SSI Rapport
SSI report

2002:17 RICHARD KLOS AND ROGER WILMOT

Review of Project SAFE: Comments on biosphere conceptual model description and risk assessment methodology

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TITLE/ TITEL: Review of Project SAFE: Comments on biosphere conceptual model description and risk assessment methodology/Granskning av SAFE-projektet: Kommentarer på beskrivningen av konceptuella modeller för biosfären och metoder för utvärdering av risk.

SSI rapport : 2002:17
september 2002
ISSN 0282-4434

SUMMARY: The Swedish Nuclear Fuel and Waste Management Company's (SKB's) most recent assessment of the safety of the Forsmark repository for low-level and intermediate-level waste (Project SAFE) is currently undergoing review by the Swedish regulators. As part of its review, the Swedish Radiation Protection Institute (SSI) identified that two components of SAFE require more detailed review: (i) the conceptual model description of the biosphere system, and (ii) SKB's risk assessment methodology.

We have reviewed the biosphere system interaction matrix and how this has been used in the identification, justification and description of biosphere models for radiological assessment purposes. The risk assessment methodology has been reviewed considering in particular issues associated with scenario selection, assessment timescale, and the probability and risk associated with the well scenario.

There is an extensive range of supporting information on which biosphere modelling in Project SAFE is based. However, the link between this material and the biosphere models themselves is not clearly set out. This leads to some contradictions and mismatches between description and implementation. One example concerns the representation of the geosphere-biosphere interface. The supporting description of lakes indicates that interaction between groundwaters entering the biosphere through lake bed sediments could lead to accumulations of radionuclides in sediments. These sediments may become agricultural areas at some time in the future. In the numerical modelling of the biosphere carried out in Project SAFE, the direct accumulation of contaminants in bed sediments is not represented. Application of a more rigorous procedure to ensure numerical models are fit for purpose is recommended, paying more attention to issues associated with the geosphere-biosphere interface.

A more structured approach to risk assessment would be beneficial, with a better explanation of the difference between conditional and overall risk. More specifically, the risk assessment should take account of climate change as part of the *base* scenario. Assumptions regarding the number of persons exposed in the well scenario are not well justified, and the reasoning behind the limitation of the assessment to a period of 10 000 years should be made more robust.

SAMMANFATTNING: Svensk Kärnbränslehantering AB (SKB) har uppdaterat sin säkerhetsanalys för slutförvaret för radioaktivt driftavfall (SFR 1), vilket har dokumenterats i SAFE-projektet. Som en del i SSI:s och SKI:s gemensamma granskning av SAFE-projektet har SSI definierat två områden av SAFE som kräver fördjupad granskning: (i) de modeller som SKB utvecklat och använt för analyser av biosfären och (ii) SKB:s metodik för karakterisering av risk.

Vi har granskat den interaktionsmatris som utvecklats för biosfären och hur den har utnyttjats för att identifiera, rättfärdiga och beskriva de biosfärsmodeller som använts för att beräkna radiologiska doser. Metodiken för att bestämma risk har främst granskats med avseende på val av scenarier, val tidsskala för analyserna samt sannolikhet och risk för brunnsscenariot.

Biosfärsmodelleringen i SAFE-projektet bygger på ett omfattande underlagsmaterial men kopplingen mellan detta material och de använda modellerna har inte redovisats på ett tydligt sätt. Detta har lett till att beskrivningen av biosfären och de genomförda beräkningarna inte är konsistenta i alla avseenden. Ett exempel är hur övergången mellan geosfär och biosfär har representerats. I underlagsrapporterna för sjöar anges att grundvatten som strömmar ut i biosfären genom bottensediment

kan leda till ackumulation av radionuklider i sedimenten. Dessa sediment kan någon gång i framtiden komma att användas som jordbruksmark. I de numeriska beräkningarna för biosfären i SAFE tas dock ej hänsyn till denna typ av direkt ackumulation av föroreningar i bottensedimenten. SKB rekommenderas därför att använda en mer rigorös procedur som garanterar att de numeriska modellerna är adekvata för sitt syfte, särskilt med hänsyn till frågeställningar i övergången mellan geosfär och biosfär.

