclides and chemotoxic species.

Exposure modes fall into three main classes: ingestion, inhalation and external exposure. A more detailed consideration results in the following list:

- external irradiation
  - from gases, vapours and aerosols present in the atmosphere;
  - from radioactive materials present in soils and sediments;
  - from immersion in, or proximity to, contaminated water;
  - from contaminated non-food products (building materials, furniture, clothing, etc.);
  - from contaminated plant surfaces or animals;
  - from dermal contamination;
- internal exposure
  - from drinking or eating contaminated water, foodstuffs and other materials;
  - from ingestion of soils and sediments (in association with food products or pica);
  - from inhalation of gaseous materials or aerosols;
  - from dermal absorption;
  - via wounds.

Corresponding FEPs:	NEA, 1998	Exposure modes (3.3.04)
	BIOMOVS II, 1996	External irradiation processes (2.3.2)
		Internal exposure processes (2.3.3)

3.3.3 Human Habits

FEPs related to the ‘passive’ behaviour of members of potential exposure groups, which influences their exposure to contaminated materials.

The assumed habits of exposure groups should be consistent with assumptions concerning the inter-relationships of individuals within the local community as well as the broader social context. For example, does the community living within the biosphere system import or export materials from/to elsewhere? Aspects of human behaviour relevant to the determination of exposure include:

- use of biosphere resources for water supply, foodstuffs and animal feed;
- non-food uses of biosphere resources;
- occupation factors (time and location for performing different activities).

Human habits will vary with age, sex and occupation – a sufficiently representative set of assumptions is required in order to perform a credible radiological assessment. There is no specific guidance in the SSI regulations regarding the definition of behaviour appropriate to comparisons of calculated exposures with regulatory criteria.

Corresponding FEPs:	NEA, 1998	Habits (non diet-related behaviour) (2.4.04)
	BIOMOVS II, 1996	Location/shielding factors (2.3.1.4)

3.3.4 Drinking Water and Foodstuffs

FEPs related to the presence of radionuclides and chemotoxic species in drinking water, foodstuffs or other materials consumed by members of potential exposure groups.

Internal exposures associated with ingestion will depend on the assumed diet and fluid intake (both composition and quantity) for members of potential exposure groups, as well as the proportion of the diet that is delivered from the contaminated biosphere. In addition to water, potentially relevant components of diet include plant-based food products:

- grain (wheat, rice, etc.);
- root vegetables;
- leaf vegetables;
- legumes;
- fruit vegetables;
- fruit and nuts;
- fungi;
- soil (in association with food products or pica).

and animal-derived food products:

- meat and offal (cow, sheep, pig, horse, goat, poultry);
- milk (cow, sheep, goat, horse);
- eggs;
- fish;
- game birds and animals;
- as well as other materials (pharmaceuticals etc) derived from such products.

Corresponding FEPs:	NEA, 1998	Diet and fluid intake (2.4.03) Concentrations in drinking water and foodstuffs (3.3.01)
	BIOMOVS II, 1996	Diet (2.3.1.5)

3.3.5 Non-food Products

FEPs related to the potential exposures to radionuclides and chemotoxic species in environmental media other than water and foodstuffs.

It may be necessary to evaluate the concentrations of contaminants in environmental media in order to evaluate exposure pathways from non-food uses of biosphere products. These include:

- construction (wood, soil, sediments, rocks, other plant materials);
- tools (wood);
- energy (wood, peat, waste products);
- furniture (wood, animal products, plant materials);
- clothing (animal and plant products);
- cosmetics (plant products, soils and sediments);
- fodder (pasture and fodder crops) consumed by domesticated animals.

Corresponding FEPs:	NEA, 1998	Concentrations in non-food products (3.3.03)

3.3.6 Other Environmental Media

FEPs related to the presence of radionuclides and chemotoxic species in other environmental media

It may be necessary to compare the calculated contaminant concentration of radionuclides and other contaminants in environmental media with naturally-occurring concentrations of similar species (see 0.2). An important consideration is the spatial extent over which such concentrations are evaluated – averaging approaches invoked in models designed to determine radiological exposure will not necessarily be appropriate to the determination of representative concentrations in environmental media. There is no explicit requirement in SSI's regulations to evaluate future modification of the radiation environment.

Corresponding FEPs:	NEA, 1998	Concentrations in other environmental media (3.3.02)

3.3.7 Dosimetry

FEPs related to the relationship between exposure to contaminants and the resulting dose.

Dosimetry involves estimation of radiation dose to individual organs, tissues or the whole body, as a result of exposure to radionuclides. Radiation dose will depend on the type of radiation, the mode of exposure, the metabolism of the particular physicochemical form of ingested or inhaled species, and the source-target geometry for external exposure.

Corresponding FEPs:	NEA, 1998	Dosimetry (3.3.05)

3.3.8 Radiological Effects

FEPs related to the effect of radiation on man or other organisms.

Below the threshold for non-stochastic effects, the detriment to humans from radiation exposure is generally assumed to be linearly proportional to the magnitude of the dose. Whereas the dose-effect relationships for humans are generally well defined (by ICRP), the relevant 'response' in the context of potential harm from radiation exposure to other organisms is much less well understood.

Corresponding FEPs:	NEA, 1998	Radiological toxicity/effects (3.3.06)

3.3.9 Non-radiological Effects

FEPs related to the effects of chemotoxic species on man or other organisms.

Corresponding FEPs:	NEA, 1998	Non-radiological toxicity/effects (3.3.07)

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Biosphere Modelling and Related Amber Case Files

1 Introduction

SKB (formerly the Swedish Nuclear Fuel Supply Co, SKBF) are due to submit a revised performance assessment (PA) for the continued operation of the SFR disposal site for low and intermediate level radioactive wastes by the end of 2000. SKB have recently published their prestudy for their project SAFE (Safety Assessment of Final Repository for Radioactive Operational Wastes) [SKB, 1998]. SSI's responsibility for scrutiny of the SKB PA is shared with the Swedish Nuclear Power Inspectorate (SKI).

SSI wishes to develop an independent PA capability for a time-dependent biosphere in preparation for the examination of the revised SFR safety case. The importance of such a capability in the context of SSI's overall review methodology is discussed by Watkins [1999].

This report documents the model development that has been undertaken by QuantiSci using the Amber computer code. In order to demonstrate the capability of Amber to model the SFR system, Section 2 describes the implementation of a simplified version of the models of both the near-field/geosphere and biosphere developed at the time of the original safety analysis. This work enables confidence to be gained in the use of Amber for SFR prior to the development of new models.

The biosphere models currently available do not allow key time-dependent processes to be fully represented, and Section 3 describes the development of a more detailed Prototype Amber Case File with a full time-dependent capability. This section commences with a discussion of the context within which the model is being developed (the assessment context), and goes on to discuss the key features, events and processes that need to be represented. In this work, as in any PA, the management of the geosphere-biosphere interface is an important issue. The way that this is dealt with uses ideas from a general discussion on geosphere-biosphere interface issues given in Appendix 1. The prototype Amber model includes sub-models for the whole system. Section 3 includes a detailed discussion of the 'Interface' and 'Biosphere' sub-models, whilst details of the 'Repository' and 'Geosphere' sub-models are given in SKI [1999].

The Prototype Amber Case file produced for SFR could provide the basis for an assessment capability for a deep repository (SFL). Section 4 includes a brief discussion of how this might be done.

Finally, Section 5 summarises the technical progress that has been made for SSI's programme for the review of the safety of the existing SFR and possible future SFL repositories.

1.1 Background Information on SFR

Documents referred to in this report give full information on matters such as the location and design of SFR. All this information is not repeated here, but for convenience, some of the data that will be frequently referred to are brought together.

SFR-1 has been designed as a facility for disposal of low level radioactive operational waste (LLW) and intermediate level waste (ILW) and the central interim store for spent nuclear fuel (CLAB) from the Swedish nuclear power plants. Radioactive wastes from industry, medicine and research are also disposed in SFR-1. The facility is situated in the crystalline bedrock formation beneath the Öregrundsgrepen and Bothnian Sea marine waters of the Baltic Sea, about 1 km off the coast near the Forsmark nuclear power plant in northern Uppland. The area is currently in isostatic rebound. This means that the seabed is rising and consequently the sea level appears to be falling.

The SFR storage vaults are approximately 60 m below the seabed. The underground part of the repository is accessed through two tunnels and the vaults are interconnected through a system of tunnels. Currently, the waste capacity in the existing parts of the facility is about 60,000 m^3, of which 23,000 m^3 has been utilised. Fuller details can be obtained from SKB [1987a, 1998].

SFR-1 is divided into four types of rock vaults:

- the silo (where the most radioactively contaminated material is disposed);
- rock vault for intermediate level waste, ILW (called the BMA);
- rock vaults for concrete tanks (called the BTFs);
- rock vault for low level waste, LLW (called the BLA).

The silo is designed for around 18,500 m^3 of conditioned waste, mainly ion-exchange resins in a concrete or bitumen matrix. The waste is normally packed in concrete or steel moulds or in 200 litre steel drums. The silo itself consists of a concrete cylinder (about 50 m high by 30 m diameter with 0.8 m thick walls), which is divided into vertical shafts with different levels each containing four moulds or 16 drums. The voids between the waste packages are backfilled with porous concrete. Between the silo walls and the surrounding rock is a bentonite backfill about 1.2 m thick. The 1 m thick concrete floor of the silo rests on a sand-bentonite mixture (90:10). It is planned that the 1 m thick concrete lid will have gas vents to allow the escape of gas from the silo. The lid will be covered with a layer of sand, then 1.5 m of 90/10 sand-bentonite followed by sand, gravel or sand stabilised in cement.

The BMA vault is designed to accept similar wastes to that of the silo but with lower radioactivity levels. The vault is 160 m long and has a cross-section of around 300 m^2. The structure that contains the wastes within the vault is constructed of concrete and is divided into 15 compartments with concrete walls between each section. The waste is emplaced on top of the concrete floor in stacks with a concrete lid on the top. Between the concrete structure and the rock vault wall is a space of about 2 m that will be filled with sand at closure. The space above the concrete structure up to the vault ceiling will probably be left unfilled.

There are two BTFs that will contain concrete tanks for the emplacement of wastes such as dewatered LLW ion exchange resins and drums of ashes. Each BTF vault is 160 m long with a cross section of about 130 m^2. The concrete tanks each have a volume of 10 m^3. They are placed in two tiers each with four tanks. A concrete radiation protection lid is placed on top of the tiers whilst the space between tanks is backfilled with concrete and the space between the tanks and the rock vault wall will be filled with sand stabilised in cement. The space above the lids is likely to be left mainly unfilled.

The BLA is mainly for LLW trash placed in either steel drums or bales within steel containers. The vault is 160 m long with a cross-section of 180 m^2. The containers stand in two rows on a concrete base, with three full height or six half height tiers to a row. No backfill is planned.

2 Amber Implementation of Existing Models

The modelling undertaken at the time of the original safety case submission for SFR considered two periods: the saltwater period, when fluxes of radionuclides to the biosphere entered the local marine environment, and the inland period, when radionuclides entered a lake or a well. The change occurred due to land rise resulting in changes in the surface environment. It should be noted that two separate sets of calculations were undertaken for the two different periods; no attempt was made to undertake a single consistent set of calculations with a transition between the two cases.

In order to gain confidence in the use of Amber for SFR, a demonstration Amber Case File was produced by reproducing a version of previously reported models. Although SSI's interests lie in the modelling of the biosphere, it is necessary to provide models for the whole system in order to provide a suitable flux of radionuclides into the biosphere. For the near-field, the models described by SKB [1987a], henceforth referred to as the NF report, provided the basis for the Amber models, and those models are described in Section 2.1. A very simple geosphere model was used, based on that employed by SSI [1989], and this is described in Section 2.2. The biosphere model employed was also taken from SSI [1989], and this is described in Section 2.3. A large number of calculations using the resulting Case File have been undertaken and compared with results given in the NF report. A selection of these calculations is described in Section 2.4, concentrating on the silo and the system as a whole.

In Section 2.5 the experience gained from the use of the demonstration Amber Case File is summarised.

Some of the detailed information on Amber parameter values for the demonstration case file is given in Appendix 2.

2.1 The Near-field

SFR-1 is divided into four types of rock vaults:

- the Silo;
- Rock Vault for Intermediate Level Waste (BMA);
- Rock Vault for Concrete Tanks (BTF);
- Rock Vault for Low Level Waste (BLA).

Amber sub-models for each of these facilities have been set up, based mainly on information available in the NF report.

The NF report uses the concept of 'capacity' when describing radionuclide transport in the near-field. This parameter κ has units of m^3 and can be defined in a similar fashion to equation 5-3 of the NF report:

$$\kappa = \sum V(\varepsilon + \rho K_d)$$

where V is the volume material in the compartment, ε is the porosity, K_d is the distribution coefficient and ρ is the bulk density. The summation is over the different materials in the compartment, although for simplicity all the Amber compartments are assumed to be composed of a single material. The capacity of a compartment is related to the retardation coefficient for radionuclide transport R, for the materials involved:

$$\kappa = \sum V \varepsilon R$$

The concentration of radionuclides in the porewater of any compartment can be obtained from an expression corresponding to equation 5-4 in the NF report:

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

where I is the total amount of radioactivity in the compartment.

If the flux of radionuclides between two compartments is diffusive, that flux can be approximated by an expression corresponding to that given in equation 5-1 of the NF report:

$$F = -\frac{A D_e \Delta c}{\Delta}$$

where A is the cross-sectional area relevant to the transport, D_e is the effective diffusion coefficient, Δc is the difference in concentrations between the two compartments, and Δ is a representative diffusion length. Employing the expression above for the porewater concentration, the expression used in Amber for diffusive transfers between compartments becomes:

$$\lambda = \frac{A D_e}{\kappa \Delta}$$

The diffusive flux is represented by the combination of a ‘forward’ and ‘backward’ exchange coefficient.

The corresponding expression for an advective flux, corresponding to equation 5-1 in the NF report is:

$$F = A v c$$

$$\lambda = \frac{A v}{\kappa}$$

where v is the Darcy velocity.

2.1.1 THE SILO

The Silo sub-model is shown in Figure 1.

The contents of the silo (waste matrix, packages and porous backfill) are assumed to act as a uniformly mixed ‘soup’, represented in the Amber model by the ‘SFRSilo’ compartment. Inside the silo the compartment walls are assumed initially to be uncontaminated; these are represented in the Amber model by the single compartment ‘CompartmentWalls’.

Radioactivity can leave the silo through 3 routes (see Table A2.1, Appendix 2); through the top, through the bottom, or through the mantle (the side walls). Releases through the mantle have to pass through the wall of the silo (represented in the Amber model by the single compartment ‘SiloWall’) and then the surrounding bentonite buffer (represented in the Amber model by the single compartment ‘BentoniteBuffer’).

Releases through the top of the silo can either pass through the lid of the silo (represented in the Amber model by the single compartment ‘SiloLid’) or the small gas devices placed in the lid to allow gas to escape (represented in the Amber model by the single compartment ‘GasDevices’). Having passed through the lid or the gas devices, radionuclides must pass through the cover material of sand/bentonite mix (represented in the Amber model by the single compartment ‘SandBentoniteCover’).

Releases through the bottom of the silo have to pass through the base of the silo (represented in the Amber model by the single compartment ‘SiloBottom’) and then through the cover material of sand/bentonite mix (represented in the Amber model by the single compartment ‘Sand-BentoniteBase’).

Table 1 gives details of the materials of which the compartments are assumed to be composed in the saltwater period. The silo is assumed to consist of simple concrete, rather than a mixture of concrete and porous concrete, as specified in the NF report; this makes little difference to the ensuing radionuclide transport calculations.

In the saltwater period, all the barriers are assumed to be intact, so that the only transport mechanisms are by diffusion. In order to represent diffusion processes in detail, it would be necessary to split each part of the system into a number of sub-compartments. However, despite the significant approximations involved, it has been found that using single compartments for each part of the system can derive quite adequate approximations of fluxes to the biosphere.

Near-field/Geosphere Interface

The fluxes of radionuclides from the edge of the near-field (the bentonite buffer around the mantle, and the sand and bentonite layers under the base and over the top of the silo) into the geosphere depend upon the boundary conditions that are assumed. In the NF report a boundary condition was applied which depends upon the ‘equivalent water flow rate’, *Q*, assumed to be flowing past the relevant boundary:

$$F = Q c_g$$

Table 1
Materials assumed for Near-field Compartments in the Saltwater and Inland Periods.