En mer strukturerad ansats för riskanalysen skulle vara värdefull för att tydliggöra skillnaderna mellan betingade risker och den totala riskuppskattningen. Mer specifikt borde riskanalysen ta hänsyn till klimatförändringar som en del av basscenariot. Vidare är antagandena om hur många personer som exponeras i brunnsscenariot otillräckligt underbyggda. Skälen till att begränsa analyserna till en tidsperiod av 10 000 år behöver också motiveras bättre.

Förord

Svensk Kärnbränslehantering AB (SKB) redovisade sommaren 2001 en förnyad säkerhetsanalys av slutförvaret för radioaktivt driftavfall vid Forsmark, SFR 1, etapp 1. I SSI:s och Statens kärnkraftinspektions (SKI) drifttillstånd från 1988 och 1992 anges att SKB ska lämna en sådan uppdaterad analys till myndigheterna minst var tionde år så länge förvaret är i drift. SSI och SKI har i sin gemensamma granskning av SKB:s säkerhetsredovisning för SFR 1, framförallt vad gäller förvarets skyddsförmåga efter förslutning, tagit hjälp av oberoende internationella experter som detaljgranskat viktiga delar av SKB:s säkerhetsredovisning.

Denna rapport redovisar en av flera konsultgranskning av SKB:s säkerhetsredovisning för SFR 1, som utförts på uppdrag av SSI. Granskningen täcker in två specifika ämnesområden i SKB:s analyser: (1) de modeller som SKB utvecklat och använt för analyser av biosfären och dess framtida utveckling och (2) SKB:s metodik för karakterisering av risk från slutförvaret. Båda dessa områden är centrala för SSI:s bedömning av hur väl SKB uppfyllt de krav som ställs i SSI:s föreskrifter om slutligt omhändertagande av använt kärnbränsle och kärnavfall (SSI FS 1998:1).

Arbetet har utförts av Ryk Kłos och Roger Wilmot vid konsultföretaget Galson Sciences Ltd i England, på uppdrag av Björn Dverstorp, avdelningen för avfall och miljö. Författarna svarar själva för innehållet i denna rapport. SSI:s samlade bedömning av SKB:s redovisning kommer att redovisas i en särskild granskningsrapport som tas fram gemensamt av myndigheterna SSI och SKI.

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) has updated its safety reporting for the SFR-1 repository for low-level and intermediate-level radioactive waste. This is documented as Project SAFE. As part of its review, the Swedish Radiation Protection Authority (SSI) has identified that two components of SAFE require additional review: (i) the conceptual model description of the biosphere system, and (ii) SKB's risk assessment methodology. This document sets out the findings of the review carried out by Galson Sciences.

1.1 SAFE biosphere system

Review of the SAFE biosphere system in the context of performance assessment is based on the level of characterisation provided by the Project SAFE biosphere system interaction matrix and how this impacts the system modelled in the SAFE assessment. Specific areas covered in this review are:

i. Biosphere system identification and justification, as characterised in the Project SAFE biosphere system interaction matrix.
ii. The characterisation and development of ecosystem-level conceptual models and particularly the methods used to describe ecosystem evolution as a component of the overall safety case.
iii. Definition of exposure pathways in the context of the relevant ecosystems.
iv. The documentation of expert judgements of biosphere FEPs and interactions, including the traceability of the judgements and decisions that lead to the definition of the numerical assessment models.
v. The treatment of the evolution of the geosphere-biosphere interface as a function of time. Changes in sea-level give rise to land emerging from the sea. Of interest is the potential for the accumulation, retention and fate of radionuclides in areas that received direct release at earlier times but that become spatially separated from the release area as the shoreline moves.

Chapter 2 of this report sets out the methodology of our review of the SAFE biosphere system; this methodology is based on the BIOMASS Reference Biospheres Methodology [IAEA, 2001a, 2001b, 2001c]. Chapter 3 deals with the specific review areas set out above, and the conclusions are set out in Chapter 5.

1.2 Risk assessment

The topics considered here in relation to the assessment of risk are:

- scenario selection
- assessment of risk
- probability of the well scenario
- risks from the well scenario, and
- timescale of the assessment.

The material addressed is primarily Chapter 5 of SKB's SSR Report [Version 1.0, 2001-06-30]. The review is presented in Chapter 4 in this review, with conclusions in Chapter 5.

2 Scope and focus of the SAFE biosphere review

2.1 The importance of conceptual models

SKB [2001a] sets out the performance assessments targets for Project SAFE. Numerical risk (and implicitly dose) targets are given for the protection of human health. Broader protection of the environment is also required but it is acknowledged that numerical dose targets for non-human biota are not practicable with current knowledge. Consequently, there is a need to produce numerically based models that are supported by semi-quantitative analysis.

The aim of the SKB documentation should therefore be to produce a comprehensive conceptual model based on system identification, justification and description. Those aspects that are amenable to numerical treatment should then be identified, justified and analytically described. This second stage of description defines the numerical models to be used in the quantitative part of the performance assessment.

In order to build confidence in assessments, there is a need for a careful and precise transformation from generalised system information into a conceptual description embodying necessary and sufficient detail on which performance assessment (PA) models can be based. There have been many attempts to systematise the procedures and a variety of tools came into use during the 1990s. Important amongst these, and playing a central role in SKB's performance assessment procedure, is the interaction matrix (IM), where interactions between key elements of the system are described graphically. The system can then be characterised by a systematic review of the interactions, and the interaction can be seen as a summary of the conceptual model (CM) for the PA system.

Questions of suitability may be expressed as:

- How does background knowledge about the system contribute to the content of the conceptual model as represented by the interaction matrix?
- How is the information in the matrix used to support the performance assessment in terms of qualitative understanding as well as the quantitative aspects of the numerical assessment models (NAMs)?

The development and justification of CMs is therefore at the heart of performance assessment. This process embodies concepts required for the PA, including not only those, which are directly accounted for in the NAMs, but also those which cannot be treated numerically. A vitally important task in the definition of the CM is the documentation of decisions about which features, events and processes (FEPs) are included (and how) and which are not.

Figure 1 illustrates the progress from reality to PA model. The conceptual model is an abstraction of reality. It should include those aspects of reality that are pertinent to the assessment task. FEPs included should be documented and the reason for rejection of those not included should be given. This process may require supporting calculations or other evaluation of the potential importance. As a result, some FEPs may be recognised as potentially important but a decision as to their role in the PA cannot be judged with available information. These are the 'deferred'

FEPs. The numerical assessment model is an abstraction of the CM. A similar process must take place by which the elements of reality contained in the CM are translated into tools for numerical assessment.