Compartment	Material	Volume (m^3)
CompartmentWalls	Aged concrete/Degraded concrete	3,485
SFRSilo	Aged concrete/Degraded concrete	16,884
SiloWall	Aged concrete/Degraded concrete	2,267
BentoniteBuffer	Bentonite	5,573
GasDevices	Sand	0.5
SiloLid	Aged concrete/Degraded concrete	594
SandBentoniteCover	Sand/Bentonite mix	891
SiloBottom	Aged Concrete/Degraded concrete	594
SandBentoniteBase	Sand/Bentonite mix	891
BMAWasteMatrix	Waste matrix	8,723
BMACompartments	Aged concrete/Degraded concrete	2,690
BMAWater	Water	4,927
BMAInternalWalls	Aged concrete/Degraded concrete	1,040
BMAExternalWalls	Aged concrete/Degraded concrete	1,600
BMAFloor	Aged concrete/Degraded concrete	570
BMAVoidSpace	Water	17,420
SFRBLA	Water	18,900
SFRBTF	Water	2,844
TankWalls	Aged concrete/Degraded concrete	2,607
BTFVoidSpace	Water	5,688

In the Amber modelling, c_g in the above equation has been taken to be the concentration in the flowing water, and in the saltwater period the flux has been taken to depend linearly on the difference between c_g and c_n, the concentration in the relevant near-field compartment, as given in the algorithms described previously. One then has:

$$Q\, c_g \quad = \quad \frac{A\, D_e\, \Delta c}{\Delta}(c_n - c_g)$$

This can be used to obtain an expression for c_g that can be used to define the flux directly in terms of c_n. If the constant of proportionality is taken to be α, then:

$$F \quad = \quad \alpha\, c_n$$

$$\alpha \quad = \quad \frac{Q}{1 + \dfrac{Q\, \Delta}{A\, D_e}}$$

The values of Q quoted for the saltwater period in the NF report are 2 m^3 y^{-1} for the top of the silo, 0.064 m^3 y^{-1} for the mantle and 0.02 m^3 y^{-1} for the bottom of the silo. These values are critical in determining the flux of radionuclides out of the near-field in the saltwater period.

2.1.2 ROCK VAULT FOR INTERMEDIATE LEVEL WASTE (BMA)

The BMA sub-model is shown in Figure 2.

The contents of the vault (waste matrix, compartment construction and water inside the compartment) are assumed to act as a uniformly mixed 'soup'; represented in the Amber model by three compartments ('BMAWasteMatrix', 'BMACompartments' and 'BMAWater') with rapid exchanges between the compartments to ensure that porewater concentrations are the same in each. Inside the vault the internal walls are assumed initially to be uncontaminated; these are represented in the Amber model by the single compartment 'BMAInternalWalls'. The void space above at the top of the vault is assumed to be filled with water, and is represented in the Amber model by the compartment 'BMAVoidSpace'.

In the saltwater period radioactivity can enter the water in the void space at the top of the cavern by advection or diffusion through the floor or the external walls (and lid). In each case the transfers are modelled in a similar way to corresponding transfers for the silo.

Table 1 gives details of the materials of which the compartments are assumed to be composed of in the saltwater period. The waste matrix is taken to have a porosity of 0.4.

In the inland period, the barriers are assumed to be ineffective, so that radioactivity is assumed to be uniformly mixed throughout the near-field compartments. This is simulated in Amber by rapid exchanges between all the compartments interacting with 'BMAWasteMatrix' for the relevant period to provide a uniform porewater concentration throughout the system.

2.1.3 ROCK VAULT FOR CONCRETE TANKS (BTF)

The BTF sub-model is shown in Figure 3.

The waste contents of the tanks are included in the compartment 'SFRBTF'. No sorption is assumed in this compartment, so the Amber parameters reflect that water-filled volume available. A separate compartment, 'BTFTankWalls', represents the walls of the tanks. For a short period (100 years) the sole release mechanism considered is diffusion through the tank walls directly into the geosphere. For that period the walls are assumed to have the properties of fresh concrete.

After the integrity of the tanks walls are assumed to break down, for the remainder of the saltwater period it is assumed that both diffusive and advective processes transport radionuclides into the water-filled void in the cavern (Amber compartment 'BTFVoidSpace'). For this period the tank walls are assumed to have the properties of aged concrete.

In the inland period equilibrium is assumed between the tank internals, the tank walls and the void space. This is simulated in Amber by rapid exchanges between the three compartments.

2.1.4 ROCK VAULT FOR LOW LEVEL WASTE (BLA)

The BLA sub-model is shown in Figure 4. It is the simplest model where the contents of the vault are represented by a single compartment, 'SFRBLA'. The compartment is used with no allowance for sorption, and radionuclides are released directly to the geosphere by advection.

2.2 The Geosphere

In the safety assessments carried out at the time of the original safety submission for SFR, little credit was taken for the geosphere barrier. SSI [1989] assumed a simple transfer rate between the geosphere and the biosphere of 0.003 y^{-1} in the saltwater period, and 0.0017 y^{-1} in the inland period. These simple assumptions have been retained in the Amber Case File.

2.3 The Biosphere

Figure 5 shows the biosphere model in the Amber case file, which is taken directly from SSI [1989]. In the saltwater period the release from the geosphere enters a regional coastal area known as the Öregrundsgrepen. This exchanges water volumes with the Bothnian Sea, which in turn exchanges water volumes with the Baltic Sea proper. Each of these water compartments has associated with it a sediment compartment.

In the inland period, the release from the geosphere enters a lake, which has associated with it surface and deep sediment compartments. Fresh water from the lake discharges to the Bothnian Sea.

The demonstration Amber model enables doses to the critical group to be calculated for the consumption of sea fish from the regional waters in the saltwater period, and from the consumption of lake fish from the lake in the inland period. In both cases the doses, H, are calculated from:

$$H \quad = \quad \kappa\, I\, F\, C$$

where κ is the dose per unit activity ingested (Sv Bq^{-1}), I the ingestion rate for the fish (kg y^{-1}), F is the relevant concentration factor for the fish (m^3 kg^{-1}) and C is the radionuclide concentration in relevant aquatic compartment (Bq m^{-3}).

The biosphere model employed by SKB [1987b] differs from the demonstration Amber model in a number of ways including:

1. The aquatic compartments are structured somewhat differently. There is a smaller local seawater compartment into which radionuclide discharges are made in the saltwater period, which exchanges water volumes with the Öregrundsgrepen. However, there is no distinction made between the Bothnian Sea and the rest of the Baltic.
2. Additional regional and global compartments are included in order to be able to calculate collective doses.
3. Local and regional groundwater and soil compartments are used for the inland period in order to be able to calculate doses from well water consumption, and the use of well water to irrigate crops.

2.4 Model Calculations

Some example calculations are shown here to illustrate the good correspondence between the Amber model and the original models.

Saltwater Period Releases

Figure 6 shows the total flux of radionuclides from the silo near-field for the saltwater period. This corresponds closely with Figure 6.3 of the NF report.

Figure 7 shows the fractional release rate of organic carbon from the silo near-field for the saltwater period. This compares well with Figure 6.8 of the NF report.

Inland Period Releases

Figure 8 shows the radionuclide release rates from the silo during the inland period. The initial release rates at 2,500 years correspond very closely with those given in Figure 6.13 and Table 6.9 of the NF report, and for long-lived radionuclides that are sorbed onto the degraded concrete (e.g., Tc-99, Pu-239 and Pu-240), the shapes of the curves are very similar. For radionuclides not so strongly sorbed (e.g., organic C-14, Cs-135 and Ni-59), the shapes of the curves are rather different; the SKB calculation show a ‘flat’ release rate followed by a rapid decay, whilst the Amber calculations show a more steady gradual reduction in release rate. This difference is due to the assumption in the Amber calculations that radionuclides remain uniformly mixed throughout the silo. In the SKB calculations the profile of radioactivity is initially uniform, but subsequently the profile becomes non-uniform due to the combined effects of advection from one end of the silo and diffusion inside it. Splitting the Amber ‘SFRSilo’ compartment into a number of sub-compartments could more closely simulate the SKB calculations, but it is considered that the representation of the flux to the geosphere is quite adequate for the current application.

Total Releases

Figure 9 gives the total releases into the geosphere for each repository for the saltwater period. This compares well with Figure 10.1 of the NF report. Figure 10 gives the corresponding total releases for the inland period. Again, these compare well with Figure 10.2 of the NF report.

Critical Group Doses: Saltwater Period

Calculations of critical group doses from the consumption of fish from regional seawaters in the saltwater period have been compared with those given in SSI [1989]. Because of the different near-field models used (the SSI calculations used radionuclide-independent transfer rates out of the near-field), the calculations are not directly comparable, but similar magnitudes and patterns of doses are seen. Figure 11 shows the calculated doses for the most significant radionuclide in this period, Cs-137. In this case the calculations compare reasonably closely with Figure A6 of SSI [1989].

Critical Group Doses: Inland Period

Calculations of critical group doses from the consumption of fish from the lake in the inland period have been compared with those given in SSI [1989]. Because of the different near-field models used (the SSI calculations used radionuclide-independent transfer rates out of the near-field), the calculations are not directly comparable, but similar magnitudes and patterns of doses are seen. Figure 12 shows the calculated doses for Pu-239. In this case the Amber calculations are around two orders of magnitude less than those shown in Figure A18 of SSI [1989], as Amber calculates much slower release rates from the near-field.

2.5 Summary

The implementation of SKB’s near-field models and SKI’s biosphere model in Amber has given confidence in the suitability of Amber for use as a performance assessment tool for the SFR. The biosphere model is extremely simple, and does not account for time dependent processes. There are no fundamental difficulties associated with developing the existing model into one that is capable of handling such processes.

3 A Prototype Time-Dependent Amber Model for SFR

Before developing a new prototype Amber model to allow for time dependent processes, it is helpful to review the context in which the model is being developed. This discussion of the assessment context for SKB's Performance Assessment for SFR is discussed in Section 3.1; this provides the basis for the model development for SSI. As stated by Watkins [1999], SSI's PA methodology does not have to be as comprehensive as SKB's, as it does not need to be capable of making the safety case for SFR, but is to be used as a tool in reviewing such a case by SKB.

This is followed in Section 3.2 by a discussion of the key features, events and processes that need to be considered, with particular emphasis on the geosphere-biosphere interface. As the SSI model does not have to be complete in the sense that will be required of SKB, an informal approach is used to FEP representation in the revised Amber model, but taking account of the FEP list given by Egan [1999].

The new prototype time-dependent model for SFR is being developed as four sub-models. The Repository and Geosphere sub-models are being developed for SKI, and these are described in SKI [1999]; these can be used to provide the source flux of radionuclides into the Geosphere-Biosphere Interface sub-model, which is described in Section 3.3 and the Biosphere sub-model, which is described in Section 3.4.

The prototype Amber model will not address all of the issues referred to in the assessment context of Section 3.1, as the development of the PA tools are still at an early stage; further development will be required as the project to review SKB's safety assessment for SFR proceeds. Some of the key issues that have not yet been addressed are discussed later, in Section 5.

3.1 The Assessment Context

Definition of the Assessment Context – Biosphere Component

In Sweden, as in many countries throughout the world (including Finland, Japan, Switzerland and the USA), PA programmes are in place to assess the safety of underground repositories for the emplacement of radioactive wastes. A post-closure PA is generally undertaken to provide confidence to government, regulatory authorities, the general public and technical/scientific personnel that the repository has been sited and engineered to ensure the safety of people and protection of the environment over very long timescales. The PA assessment context is intended to provide answers to the two questions:

- What are you trying to assess?
- Why are you trying to assess it?

In a quantitative PA, these questions become:

- What are you trying to calculate?
- Why are you trying to calculate it?

A PA consists of many parts related to the performance of the engineered barriers and the movement of radionuclides through the near-field, geosphere (far-field) and the biosphere. It is important that the overall assessment context for the whole PA is developed in such a way that it provides a coherent and consistent context for each of the parts.

This section of the report is concerned with the biosphere component of the assessment context. In the framework of the biosphere, and developments in Theme 1 of the on-going IAEA co-ordinated research programme on biosphere modelling and assessment methods (BIOMASS), eight elements of the assessment context have been identified:

- purpose of the assessment;
- assessment end-points;
- assessment philosophy;
- repository system;
- site context;
- source terms and the geosphere-biosphere interface;
- timeframes for the assessment;
- societal assumptions.

In the following sub-sections, these eight elements are discussed with specific reference to what was presented previously by SKB (e.g., SKB [1987a], [1987b]), what is expected to be presented by them for the forthcoming re-authorisation PA (based on for example, SKB [1998]), recent regulatory developments within Sweden [SSI, 1998a, b] and information presented in Smith [1999] concerning these new regulations.

The Purpose of the Assessment

It is assumed that the purpose of the forthcoming SKB PA is demonstration of regulatory compliance with the new Swedish regulations [SSI, 1998a].

A PA for the operation of SFR-1 was presented to the Swedish regulatory authorities (SSI and SKI) in 1987. Licence for operation was granted in March 1988, but with the requirement for complementary analyses of some specific issues. The result of the complementary analyses was presented in an extended safety report in 1991 [SKB, 1991]. In the operational licence for SFR-1 it was stated that renewed safety assessments should be carried out at least each ten years. In order to meet this requirement, SKB will update the safety analysis and prepare a new application for re-authorisation of the disposal facility not later than the year 2000. Since submission of the original extended safety report in 1991, the Swedish regulations have been updated [SSI, 1998a] and some guidance on application of the regulations has been provided [SSI, 1998b]. The new application for re-authorisation will have to take account of the new regulatory requirements.

SKB’s new PA will seek to demonstrate that the SFR facility continues to operate safely with respect to the impact on humans and the environment. From this perspective, the purpose of the biosphere part of the assessment is to provide information on the radiological significance of potential future discharges of radionuclides from the near-field and geosphere into the biosphere.

In order to investigate SKB’s safety case, SSI wishes to develop its own biosphere assessment capability. The purpose of the biosphere model developed in collaboration with SSI should therefore be similar to that of SKB outlined above.

End-points of the Assessment

Three endpoints are stated in SSI [1998a]. They are:

- annual individual dose and risks from expected releases;
- collective doses from outflows in the first 100 years integrated over the first 10,000 years;
- radiological impacts on the environment.

These requirements imply that calculations should be provided for:

- a range of exposure groups to assess potential annual individual doses and risks;
- collective doses;
- environmental concentrations in various media as input to any environmental risk assessment methodology developed by or for the SSI.

Assessment Philosophy

The new regulations do not provide guidance on this aspect, therefore it is assumed that cautious but realistic assumptions for individual dose and risk calculations should be used. Realistic assumptions should be used for collective dose estimations.

Repository System

See information given in Section 1.1.

Site Context

See information given in Section 1.1.

Topography

The repository is located under the seabed. It is assumed that there is a seabed depression in the vicinity of the repository so that as the seabed rises with a release of the isostatic pressure, there will be a lake, which may subsequently dry out as land continues to rise, and the hydrogeological/hydrological regime changes.

Climate

Current climatic conditions are boreal. Over timeframes of 10,000 years or more the climate will move to colder conditions as glacial/interglacial cycling occurs due to orbital forcing.

Lithostratigraphy

Crystalline bedrock under the Öregrundsgrepen and Bothnian Sea marine waters.

Geological Stability and Resources

The area is currently in isostatic rebound. This means that the seabed is rising and consequently there is an apparent sea level fall. The seabed is not currently used for any resources other than the construction (and possible extension) of the radioactive waste repository.

Landuse

There is no land over the current repository location as it is beneath the seabed. The marine waters of the Bothnian and Baltic seas are used as a fishing resource. No other mineral exploitation.

Surface Water Bodies

As noted above, the repository is sited beneath the Öregrundsgrepen that is connected to the Bothnian Sea. Over a period of around 1,000 years as land rises with isostatic rebound, radionuclide releases may occur to a lake whose water will change from salt water to brackish to fresh water as precipitation, runoff and groundwater discharge dilutes the original marine waters.

Source Terms and Geosphere-Biosphere Interface

Source Terms

The source terms to the biosphere are derived from radionuclide releases calculated in other parts of the PA (i.e., from the near-field and far-field modelling). The source term includes long-lived and/or mobile radionuclides present in the ILW and LLW. Some radionuclides stated to be of specific interest are: C-14, Cl-36, Ni-59, Sr-90 and TRU radionuclides [SKB, 1998].

Smith [1999] has recommended that in addition to the radionuclides assessed in the Geosphere model, short-lived daughters should be included, as they may have been neglected in the geosphere modelling. The list of radionuclides to consider is therefore given as: C-14, Cl-36, Ni-59, Se-79, Nb-94, Tc-99, I-129, Cs-135, Np-237 and daughters, Pu-239 and daughters, Pu-240 and daughters and Pu-242 and daughters.

Geosphere-Biosphere Interface

Given information from the previous safety case and that provided in SKB [1998] and Smith [1999], it is assumed that the two main potential release modes are:

- groundwater releases;
- gaseous releases.

Potential biosphere receptors

- marine waters/sediments (during the marine phase);
- fresh waters/sediments (during the inland phase);
- well, into deep or near-surface aquifers (during the inland phase);
- terrestrial soils/sediments or bogs (during the inland phase).

The marine and inland phases have to be considered because it is known that the land in the vicinity of the repository is rising due to isostatic rebound. With land rise the sea-level apparently falls and the rate of land rise is such that it is considered that within 1,000 years after repository closure the repository will be located on dry land rather than under the sea.

Timeframes

The timeframes considered in the recent Swedish regulations are:

- before 1,000 years;
- after 1,000 years.

Quantitative calculations are required for the first timeframe. However, in order to quantify more fully the potential impacts on humans and the environment, Smith [1999] recommends that a biosphere model should be capable of calculating results for timeframes of 10,000 years or longer. Therefore it is assumed that in order to investigate the potential impacts of land rise (isostatic rebound) the SSI biosphere modelling capability should encompass this longer timeframe.

Societal Assumptions

Smith [1999] has recommended that one calculation case should assume conditions are the same as those at the time of the licence application. This means that present day lifestyles and practices should be assumed.

The issue of potential future exposure group definition is the subject of many national and international discussions since it is impossible accurately to predict human behaviour and societal patterns over the long timescales involved. In practice, one of two general approaches for the definition of exposure groups is normally adopted for performing exposure group dose and risk assessments. In the first approach, the locations and characteristics of the potentially exposed individuals are defined first (including size, age, diet and behaviour) before the conceptual model of contaminant migration has been developed. This may result in the omission of critical pathways. In the second approach, general exposure pathways are first defined according to how particular radionuclides emerge from the geosphere and migrate through various biosphere media. Then, likely exposure groups are defined according to the radionuclide migration pathways. This approach has the advantage of identifying the important media first without prejudicing exposure group assumptions.

For the present study, for longer timeframes, it is advised that the second approach is adopted and that potential exposure group assumptions should be consistent with the evolving biosphere as potential biosphere release receptors move from marine sediments/water to terrestrial freshwater/sediments and then to terrestrial bog/soils and radionuclide migration pathways associated with such receptors are identified. However, in order to simplify the representation of the exposure groups in such an evolving biosphere, an approach based on taking particular ‘timeslices’ during the biosphere evolution should be used. In keeping with the cautious, but reasonable philosophy, the exposure group should obtain all of its food and most of its other resources from local production. This approach could be reviewed in the future when, for example, the international co-ordinated research programme BIOMASS (BIOsphere Modelling and ASSessment methods) has provided guidance on critical and exposure group definition for evolving biospheres.

3.2 Key Features Events and Processes

Based upon the experience gained from previous PA calculations (see Section 2), the assessment context (Section 3.1) and the review of key features events and processes (FEPs) by Egan [1999], some of the key issues that need to be addressed in the prototype Amber model include:

- The model should be able to represent the continuous change from saltwater to inland conditions, depending directly on the uplift rate.
- It will be assumed that the lake produced in inland conditions will age, resulting in the production of a bog.
- ‘Standard’ algorithms will be used for biosphere exposure pathways. This will result in a list of data requirements. It is anticipated that as the project to review the SFR safety case progresses, it will be possible to include more site-specific data.

3.3 The Geosphere-Biosphere Interface Sub-Model

Some of the general issues involved in the specification of the geosphere-biosphere interface are discussed in Appendix 1. In the remainder of this sub-section, the sub-model that has been developed in the present project will be described.

Sub-Model Structure

Figure 13 shows the overall structure of the prototype time-dependent Amber model for SFR. The Repository and Geosphere sub-models are being developed for SKI and are described in SKI [1999]. In this section the Geosphere-Biosphere Interface sub-model will be described.

The structure of the Geosphere-Biosphere Interface (GBI) sub-model is shown in Figure 14. The prototype model is two-dimensional with four areas of land considered in the modelling plane. The choice of the parts of the system that are included in the GBI sub-model is, to a large extent, arbitrary. Initially the whole of the system being modelled is under the sea, but subsequently individual areas become exposed. What might be considered to be the geosphere-biosphere interface will change with time. This does not represent a significant problem as far as developing the Amber Case File is concerned, as the whole of the system is modelled.

The pragmatic choice has been made to include in the GBI sub-model the top-most parts of the land surface which may become unsaturated when the sea retreats; rock which is saturated at all times is included in the Geosphere sub-model, but rock which may become unsaturated at some time is included in the GBI sub-model.

Table 2 gives some details for the GBI compartments. The different types of compartments are:

- The upper sediments compartments, which represent the top layer of sediments when the area concerned, is under the sea; these are treated as upper soil compartments when the sea has retreated.
- The lower sediments compartments, which represent the lower layer of sediments when the area concerned, is under the sea; these are treated as lower soil compartments when the sea has retreated.
- The top rock compartments that represent the top-most layer of saturated rock when the area concerned is under the sea; these may become unsaturated when the sea has retreated.
- The lake compartment. When the sea has retreated from the third area of land, it is assumed that a lake is formed above the third and fourth areas of land. The inclusion of the lake in the GBI model is convenient, although it could equally be included in the Biosphere sub-model.

The lake is assumed to decrease in depth as the land continues to rise. This results in the lake drying up. Alternative approaches to the evolution of an ageing lake (e.g., [BIOMOVS, 1989]) could be considered as the SFR model is developed.

Table 2
Dimensions of Geosphere-Biosphere Interface Compartments.

Compartment	Description	Length (m)	Depth (m)
I_UpperSediments1	Upper sediments/upper soil immediately above the Repository sub-model	240	0.3
I_LowerSediments1	Lower sediments/lower soil immediately above the Repository sub-model	240	0.3
I_TopRock1	Topmost region of rock above the Repository sub-model which is unsaturated when sea level falls	240	1.4
I_UpperSediments2	Upper sediments/upper soil immediately 'downstream' of the Repository sub-model	500	0.3
I_LowerSediments2	Lower sediments/lower soil immediately 'downstream' of the Repository sub-model	500	0.3
I_TopRock2	Topmost region of rock immediately 'downstream' of the Repository sub-model which is unsaturated when sea level falls	500	1.4
I_UpperSediments3	Upper sediments/upper soil in the region where discharges from the upper part of SFR will emerge when groundwater flows are horizontal	500	0.3
I_LowerSediments3	Lower sediments/lower soil in the region where discharges from the upper part of SFR will emerge when groundwater flows are horizontal	500	0.3
I_TopRock3	Topmost region of rock in the region where discharges from the upper part of SFR will emerge when groundwater flows are horizontal which is unsaturated when sea level falls	500	1.4
I_UpperSediments4	Upper sediments/upper soil in the region where discharges from the lower part of SFR will emerge when groundwater flows are horizontal	500	0.3
I_LowerSediments4	Lower sediments/lower soil in the region where discharges from the lower part of SFR will emerge when groundwater flows are horizontal	500	0.3
I_TopRock4	Topmost region of rock in the region where discharges from the lower part of SFR will emerge when groundwater flows are horizontal which is unsaturated when sea level falls	500	1.4
I_Lake	Lake formed in areas 3 and 4 when the sea has receded	1,000	3

Transition Times

The transition times between the different states of the system are taken to be related to the rate of land uplift U (m y^{-1}). The time when the first two areas in the GBI model become dry land area given by:

$$\tau_i = \frac{D_i}{U}$$

where D_i is the initial depth of the sea above area i. It is assumed that the lake is formed when the second area of land dries up. The lake is present until it dries up at a time given by the same algorithm. With the numerical values employed for the initial sea depths and the land uplift rate, the first area becomes dry land after 1,000 years, the second after 1,500 years, and the lake is present between 1,500 years and 2,000 years.

Once an area has become dry land, it is assumed that in Areas 1–3, the water table falls at a rate determined by the rate of land uplift until it reaches the bottom of the top rock compartment. Each compartment is assumed to change from being saturated to being partially saturated when the water table drops below the base of the compartment in question. For Area 4, it is assumed that the water table stays close to the surface after the lake has dried up, creating a boggy environment.

Inter-Compartment Transfers when Land is Under the Sea

When any of the four areas of land are under seawater, radionuclides transferred from the Geosphere sub-model to the GBI sub-model will be transported according to the general hydrogeological regime assumed. For simplicity, it is assumed that in these conditions radionuclides will be transported upwards through the sediments into the sea according to the magnitude of the geosphere Darcy velocity.

The advective vertical transfer rate between the compartments is then:

$$\lambda = \frac{v}{\vartheta R H}$$

where v is the magnitude of Darcy velocity (m y^{-1}), θ is the porosity of the donor compartment, R is the retardation factor for the radionuclide concerned in the donor compartment, and H is the height of the donor compartment. In the Interface sub-model it is assumed that whilst land is under the sea, groundwater movement is vertically upwards. This algorithm is also relevant to the transfer from the upper sediments compartments into the sea.

In addition to advective transfers of radionuclides, it is assumed that there are additional transfers due to bioturbation and other related processes. In this case the transfer is represented by:

$$\lambda = \frac{\beta}{H}$$

where β is a bioturbation rate (m y^{-1}). This transfer can also be used to represent transport due to processes such as variations in the depth of the water table. In the prototype model detailed consideration has not been given to these processes, but this will need to be addressed again as the model is developed.

There is a transfer back from the marine environment to the upper sediments as a result of sedimentation – this is specified in the section on the Biosphere sub-model.

Inter-Compartment Transfers when the Sea has Receded

When the sea has receded and the land is not covered with water, vertical transfers towards the water table are defined by:

$$\lambda = \frac{I}{\vartheta \, \varepsilon \, R \, H}$$

where I is the infiltration rate (m y^{-1}) and ε is the degree of saturation of the donor compartment. In addition 'bioturbation' transfers are represented, as in the period when the sea is under the land, but it is possible to employ a different bioturbation rate if required.

Inter-Compartment Transfers in the Presence of the Lake

The transfer of radionuclides from the land to the lake is represented in the same way as when the sea is present. The flux of radionuclides from the lake back to the upper sediments compartments is determined by the scavenging rate:

$$\lambda = \frac{K_d \, \sigma}{(1 + K_d \; S) \, H}$$

where K_d is the appropriate sorption coefficient for the radionuclide in question on suspended sediment, S is the suspended sediment load (kg m^{-3}) and σ is the sedimentation rate (kg m^{-2} y^{-1}). The net flux from the lake to upper sediments is apportioned to Areas 3 and 4 on the basis of area.

Radionuclides are assumed to leave the lake and be transferred directly to the regional waters compartment in the Biosphere sub-model. This transport will be in a small river, but this is not modelled explicitly as transfer rates would be very rapid, and radionuclide concentrations in the lake are of more interest for radiological assessments than those in the river.

The transfer rate from the lake to the Biosphere sub-model is represented according to:

$$\lambda = \frac{\lambda_0 \, H_o}{H}$$

where H_0 is the initial lake depth and λ_0 is an initial turnover rate. The depth of the lake is assumed to decrease with the rate of land uplift.

Transfers between other compartments are assumed to be the same in the presence of the lake as when the area concerned was under the sea.

3.4 The Biosphere Sub-Model

Sub-Model Structure

The structure of the Biosphere sub-model is shown in Figure 15. The model is currently very simple with model compartments for an area of regional waters and the Baltic, each with associated compartments for bottom sediments. The compartment for other oceans is effectively a sink compartment. The simplicity of the Biosphere sub-model reflects the fact that the most significant radiological impacts are likely to arise from radionuclide concentrations in environmental materials in the Interface compartment rather than the Biosphere sub-model. The model is not currently designed to provide information on either collective doses or radiological impacts to non-human biota. However, the present model can readily be expanded if required as the SFR review project proceeds.

Table 3 gives some details for the Biosphere sub-model compartments.

Table 3
Dimensions of Biosphere Sub-Model Compartments.

Compartment	**Description**	**Volume (m^3)**	**Depth (m)**
B_RegionalWaters	Upper sediments/upper soil immediately above the Repository sub-model	$3.4 \cdot 10^9$	8
B_RegionalSediment	Lower sediments/lower soil immediately above the Repository sub-model	Determined from dimensions of B_RegionalWaters	0.3
B_Baltic	Topmost region of rock above the Repository sub-model which is unsaturated when sea level falls	$4 \cdot 10^{13}$	14
B_BalticSediment	Upper sediments/upper soil immediately ‘downstream’ of the Repository sub-model	Determined from dimensions of B_Baltic	0.3

Inter-Compartment Transfers

A turnover rate for the regional waters compartments is specified, and this is used in conjunction with the relative volumes of the regional waters and Baltic compartments to specify the reverse transfer.

Net loss of activity to bottom sediments is represented in the same way as for the lake in the Interface sub-model, but with parameter values appropriate to a marine environment.

3.5 Individual Dose Calculations

Individual dose calculations are derived from the Amber calculations of radionuclide concentrations in environmental materials. In the prototype model a selection of ‘representative’ potential exposure pathways are considered. As the SFR review project proceeds a more comprehensive consideration of exposure pathways can be developed if required.

A farming critical group is assumed to be exposed by external irradiation over contaminated soils, inhalation of contaminated soils, drinking contaminated groundwater from a well and consumption of lake fish (when applicable). Other pathways (such as crop and animal product consumption) can readily be included as the model is developed.

The external exposure dose rate is calculated from:

$$H \quad = \quad \gamma \, \chi \, O$$

where γ is the external dose rate per unit soil concentration (Sv y^{-1} per Bq kg^{-1}), χ is the bulk concentration of the radionuclide in soil (Bq kg^{-1}) and O is an occupancy factor giving the fraction of time spent over the area in question. The factor γ is taken for an assumed semi-infinite mass geometry, and a conversion factor is introduced in the algorithm used in the Case File to convert hours to years.

The corresponding expression for inhalation doses is given by:

$$H \quad = \quad \kappa \, \chi \, O \, I$$

where κ is the dose per unit activity inhaled (Sv Bq^{-1}), I is the dust inhalation rate (kg y^{-1}), χ is the concentration of the radionuclide on soil grains (Bq kg^{-1}) and O is an occupancy factor giving the fraction of time spent over the area in question.

Drinking water doses are calculated from:

$$H \quad = \quad \kappa \, I \, C$$

where κ is the dose per unit activity ingested (Sv Bq^{-1}), I is the consumption rate for water (m^3 y^{-1}), and C is the relevant radionuclide concentration in the geosphere (Bq m^{-3}). C is taken to be the maximum groundwater concentration in the geosphere compartments below the area in question: it is assumed that the well ‘samples’ this concentration and does not significantly affect the groundwater flow regime (i.e., the well is ‘small’).

As in the demonstration Case File discussed in Section 2, the dose rate H (Sv y^{-1}) due to consumption of lake fish is given by:

$$H \quad = \quad \kappa \, I \, F \, C$$

where κ is the dose per unit activity ingested (Sv Bq^{-1}), I is the ingestion rate for the fish (kg y^{-1}), F is the relevant concentration factor for the fish (m^3 kg^{-1}) and C is the radionuclide concentration in lake water (Bq m^{-3}).

A marine critical group is assumed to be exposed by external irradiation over contaminated sediments, inhalation of contaminated soils and consumption of sea fish caught in the regional waters compartment. The algorithms used to calculate these doses are similar to those used for the farming critical group. Again, other pathways (such as consumption of crustaceans and molluscs) can readily be included as the model is developed.

3.6 Illustrative Calculations

The prototype model can be used to investigate radionuclide transport in different parts of the system and the resulting potential individual doses. Three illustrative examples are given here of the sort of information that can be obtained from Amber calculations.