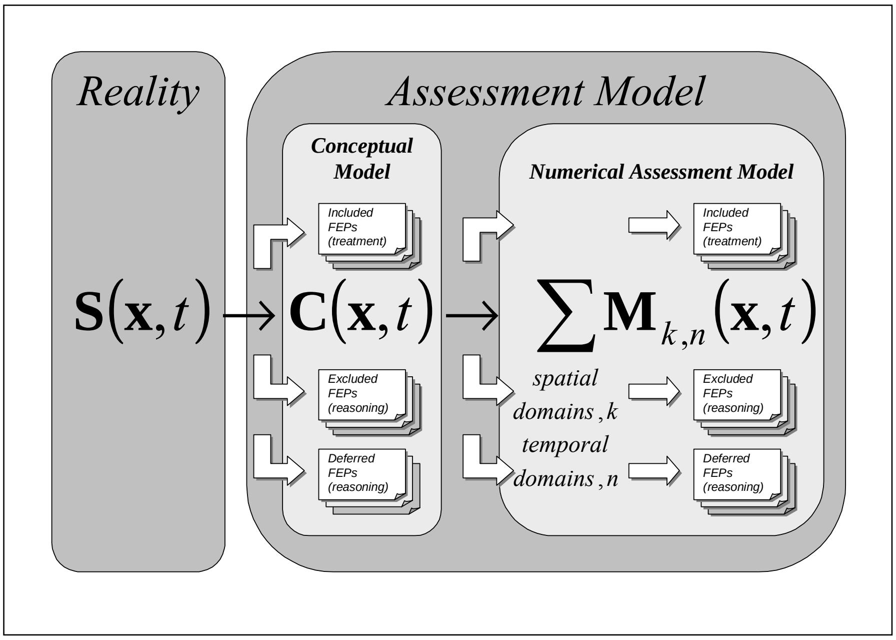

Figure 1
Illustration of the process of assessment model definition. Selected aspects of the real system (S) are translated to the conceptual model (C) which is, in turn, translated into a set of numerical assessment models ($M_{k,n}$) each with their own spatial and temporal domains. At each stage of translation decisions must be made and the reasoning and treatment documented.

The documentation of the choice made in the abstraction of reality to CM and thence to NAM is the audit trail by which it is possible to determine the adequacy of the performance assessment process. This review aims to assess the extent to which the documentation of the contents of SKB's Project SAFE CM is necessary and sufficient for purpose. As a secondary aim, the use to which the conceptual information is used in support of the overall assessment is discussed.

2.2 The reference biosphere methodology as a framework for conceptual and numerical assessment model development

The BIOMASS Reference Biosphere Methodology, RBM [IAEA, 2001b], is directly relevant to the task carried out by SKB in their definition of the biosphere component of Project SAFE. However, as the two projects were carried out in parallel, the evolving RBM had little direct influence on the development of the SAFE biosphere CM. At this review stage, however, it is possible to apply the RBM framework to discuss the contents of the biosphere models in SAFE.

The correspondence between the scope of the RBM and the scope of the SAFE documents reviewed as part of this project is not exact. Figure 2 summarises the separate tasks set out in the RBM. Alongside, the documents reviewed here are set in context, indicating to which parts of the RBM they correspond. Thus, two of the documents reviewed [SKB, 2001a; 2001b] relate to the system identification stage and two provide detailed background information describing the modelled systems [Kautsky, 2001 – biosphere; Holmén *et al*., 2001 – geosphere-biosphere interface].

The various numerical assessment sub-models making up the biosphere component of SAFE are described in detail by Karlsson *et al*. [2001], although the development and justification of the model is not described as fully as the procedures in the corresponding phase of the RBM would prompt. Similarly, the characterisation of critical groups is rather simplistic when compared with the approach suggested by BIOMASS[1]. The database for the assessment as a whole is given by SKB [2001c], and the results of the numerical calculations are summarised by Lindgren *et al*. [2001].

There are many other documents that provide additional supporting material for the main system description information in Kautsky [2001] – for example, the detailed description of the carbon budget in associated ecosystems [Kumblad, 1999], the detailed models of the accumulation and transport of bed sediments in the Öregrundsgrepen [Brydsten, 1999a; 1999b], and the description of vegetation in the present day and its likely evolution [Jerling *et al*., 2001]. These have been consulted as required but the main focus is on the documents illustrated in Figure 2.

Figure 2 also lists the stages in the RBM and the shaded bar on the left-hand side illustrates the scope of the review work carried out here. The main part of the review deals with SKB's work to identify, justify and describe the system modelled in Project SAFE. At various stages there are gaps in the documentation that the RBM would have more directly addressed. For example, the system justification stage is not as well developed as it is in the BIOMASS Example Reference Biospheres, ERBs [IAEA, 2001c]. The process has been carried out by SKB, but the audit trail, along which elements of the system identification process travel to become part of the system conceptual model, is not clear.

Similarly, while the NAMs used in the biosphere assessment of radiological impact are described in detail, the procedures by which the contents of the conceptual model are translated into elements of the NAMs is not discussed in detail and so, again, there is an appreciable gap in the overall audit trail.