Figure 16 shows calculated concentrations of a particular radionuclide, Cs-135, in two of the soil/sediment compartments in the Interface sub-model. The peak concentration appears in the lower sediments compartment in the first interface region much earlier than the corresponding peak in the lower sediments compartment in the fourth interface region. This is because of the time-dependent nature of the groundwater flow regime, with transport to the first region occurring relatively early on, when there is a significant vertical component to the Darcy velocity. Transport to the fourth region occurs later, when the Darcy velocity is essentially horizontal. This type of calculation could be used for comparisons with naturally occurring radionuclide concentrations in the environment.

Figure 17 shows calculated total drinking water doses, summed over radionuclides. As a result of changing groundwater flow conditions, the concentrations of radionuclides in well water vary with time and location. With the parameter values chosen, the highest doses are calculated to arise in the second region of the Interface sub-model around 2,000 years after repository closure.

Figure 18 shows calculated doses for all the marine pathways, summed over radionuclides. It is interesting to note that these dose rates are calculated to continue to increase (although still to relatively low values) over very long timescales. This is because of the ingrowth and transport of long-lived daughters of actinides in the SFDR inventory.

4 Model Development for a Deep Repository

The Prototype Amber Case File described in Section 3 provides the basis for an assessment capability for SFR. The Interface and Biosphere sub-models have been specifically designed to be applicable to SFR where the coastal location and land rise with resulting sea level fall are key features of the system to be modelled. For a deep repository (SFL) the key FEPs are likely to be different, and the timescales over which radionuclide transport will be required to be modelled will be much longer. Nevertheless, the general approach taken in the prototype code to system modelling should still be applicable. Key features of the approach include:

- The representation of the whole system in one Amber model, avoiding problems of model interfacing, and allowing the effective location of the geosphere-biosphere interface to change as the system evolves.
- Allowing a fully time-dependent representation of biosphere evolution.

It is likely that a very different Repository sub-model will be required for SFL, and more detailed geosphere modelling may be required. However, the level of complexity of the Interface and Biosphere sub-models is likely to remain appropriate.

5 Conclusions

1. The successful implementation in a Demonstration Amber Case File of PA models developed at the time of the original SFR safety case submission gives confidence in the use of Amber for the SFR safety case. Despite a number of simplifying assumptions, Amber was able to reproduce both near-field and biosphere calculations satisfactorily.

2. A Prototype Amber Case File has been developed which can be used as the basis for PA calculations in the review of the SFR safety case. The Geosphere-Biosphere Interface and Biosphere sub-models are linked directly to the Repository and Geosphere sub-models. The key feature of this prototype model is the ability to represent continuous changes in the system.

3. The prototype model does not address all the issues identified as being significant in the assessment context. In particular, the gas pathway has not yet been included, and collective doses and radiological impacts on the environment have not been considered. These can be addressed as the current project proceeds.

4. Although there are likely to be many differences in the models required for a deep repository (SFL), the basic methodology that is being developed for SFR should be equally applicable to SFL.

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Appendix 1

The Geosphere-Biosphere Interface

Introduction

Most performance assessments of radioactive waste disposal facilities consider the system to be assessed in terms of three main components: the near-field; the geosphere (far field); and the biosphere. Different modelling approaches are frequently employed in the three parts of the system, and it is then necessary to consider how to manage the interfaces between these. In this appendix some general issues concerned with the geosphere-biosphere interface are discussed; the problems associated with its definition are considered, and suggestions given for how such problems can be avoided or minimised.

Interface Issues

In ‘traditional’ performance assessments the transport of radionuclides in groundwater in the geosphere is often undertaken using a chosen continuum model that accounts for advective and dispersive/diffusive transport as well as interaction with the host material. For example, a one-dimensional equivalent porous medium model may be employed with linear equilibrium sorption on the host rock, but the details of the particular model employed are not important. The radionuclide flux from the geosphere is often assumed to enter the first compartment of a compartmentalised biosphere model. In this case the modelling approach for the biosphere model is different from that in the geosphere (compartments rather than continuum), and it is often assumed that the biosphere and geosphere models can be ‘decoupled’, and considered independently.

From the perspective of the Geosphere model, the boundary condition at the end of the transport calculation may be taken to be zero concentration, or the boundary condition may be set at infinity (assuming that the boundary does not affect transport in the geosphere). The zero concentration boundary condition is usually justified on the basis that transport away from the interface is assumed to be much more rapid than transport in the geosphere.

From the point of view of the biosphere model, the radionuclide input is simply a given flux (as a function of time) that is assumed to become instantaneously well mixed throughout the receptor compartment. In some assessments the degree of decoupling is taken a stage further by assuming that the timescales over which the flux from the geosphere varies are much slower than the timescales relevant to the biosphere model, so that the biosphere can be assumed to be in equilibrium, and the biosphere model is simply used to calculate dose conversion factors: the dose rate to the critical group (Sv y^{-1}) arising from unit input flux (Bq y^{-1}).

This simple illustration helps raise a number of the questions that need to be considered about the geosphere-biosphere interface. These include:

- How should the ‘geosphere’ and ‘biosphere’ be defined?
- Why should separate models be used for the geosphere and biosphere?

- Where should the interface be defined? Is there a unique answer to this question once the geosphere and biosphere have been defined?
- Is the assumption of geosphere-biosphere decoupling valid? In particular, do changes in the biosphere affect the geosphere?
- Is the boundary condition chosen at the end of the geosphere and the assumed instantaneous compartment mixing assumption appropriate?
- Are the assumptions made in the geosphere model consistent with those made in the biosphere model, in particular with respect to water flows?

All of these questions are inter-related.

The Definition of the Interface

Many performance assessments have been undertaken without a clear statement on the working definitions for the terms ‘geosphere’ and ‘biosphere’. One possible definition is:

> The biosphere consists of those areas to which man usually has access, including soils, the atmosphere and fresh water and marine environments.

This is considered to be a definition that most workers in the field of performance assessments could accept, and is consistent with the approach taken in the BIOMOVS Reference Biosphere studies [BIOMOVS, 1996a]. An alternative definition is used by Bird et al. [1992]:

> The biosphere is the portion of the earth that contains living organisms.

It is considered that this is a less satisfactory definition, partly because living organisms can be found at great depths below the surface.

Another way to look at this issue is that biosphere processes are directly affected by activities (natural and human) occurring at the surface, whilst geosphere processes are not. In reality there is no simple cut-off on this basis: changes in geomorphology and hydrology (including the formation of ice sheets) will affect groundwater flows at depth. The deeper one goes, the less important are surface processes.

Helpful as giving clear definitions of the geosphere and biosphere is, this will not lead to a unique definition of the geosphere-biosphere interface. To illustrate this, consider a situation that gives a simple one-dimensional representation of radionuclide transport in groundwater for a particular assessment. Groundwater (carrying radionuclides from a deep repository) moves through varied lithographic strata and reaches a rock that is being eroded by natural processes such as thermal cycling. The eroded rock (and associated radionuclides) becomes part of the soil layer above the rock, and various transport processes will result in an upward movement of radionuclides towards the surface. Having passed through this rock stratum the groundwater discharges into a river through the sediments at its base.

This simple illustration shows that various definitions of the interface would be possible. It is certainly true that erosion can be a significant source of radionuclides entering the biosphere (see, for example, Miller et al. [1996]), and it might not therefore be a valid assumption to neglect this process. This being the case, should the interface be at the rock/soil interface? In this case it is not obvious how a receiving biosphere compartment would be defined; if it is to be a soil compartment above the rock, then the flux of radionuclides to the river is not represented. Alternatively, should more than one interface be considered?

If the interface is to be defined for the flow of radionuclides to the river, should the interface be at the rock/sediment interface or the sediment/river interface? Biosphere models (e.g., BIOMOVS [1996b]) often allow the flux of radionuclides from the geosphere to be to a river sediment compartment or directly to the river. In the situation shown in Figure A1, presumably the geosphere flux would be taken to be to a river sediment compartment, but questions are then raised concerning the consistency of assumptions in the geosphere and biosphere; these issues will be discussed in the following sub-section.

Given the problem of defining a geosphere-biosphere interface it is natural to ask why such an interface is needed at all. Why is it not possible to define a model that encompasses both? In setting up the conceptual model for the whole system under consideration it is important that FEPs are included which concern geosphere-biosphere interactions, at least initially. This will enable biosphere processes to be identified, which affect the geosphere, and vice versa; this identification will be particularly useful in subsequent consistency checks. Models that encompass both the biosphere and geosphere need to be able to deal with the different timescales and spatial scales involved. This is particularly the case for transport processes in the unsaturated zone. The vertical movement of radionuclides in unsaturated soils will depend upon short term variations in rainfall and evaporation rates (see, for example, BIOMOVS [1996c]). Biosphere models generally represent the effects of such short term processes as effective vertical transfer rates, but even these effective rates may be much more rapid than the transfer rates in groundwater.

In practice the definition of the location of the geosphere-biosphere interface will depend upon:

- the working definitions being employed for the ‘geosphere’ and the ‘biosphere’;
- the system FEPs where biosphere processes affect the geosphere and vice versa;
- the modelling tools available for calculating radionuclide transport.

Overall, it is more important that an interface is defined, which enables consistent assumptions to be made in the two modelling areas, than to constrain this by a (necessarily imprecise) definition of what should be modelled in the biosphere and what should be modelled in the geosphere.

Consistency of Assumptions in the Geosphere and Biosphere

Returning to the simple example in Figure A1, if the biosphere receptor compartment is taken to be river sediments, a number of questions of consistency are raised which illustrate more general considerations:

- Is the cross-sectional area associated with the radionuclide plume at the end of the ‘rock’ zone consistent with the assumed dimensions of the sediment compartment?
- Is the assumption of uniform mixing in the sediment compartment valid?
- Is the boundary condition assumed at the end of the geosphere an acceptable approximation?
- Are the assumptions made about water balance in the geosphere consistent with those being made in the biosphere?

Perhaps the most important point to make here is that several of these questions can readily be checked, but this has often not been undertaken satisfactorily in past performance assessments. For example, the calculated concentration of radionuclides in pore water in the sediment compartment can be compared with that at the end of the rock zone; if the sediment concentration is not very much less than the concentration in the rock, the boundary condition assumed at the end of the geosphere is unlikely to be valid.

Perhaps the most important check to be made relates to the last question in the above list: that of water balance. In general it will be possible to continue the geosphere calculations through a sediment zone to the river on the assumption that the geosphere-biosphere interface were at the sediment/river interface rather than the rock/sediment interface. If this is done, the fluxes of both water and radionuclides into the river can be calculated. How do these compare with the fluxes calculated using the biosphere model?

Conclusions

From the consideration of the issues raised by the use of a geosphere-biosphere interface, a number of conclusions can be drawn that should help to avoid or limit the difficulties described:

- There is no single definition of the biosphere and geosphere, but for any performance assessment the working definitions for these terms should be given.
- The conceptual model for the whole system under consideration will need to include FEPs relevant to the influence of the geosphere on the biosphere and vice versa.
- Consistency checks need to be undertaken to ensure that assumptions made in the geosphere part of the system model are consistent with those made in the biosphere part of the system model. This is particularly important for groundwater and surface water flows. Near surface hydrological models may be useful in ensuring consistency in assumptions of water flows.
- If the geosphere and biosphere models are to be assumed to be independent of each other (‘decoupled’), checks need to be made that the timescales over which the flux from the geosphere varies are long compared with the timescales that govern transport in the biosphere.

Appendix 2

Amber Demonstration Case File Parameters

Table A2.1 gives a list of the Amber ‘namesets’ used in the near-field models. The four sources of radioactivity are listed in the nameset ‘Repository’. The various parts of the system are taken to be composed of various materials, listed in the nameset ‘Materials’; the different materials considered are given in the table.

Table A2.2 gives details of the various Amber parameters used in the near-field models. These include the cross-sectional areas of the compartments (taken in the direction in which radionuclides are assumed to be transported).

Tables A2.3 and A2.4 give corresponding details for the biosphere model, with parameter values taken from SSI [1989].

Table A2.1
Amber Namesets for Near-field/Geosphere Models in the Demonstration Case File.

Nameset	Description	Members
Repository	Types of vault	Silo; BTF; BMA; BLA
Materials	Materials present in near-field	Aged Concrete; Bentonite; Degraded Concrete; Fresh Concrete; Porous Concrete; Sand; Sand Bentonite; Waste Matrix; Water
Releases	Routes for release from silo	Bottom; Mantle; Top; Total

Table A2.2

Amber Parameters for Near-field/Geosphere Models in Demonstration Case File.

Parameter	Description	Units	Definition/Value
Alpha	α, constant of proportionality in boundary condition at edge of near-field for the silo.	$m^3\ y^{-1}$	
Area	A; compartment areas in direction of radionuclide transport	m^2	Areas for silo compartments given in Figure 6.2 of NF report. Corresponding values for BMA in Figure 7.2, for BTF in Figure 8.2
Bulk Density	ρ; bulk density for each of the near-field materials	$kg\ m^{-3}$	Data in Table 4.1 of NF report
Capacity	κ; retention capacity for each model compartment for each radionuclide in the saltwater period	m^3	Sum of the products of the porosity, volume and retardation coefficient for each material present for the saltwater period [equation 5-3 in NF report]
Capacity 2	Same as 'Capacity', but for the inland period	m^3	
De	Effective diffusivity for each material	$m^2\ y^{-1}$	Data in Table 4.3 of NF report
Inland Period-Flows	Water flow rates through the 4 repositories for the inland period	$m^3\ y^{-1}$	Table 4.5 of SFR 87-10
Inventory	Initial inventory of each radionuclide in each 'Repository'	Bq	Data taken from NF report Table 2.3
Kd	Kd; sorption coefficient for each radionuclide on each 'Material'	$m^3\ kg^{-1}$	Data in Table 4.4 of NF report
L	Compartment lengths	m	Silo geometry given in NF report Section 3.1 and Figure 6.2 [53 m high with 0.5 m thick walls (although given as 0.8 m in Section 3.1) surrounded by 1.2 m of bentonite. 1m thick lid covered by 1.5 m layer of sand/bentonite, and a 1 m thick bottom. Internal compartment walls are 0.2 m thick] BMA geometry given in NF report Figure 7.2 and Table 7.2. BTF in Figure 8.2
Porosity	ε; porosity for each 'Material'	–	Data in Table 4.2 of NF report
Retardation	R; retardation coefficient for each radionuclide for each 'Material'	–	
Saltwater Period-Flows	Water flow rates through the four repositories for the saltwater period	$m^3\ y^{-1}$	Table 4.5 of SFR 87-10
SwitchTime	Time when the biosphere switches from saltwater to inland. No flow through silo until this time. Degraded barrier materials assumed after this time	y	2,500 y, as assumed in NF report
Tank Integrity-Timescale	Time at which water starts to flow through BTF tanks	y	100, as assumd in Section 8 of NF report
Volumes	V; compartment volumes. Common parameter with biosphere model	m^3	Data derived from Tables 6.1, 6.2 and 6.4 of NF report for the silo. Corresponding data in Tables 7.1 and 7.2 for BMA. For BTF Tables 8.1 and 8.2. For BLA Table 9.1
Water Flow	Flow rate of water past silo model compartments	$m^3\ y^{-1}$	See Table 6.3 of SFR 87-10

Table A2.3
Amber Namesets for Biosphere Models.

Nameset	Description	Members
Foods	Foods consumed by critical group	Sea fish; Lake fish

Table A2.4
Amber Parameters for Biosphere Model.

Parameter	Description	Units	Definition/Value
ConcentrationFactor	Concentration factors for each food consumed by critical group members for each radionuclide	$m^3\ kg^{-1}$	Data for sea fish in Table A6 of SSI 89-13 Data for lake fish in Table A7 of SSI 89-13
ConsumtionRates	Consumption rates by critical group of each food	$kg\ y^{-1}$	30 kg/y for sea and lake fish, as specified in the text of SSI 89-13
Egamma	Mean gamma energy produced by disintegration for each radionuclide	MeV	
SwitchTime	Time when flux from geosphere switches from inland to lake	y	2500y, as assumed in SKB [1987a]
Volumes	Compartment volumes – common parameter with near-field model	m^3	Biosphere compartment volumes given in Figures 2 and 3 of SSI 89-13
king	Ingestion dose factors	$Sv\ Bq^{-1}$	
kinh	Inhalation dose factors	$Sv\ Bq^{-1}$	

Appendix 3

Amber Prototype Case File Parameters

Table A3.1 gives details of the Amber parameters used in the Geosphere-Biosphere Interface sub-model. Table A3.2 gives corresponding information for the Biosphere sub-model, and Table A3.3 for the parameters used to calculate individual doses.