In BIOMASS, development of NAMs was based on the construction of two levels of interaction matrix. The higher-level matrix (the phenomenological matrix) contained much the same kind of detail as found in the SAFE biosphere matrix. The lower level matrices are used to map the transfer of contaminants through the modelled system. Leading diagonal elements were chosen to represent conceptual model objects such as readily identifiable spatially defined entities (which later became model compartments in the numerical model). Details from the phenomenological matrix are then directly translatable into their appropriate modelling context in the transfer matrices[2]. This process, by which the higher-level description of relevant phenomena are converted to system radionuclide transfers, provides a useful audit trail of a kind that is not found in the SAFE documentation. Appendix A gives an overview of the BIOMASS methodology.

[1] A major part of the BIOMASS programme dealt with the identification, justification and development of models for use in the Example Reference Biospheres (ERBs) defined in the project. Further details of the implementation of the RBM are given in IAEA [2001c] and BIOMASS [2001].

[2] N.B., this is similar to the usage of interaction matrices employed in the modelling tool under development by SSI.

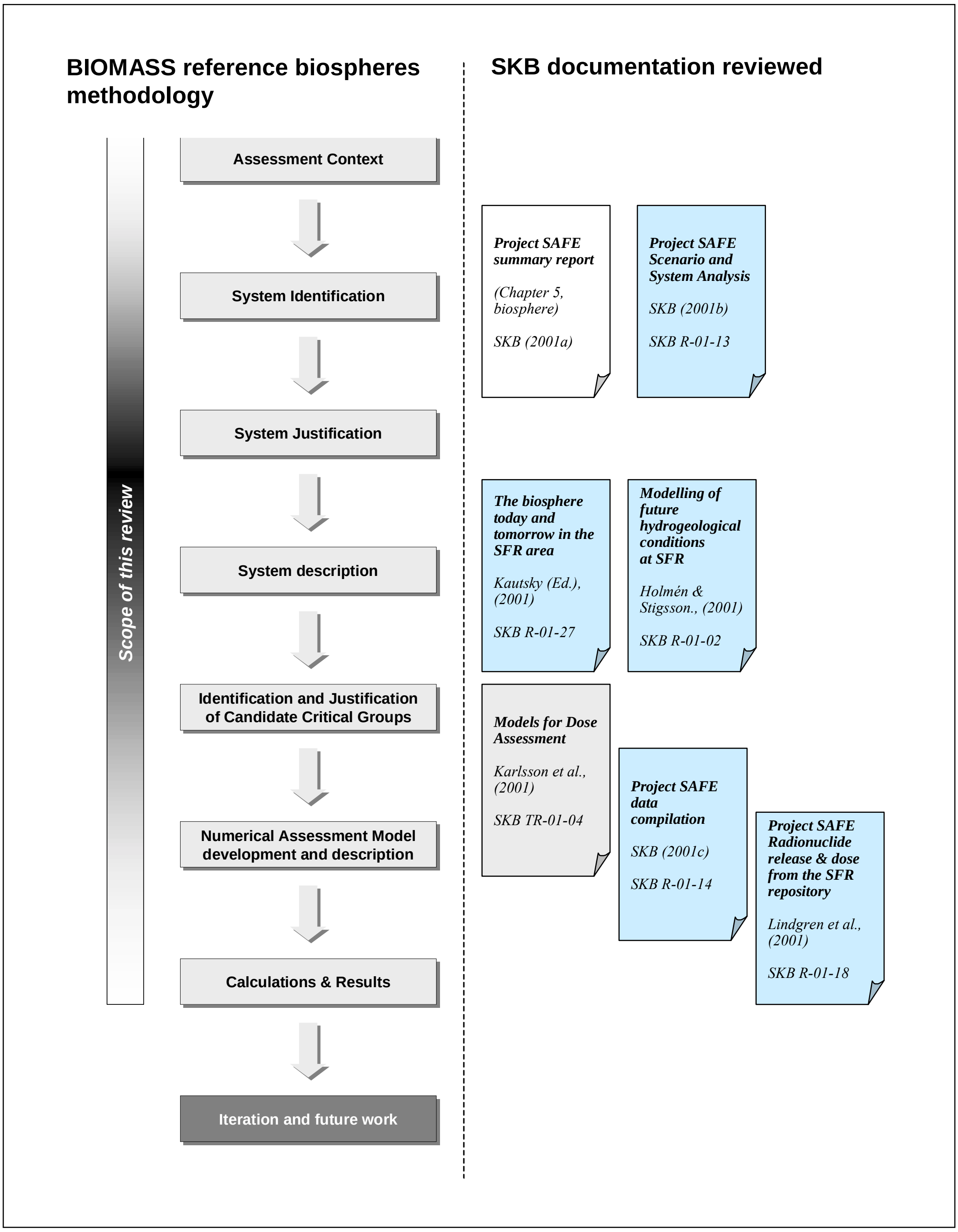

Figure 2
Comparison of the project SAFE biosphere CM definition procedure and the BIOMASS reference biospheres methodology.

3 Review of specific areas within the Project SAFE CM description

3.1 System identification, justification and description

Chapter 5 of SKB [2001a] provides details of the assessment context (although not in quite the same format as the BIOMASS version). Conditions in Sweden are such that the temporal evolution of the system must be taken into account since changes to the near-surface environment are likely on relatively short timescales as a result of land rise. This contrasts with the BIOMASS ERBs, where the generic nature of the examples allowed the choice of non-evolving systems to form the basis of the numerical examples. Furthermore, the timescale of the SAFE assessment is relatively short compared to that considered in the BIOMASS ERBs. These two factors place requirements on the implementation of system change that differ from those in BIOMASS.

System change is an essential part of SKB's assessment model description, and discussion of the implications is a major part of the documentation. However, in assessment terms, the practicalities of *numerically modelling* system change are not clearly set out despite the broad-ranging qualitative discussions. A clearer focus on the assessment requirements could have been obtained by applying the BIOMASS procedure, see Figure 3.

The Project SAFE biosphere system is not explicitly defined by regulations and there is a need to treat system change (Steps 1 and 2 of Figure 3). The most interesting question (at the third step) is the choice of whether the change is to be modelled sequentially (with a memory of past radiologically significant events) or non-sequentially (radionuclide releases to alternate system representations independently of prior releases).

In fact, Project SAFE uses the sequential approach but the lack of a systematic review leads to a measure of ambiguity in the system description. In particular, the choice of the sequential approach requires a separate identification, justification and description process be carried out for each of the system states to be represented. Attention should also be directed towards how the transitions between states are to be handled.

The Project SAFE numerical calculations are clearly carried out for step changes in biosphere conditions. That this is the case is made evident by the sharp edges in the plots at the times where there are transitions between states, see Figure 4. These are the main time-dependent features of the plots – for example, at 4000 AD (release to Öregrundsgrepen), 5000 AD (release to lake system) and 8000 AD (release to agricultural land).

The lack of a precisely set out time sequence of biosphere receptors *and* corresponding NAMs inhibits traceability. There is also a lack of discussion on the transition states, where there is release to Öregrundsgrepen and potentially to lake or, to lake and to agricultural land. It is likely that the discontinuities in the calculated doses would, in reality, be smoothed out. During transition phases, doses would come from two (or more) exposure sub-models and, to some extent, the nature of the critical group might be expected to change. The question of how closely the modelled system reflects reality remains open as a consequence of the lack of discussion.