Table A3.1
Amber Parameters for the Geosphere-Biosphere Interface Sub-Model of the Prototype Case File.

Parameter	Description	Units	Definition/Value
Area	A; compartment areas in direction of radionuclide transport	m^2	
BulkDensity	ρ; bulk density for different materials	kg m^{-3}	
G_Angle	Angle of Darcy flow velocity vector in the undisturbed geosphere	radians	
G_AngleStart	Initial value of G_Angle	radians	0
G_AngleEnd	Final value of G_Angle	radians	π
G_AngleEndTime	Time when G_Angle reaches G_AngleEnd	y	
Kd	Kd; sorption coefficient for each radionuclide on each 'Material'	m^3 kg^{-1}	
L	Compartment lengths (horizontal dimension)	m	
Porosity	ε; porosity for each 'Material'	–	
Retardation	R; retardation Coefficient for each radionuclide for each 'Material'	–	
Volumes	V; compartment volumes	m^3	
G_Darcy	Magnitude of Darcy velocity in undisturbed geosphere	m y^{-1}	
G_DarcyStart	Initial value of G_Darcy	m y^{-1}	
G_DarcyEnd	Final value of G_Darcy	m y^{-1}	
G_DarcyEndTime	Time when G_Darcy reaches G_DarcyEnd	y	
IT1-IT4	Transition times when the are concerned becomes dry land I_Transition[One]-I_Transition[Four]	y	
I_InfiltrationRate	Infiltration rate	m y^{-1}	0.1
I_InitialLakeDepth	Initial depth of lake – related to initial sea depths	m	3
I_InitialLakeTurnoverRate	Initial lake turnover rate to river/sea	y^{-1}	1
I_InitialSeaDepth	Initial sea depth over areas 4 areas	m	6/9/12/12
I_InterfaceDepth	Depth of soil/rock in each area of the interface sub-model	m	Determined by depths of component compartments
I_LakeDepth	Depth of lake	m	Reduces from initial value according to rate of land uplift
I_LakeSSL	Suspended sediment load in the lake	kg m^{-3}	0.003
I_LakeScavengingRate	Sediment scavenging rate in lake	y^{-1}	Determined by equation in main text
I_LakeSedimentation	Sedimentation rate in the lake	kg m^{-2} y^{-1}	0.3
I_LakeTurnoverRate	Lake turnover rate to river/sea	y^{-1}	Increases from initial value as mean lake depth decreases

I_LandUpliftRate	Rate of land uplift	m y^{-1}	0.006
I_SoilSaturation	Degree of saturation in unsaturated soils	–	0.4
I_Transition	Times for the four areas of the Interface sub-model when the area becomes dry land	y	Determined by initial depths of seawater and the rate of land uplift
I_Transition2	Times for the four areas of the Interface sub-model when the water table drops to the base of the top rock compartment	y	Determined by time when area becomes dry land, and the rate at which the water table is assumed to fall
I_VFactor	Combination of parameters used in calculation of downward advective transfers due to rain infiltration Height*CompPorosity*CompRetardation*DegreeOfSaturation	m	Product of depth of compartment, its porosity, its degree of saturation and the retardation factor of the radionuclide in question
I_WaterTableDepth	Depth of water table below the surface for the four areas of the Interface sub-model	m	
I_bioturb1	Bioturbation rate in sediments	m y^{-1}	0.003
I_bioturb2	Bioturbation rate in soils	m y^{-1}	0.003

Table A3.2
Amber Parameters for the Biosphere Sub-Model in the Prototype Case File.

Parameter	Description	Units	Definition/Value
Porosity	ε; porosity for each 'Material'	–	
Retardation	R; retardation coefficient for each radionuclide for each 'Material'	–	
Volumes	V; compartment volumes	m^3	
B_BalticSSL	Suspended sediment load in the Baltic Sea	kg m^{-3}	0.001
B_BalticSedimentation	Sedimentation rate in the Baltic	kg m^{-2} y^{-1}	0.2
B_BalticTurnoverRate	Turnover rate in the Baltic	y^{-1}	0.043
B_RegionalSSL	Suspended sediment load in regional waters	kg m^{-3}	0.001
B_RegionalScavengingRate	Sediment scavenging rate in regional waters	y^{-1}	Determined by equation in main text
B_RegionalSedimentation	Sedimentation rate in regional waters	kg m^{-2} y^{-1}	0.1
B_RegionalWatersTurnover	Turnover rate for regional waters	y^{-1}	26

Table A3.3
Amber Parameters for the Individual Dose Calculations.

Parameter	Description	Units	Definition/Value
AqueousConcentration	Concentration of radionuclide in the aqueous phase of the compartment in question	Bq m^{-3}	
BulkConcentration	Bulk concentration of radionuclide in compartment in question	Bq kg^{-1}	Depends on total activity in the compartment, the compartment volume and the bulk density of the compartment material
SolidConcentration	Concentration of radionuclide in solid phase in compartment in question	Bq kg^{-1}	
D_ConcentrationFactor	Concentration factors for each food type considered	m^3 kg^{-1} for fish	
D_ConsumptionRates	Consumption rates for each food type considered	kg y^{-1}	
D_DrinkingWaterDose	Dose rate due to consumption of well water	Sv y^{-1}	
D_DustInhalationRate	Rate of dust inhalation	kg y^{-1}	0.0005
D_Egamma	Gamma decay energies	MeV	
D_ExtDosSF	External dose rate from unit concentration of radioactivity in soils/sediments, assuming a semi-infinite mass geometry	(Sv h^{-1})/ (Bq kg^{-1})	
D_FarmingExternalDose	External dose rate due to occupancy over agricultural land	Sv y^{-1}	
D_FarmingInhalationDose	Dose rate due to inhalation of contaminated dust over agricultural land	Sv y^{-1}	
D_FarmingOccupancyFactor	Fraction of time spent working agricultural land	–	
D_LakeFishDose	Dose rate from the consumption of lake fish	Sv y^{-1}	
D_MarineExternalDose	External dose rate due to occupancy over marine sediments	Sv y^{-1}	
D_MarineInhalationDose	Dose rate due to inhalation of contaminated marine sediments	Sv y^{-1}	
D_SeaFishDose	Dose rate from the consumption of sea fish	Sv y^{-1}	
D_TotalDrinkingWaterDose	Dose rate due to consumption of well water summed over radionuclides	Sv y^{-1}	
D_TotalFarmingDose	Total dose rate to farming critical group summed over radionuclides	Sv y^{-1}	Summed over water consumption, inhalation, external exposure and lake fish consumption pathways
D_TotalFarmingExternalDose	External dose rate due to occupancy over agricultural land summed over radionuclides	Sv y^{-1}	

D_TotalFarmingInhalationDose	Dose rate due to inhalation of contaminated dust over agricultural land summed over radionuclides	Sv y^{-1}	
D_TotalLakeFishDose	Dose rate from the consumption of lake fish summed over radionuclides	Sv y^{-1}	
D_TotalMarineDose	Total dose rate to fishing critical group summed over radionuclides	Sv y^{-1}	Summed over inhalation, external exposure and sea fish consumption pathways
D_TotalMarineExternalDose	External dose rate due to occupancy over marine sediments summed over radionuclides	Sv y^{-1}	
D_TotalMarineInhalationDose	Dose rate due to inhalation of contaminated marine sediments summed over radionuclides	Sv y^{-1}	
D_TotalSeaFishDose	Dose rate from the consumption of sea fish summed over radionuclides	Sv y^{-1}	

Figures

Figure 1
Demonstration Amber Silo Model.

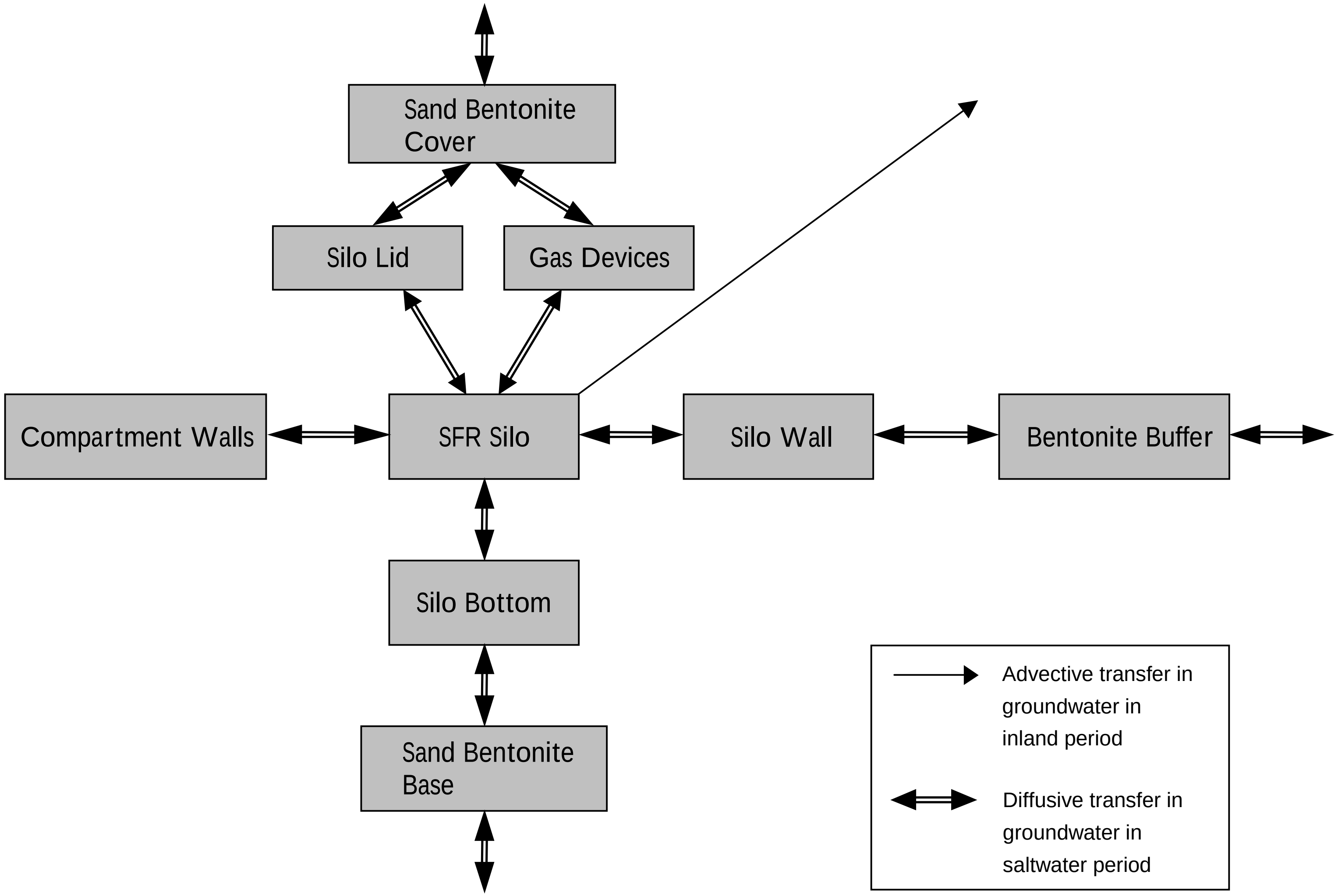


Figure 2
Demonstration Amber BMA Model.

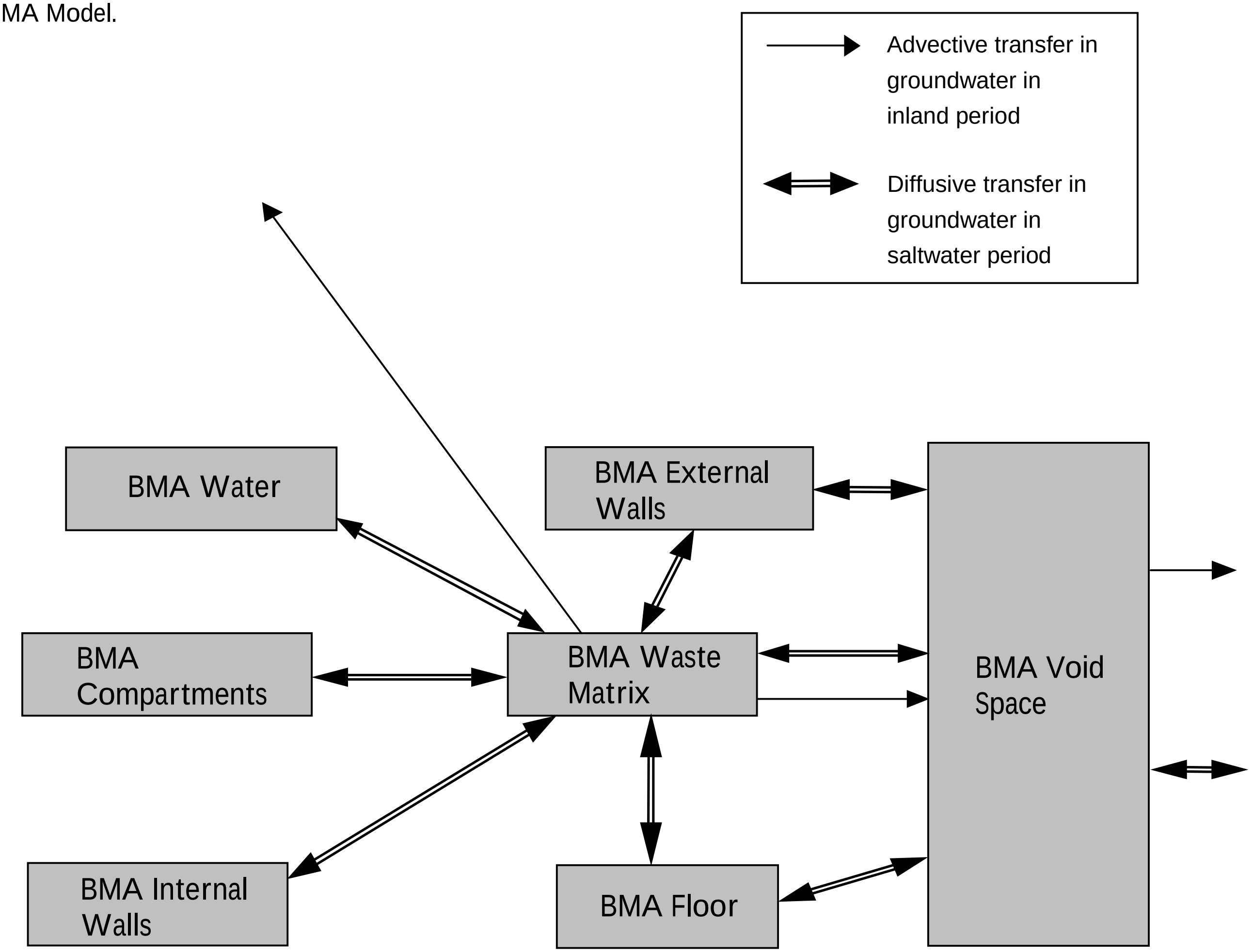


Figure 3
Demonstration Amber BTF Model.

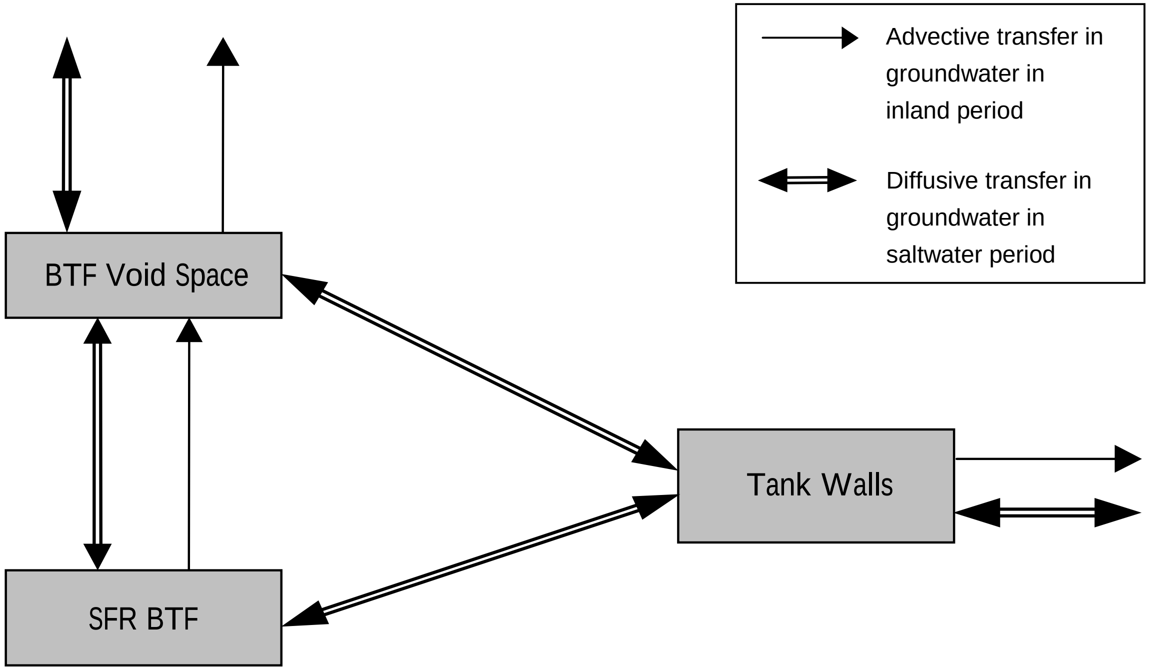


Figure 4
Demonstration Amber BLA Model.

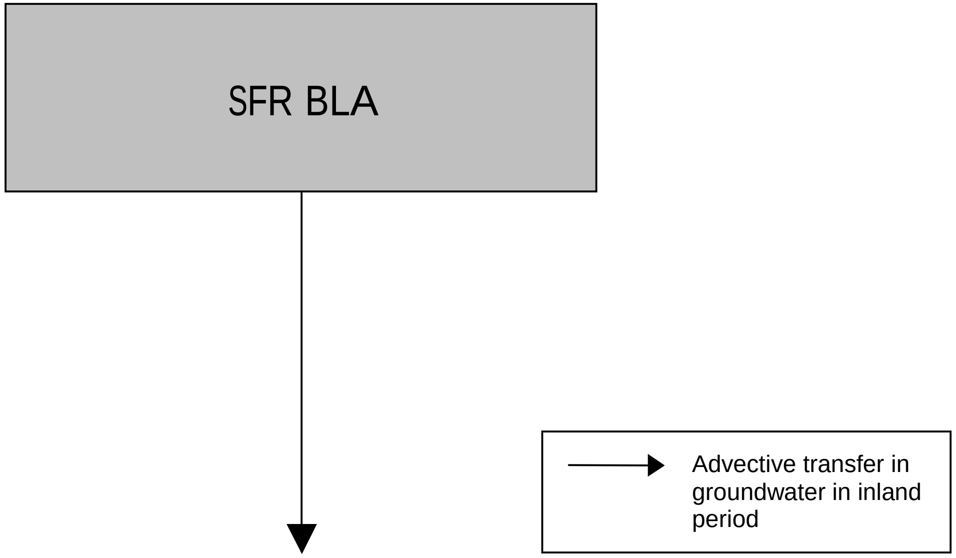


Figure 5
Demonstration Amber Biosphere Model.

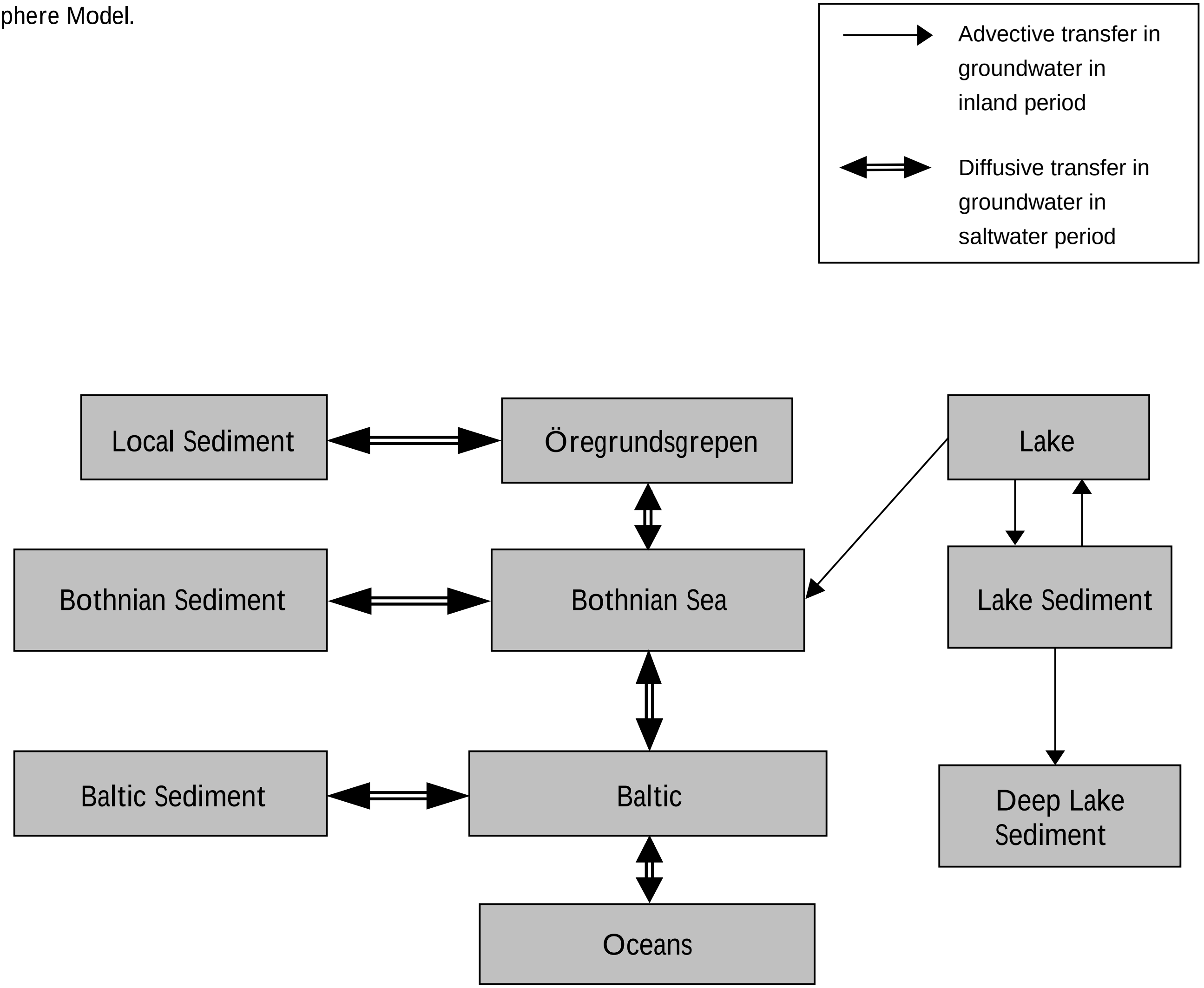


Figure 6
Flux from Silo in the Saltwater Period.

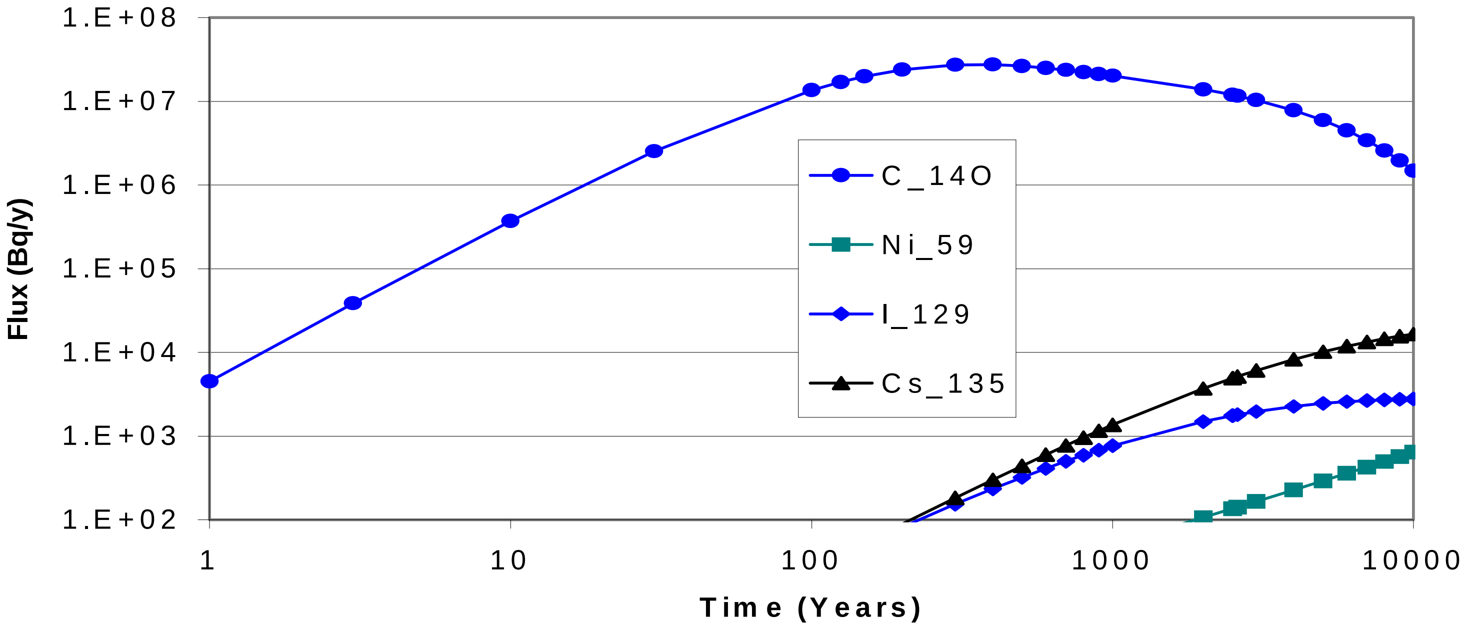


Figure 7
Flux of Organic Carbon from the Silo in the Saltwater Period.

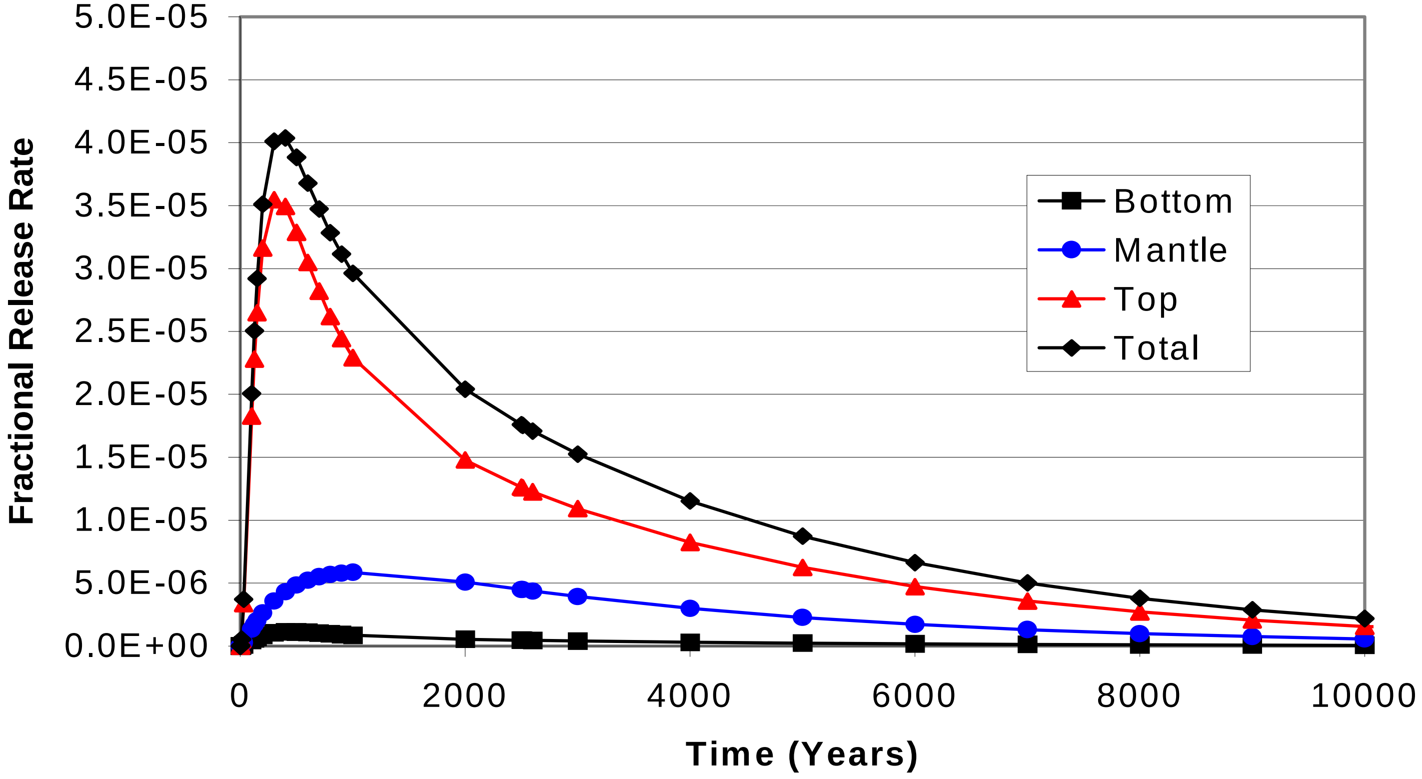


Figure 8
Flux from Silo in the Inland Period.

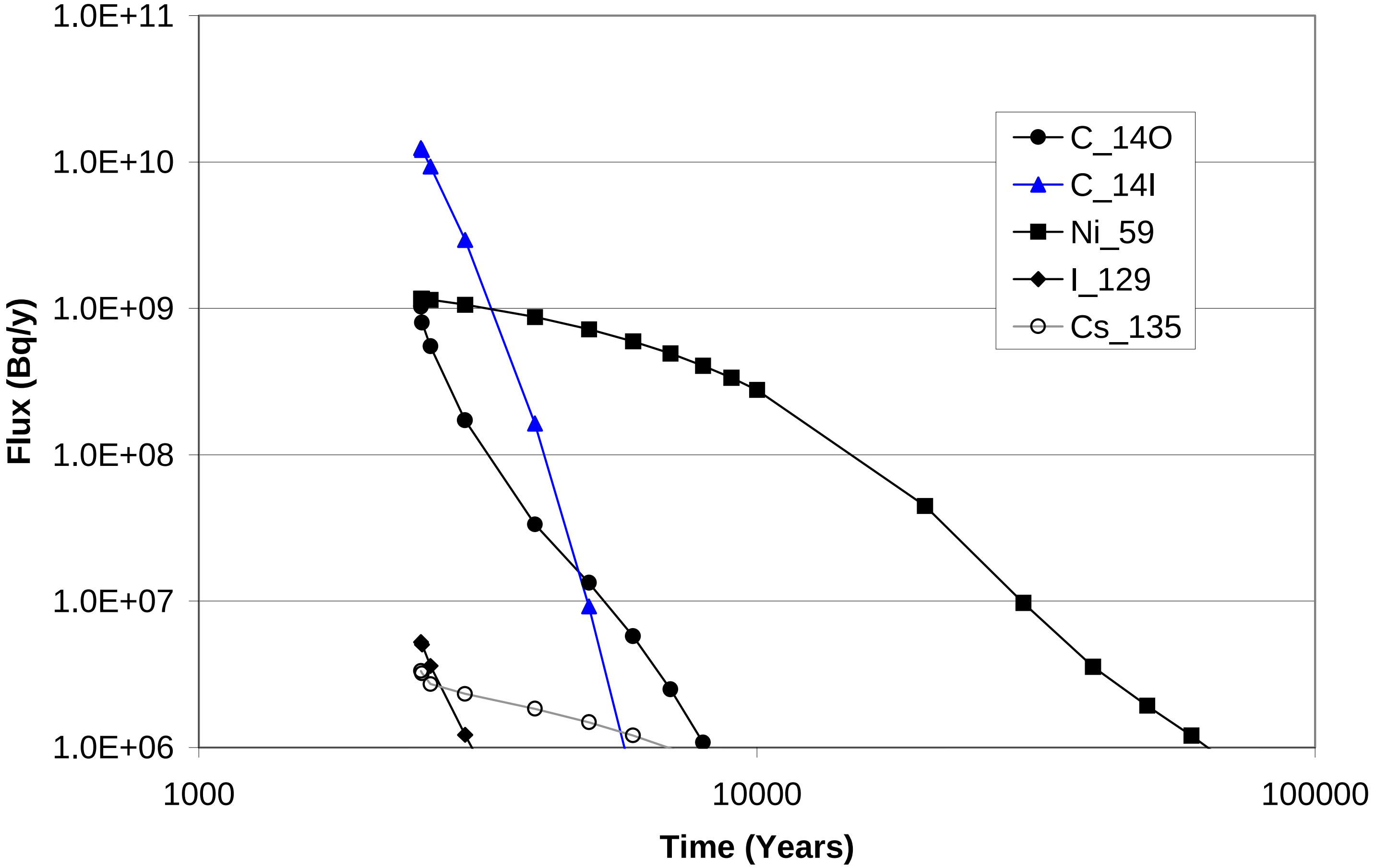


Figure 9
Total Releases in the Saltwater Period.