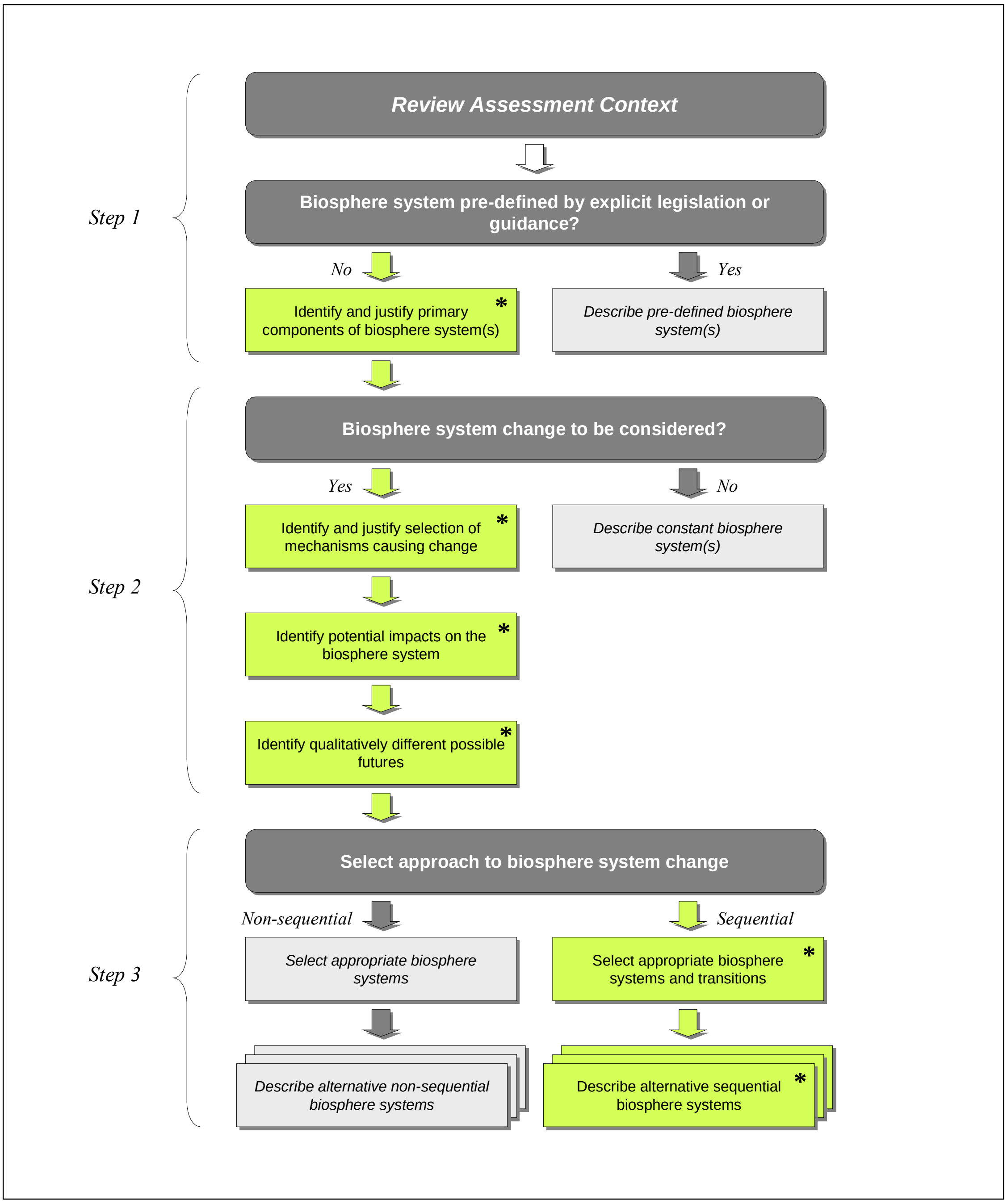

Figure 3
The BIOMASS RBM procedure for dealing with system change. The route implied by current Swedish assessment practice is indicated by asterisks. Documentation of the Project SAFE biosphere PA would have been much clearer had this frame-work been used.

The individual system states are identified in SAFE to the extent that separate descriptions are provided. At the numerical modelling stage the question of system *memory* is included but the discussion of transition from one stage to another is not dealt with in detail.