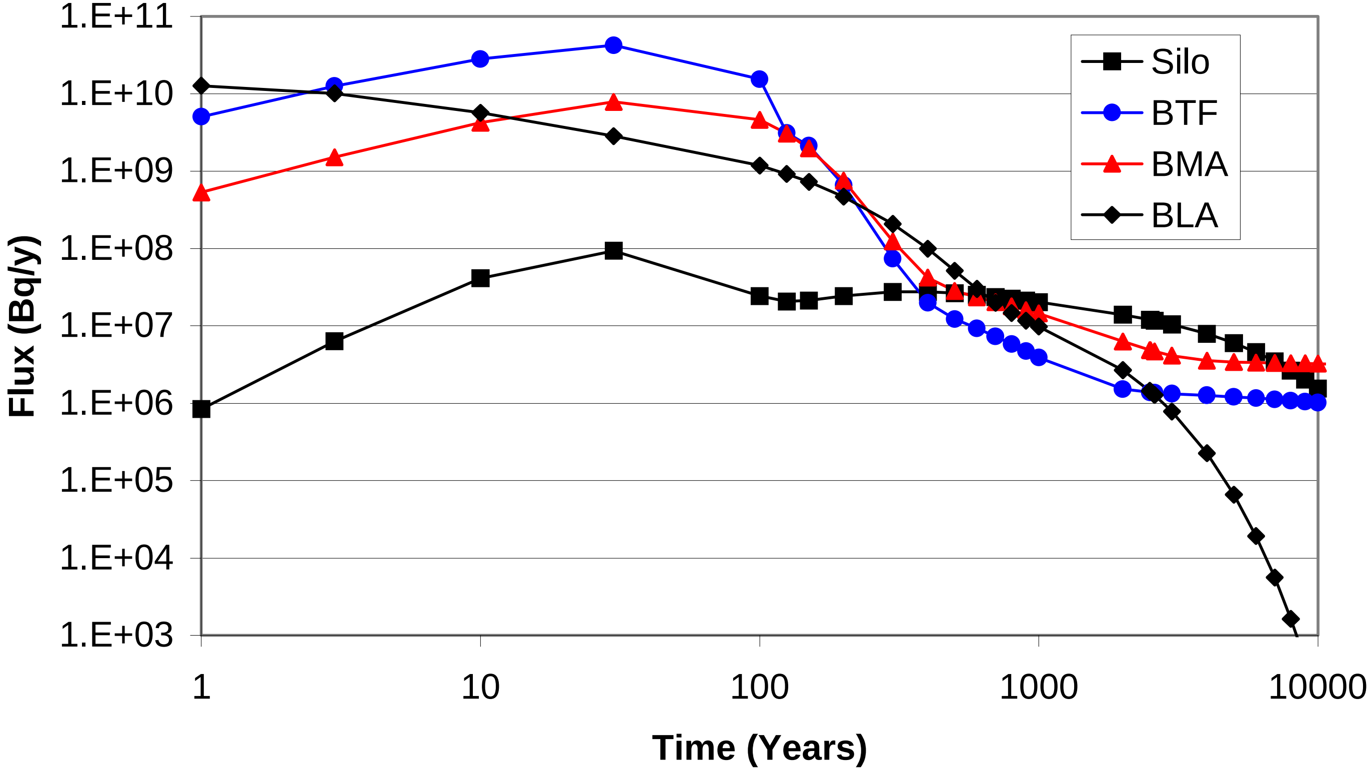


Figure 10
Total Releases in the Inland Period.

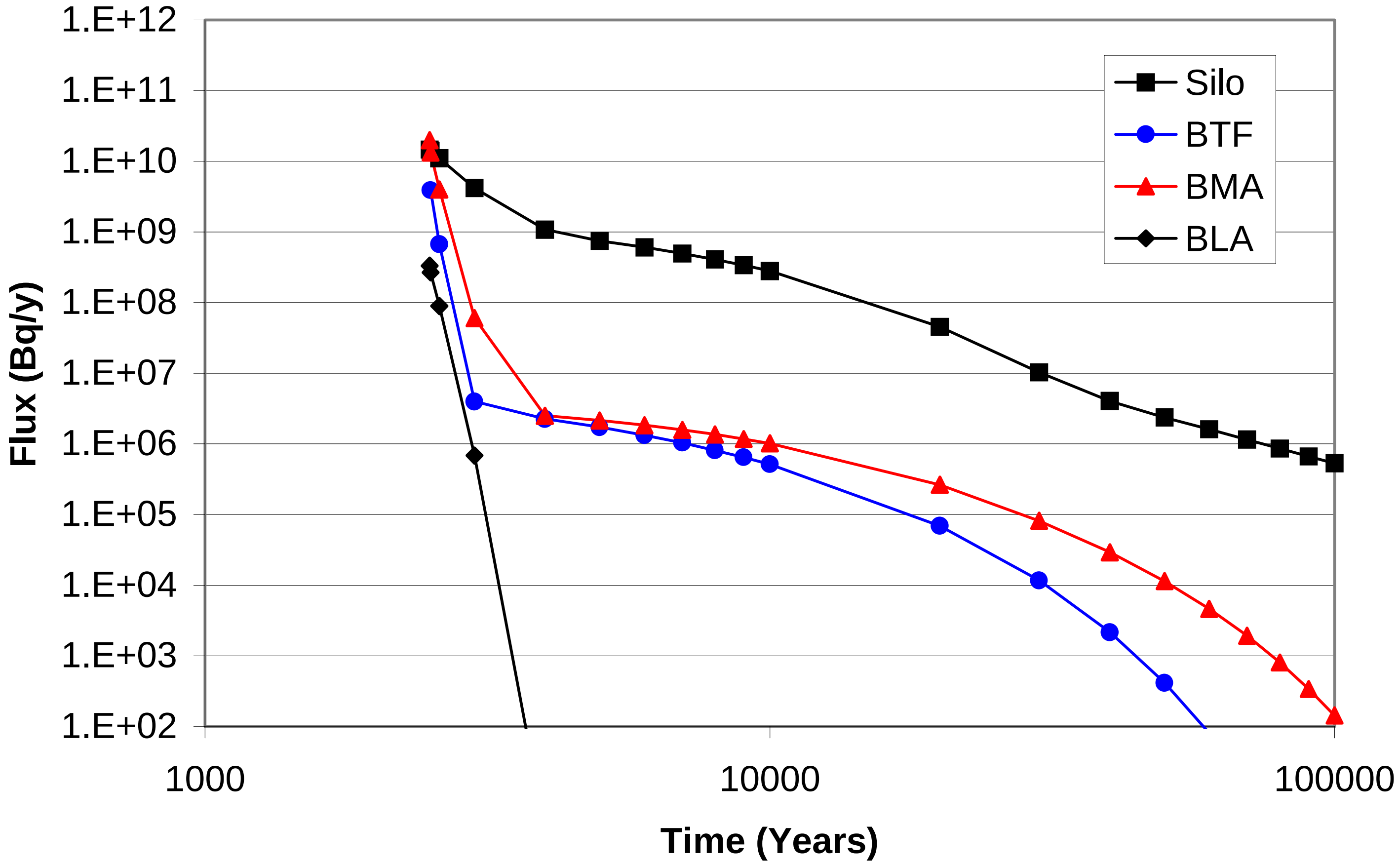


Figure 11
Cs-137 Doses in the Saltwater Period.

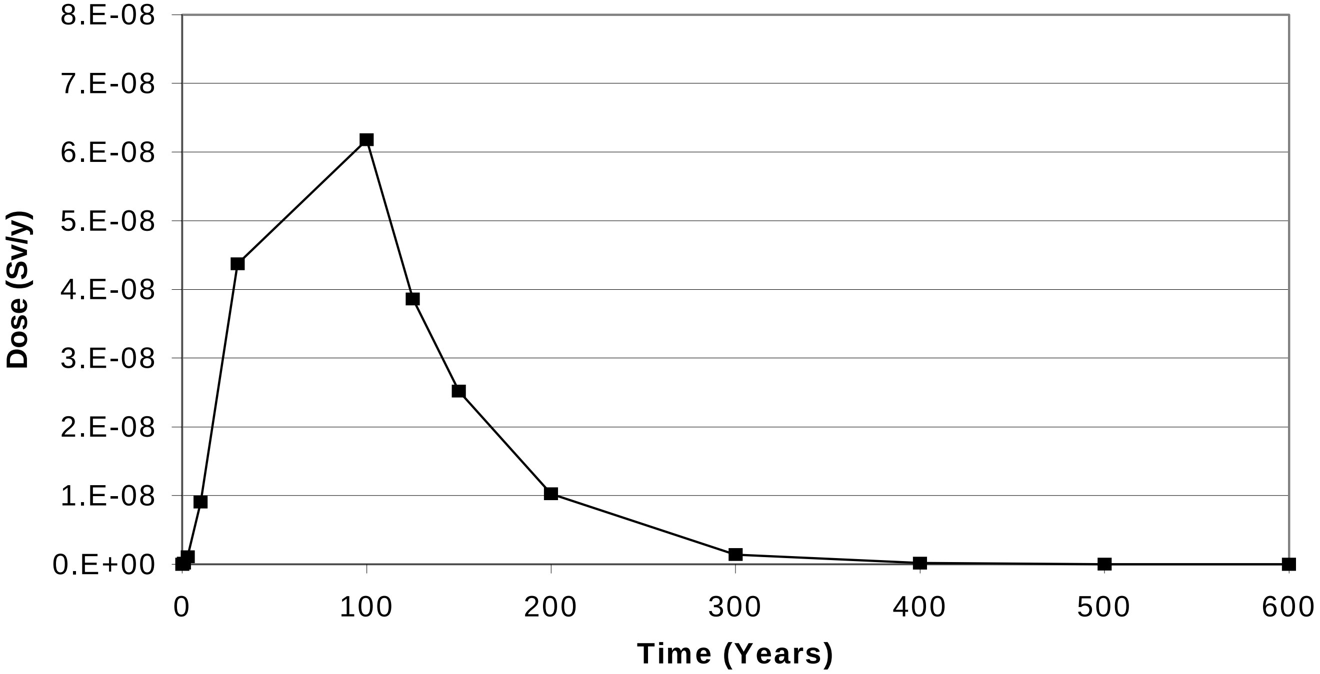


Figure 12
Pu-239 Doses in the Inland Period.

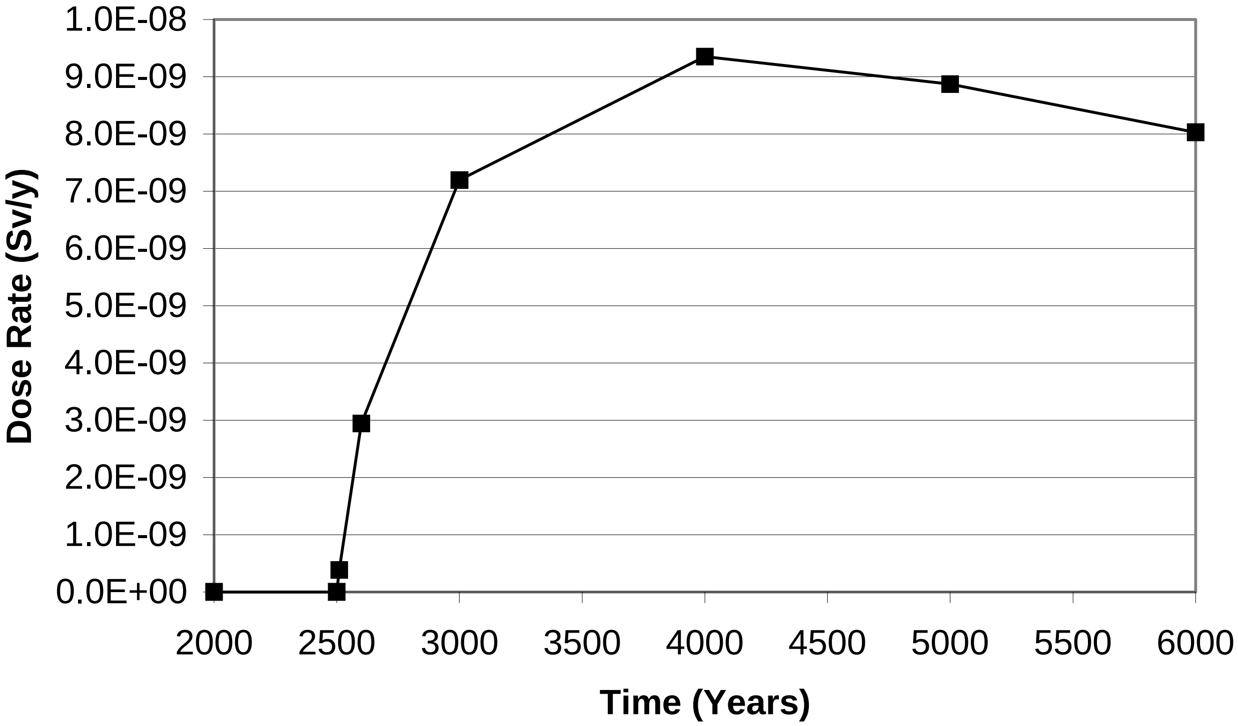


Figure 13
Structure of the Prototype Amber Case File.

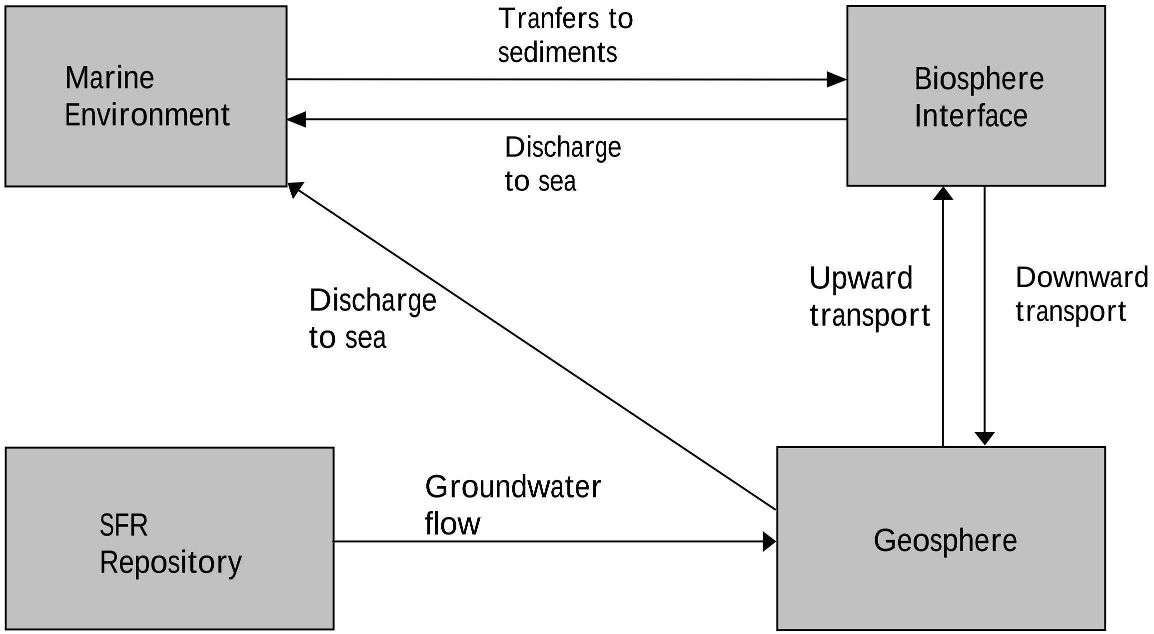


Figure 14
Structure of the Prototype Geosphere-Biosphere Interface Model.

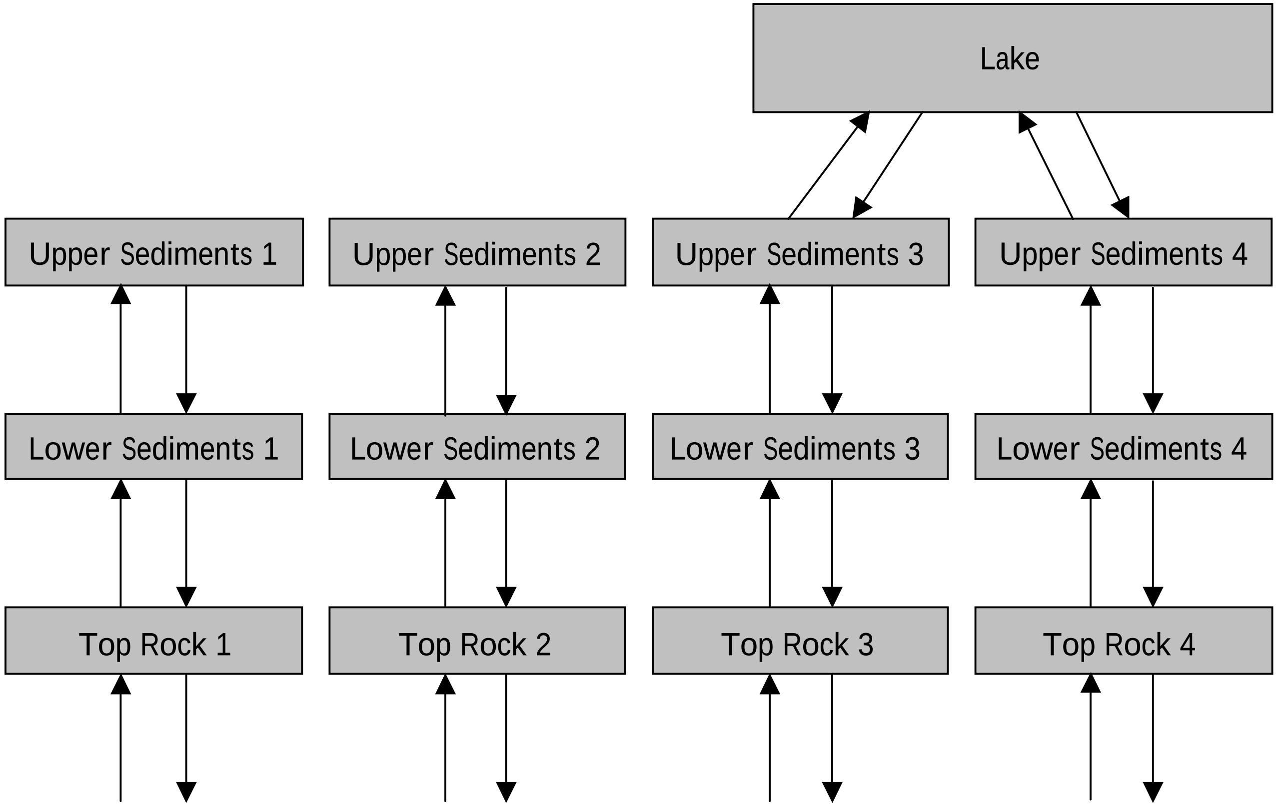


Figure 15
Structure of the Prototype Biosphere Sub-Model.

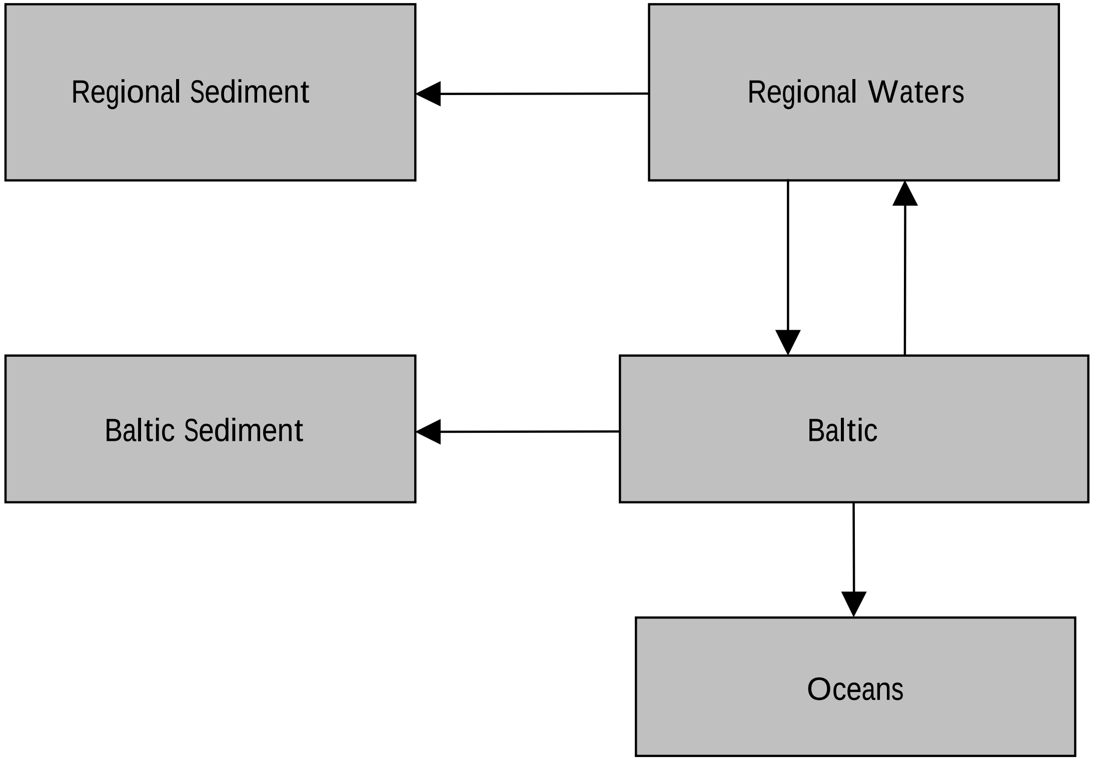


Figure 16
Illustrative Calculation of Cs-135 Concentration in Soil.

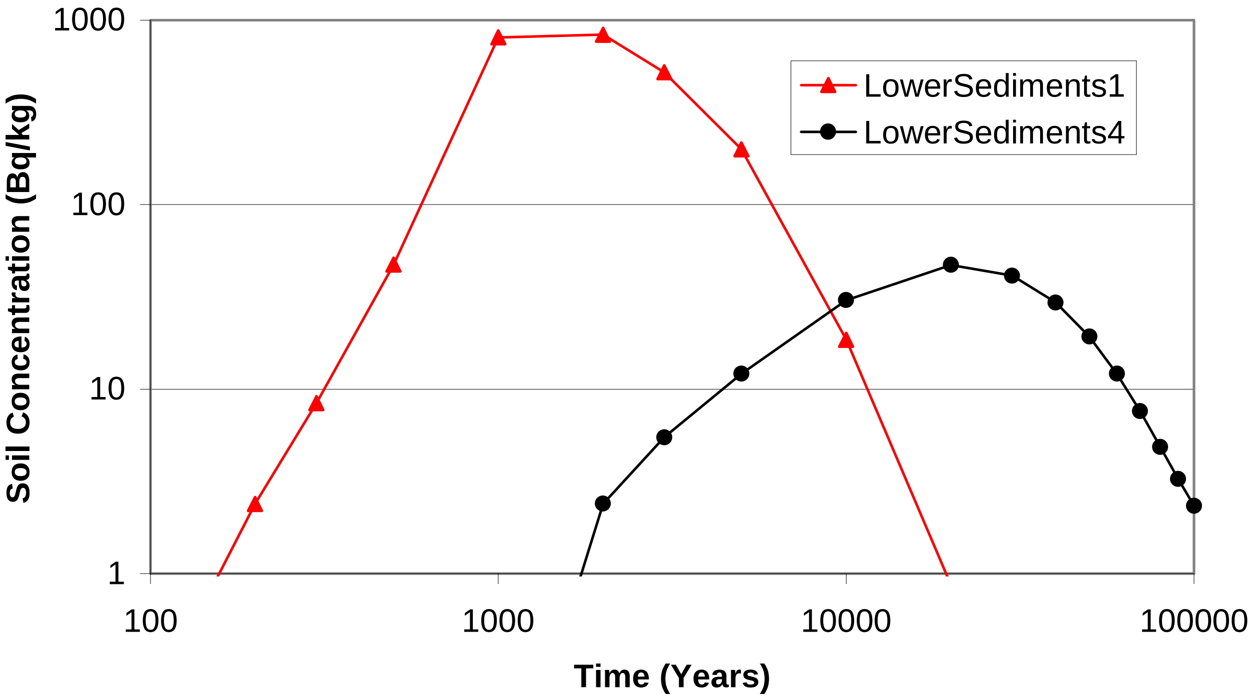


Figure 17
Illustrative Calculations of Total Drinking Water Doses.

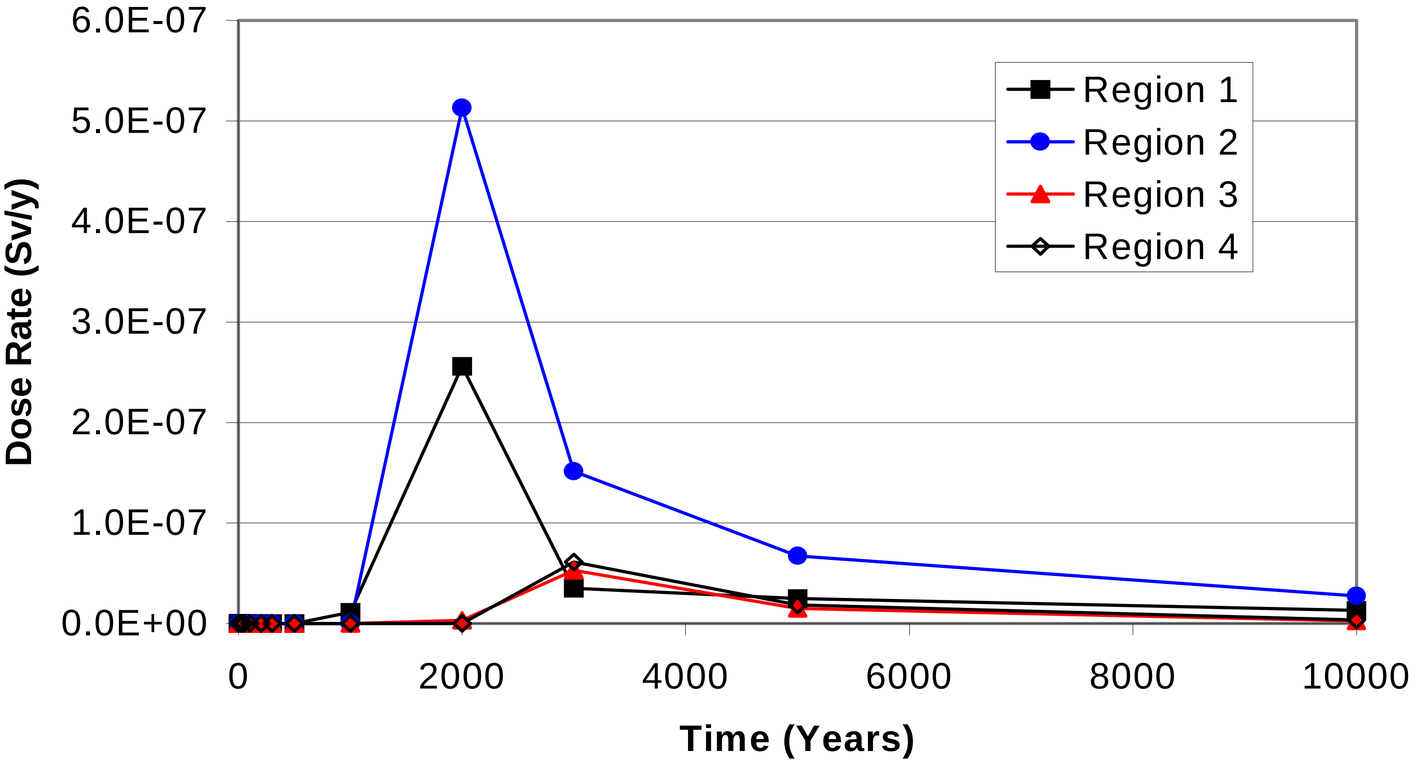
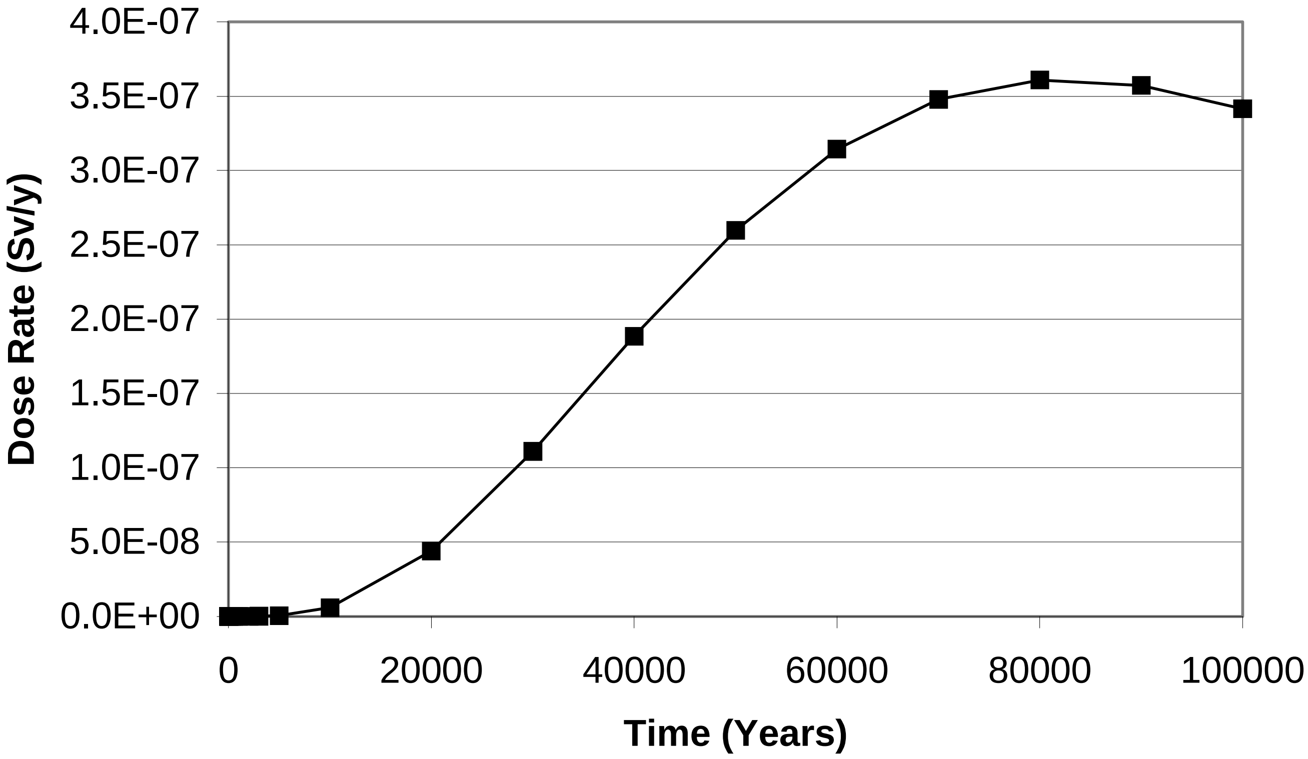


Figure 18
Illustrative Calculations of Total Marine Doses.



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