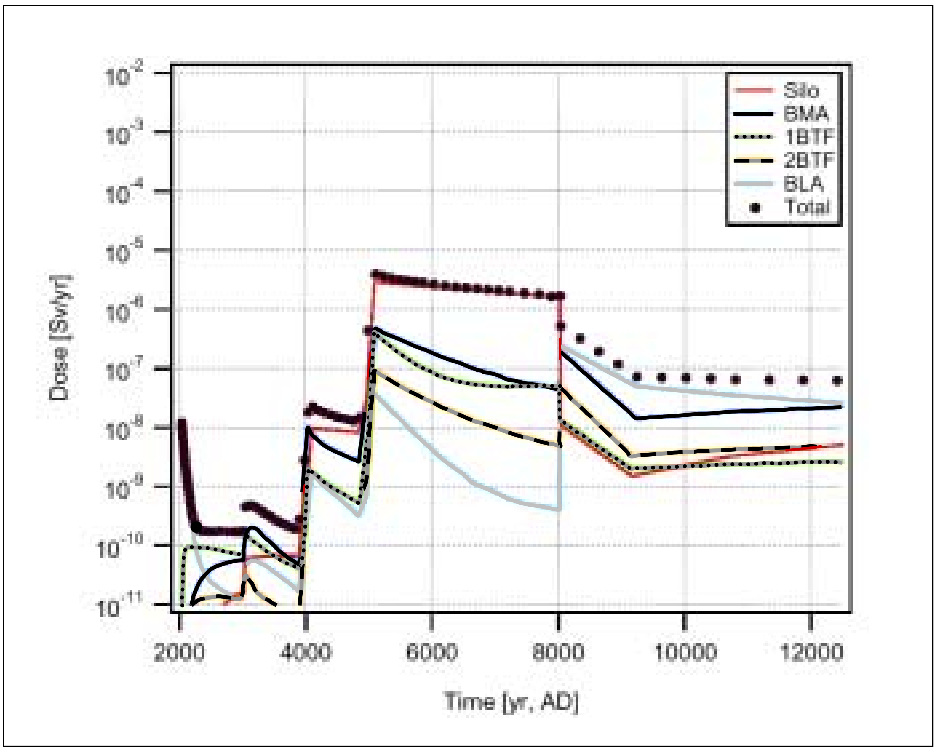

Figure 4
Total dose from release of radionuclides from SFR 1 to the reasonable biosphere [Lindgren et al., 2001]. Discontinuities in dose arise from the step change to alternate biosphere system models.

The link between the conceptualisation of the system and the numerical models would have been much clearer had there been a mapping of the numerical assessment model domains on to the physical biosphere system. At the descriptive level there is a detailed conceptual account of how the system responds to land rise but the NAMs used are not linked directly to geographical locations. A series of maps, showing release point and assessment model domain as a function of time, indicating the location of the various biosphere sub-models, would have helped.

As a result, although residual contamination in the biosphere is allowed in the NAMs, the description of how the modelled system represented at later times has evolved from that at earlier time is not clear. Transition states are not discussed other than to say that residual contamination is included in the initial conditions of later NAMs. The biosphere IM encompasses all of the FEPs but does not adequately express spatial and still temporal structures.

The approach to the numerical modelling of system evolution employed by SKB has its counterparts elsewhere. For example, BNFL [2000], in their approach to the evaluation of Drigg, employ what they call 'snapshots' of the system at key stages in the future evolution of the system. These play a similar role to the various numerically modelled stages in the SKB approach, although BNFL's NAMs are more broadly based with a clear mapping of model component to location.

The systems ecology approach adopted by SKB leads to a characterisation of the system in terms of ecosystems, each with its own spatial domain and internal physical chemical and ecological components. This is of great advantage in the understanding of the system. The current form of the ecology also impacts on what follows as conditions change. This is particularly relevant in the discussion of the east to west succession of ecosystems and provides a valuable indicator of what is to be expected at given spatial locations as a function of land rise with time. The BIOMASS examples showed a comparable spatial disaggregation of regions within the modelled system, particularly in ERB2B. These were identified as 'habitats' – forest, arable land, grassland, shrubland, marshland, river and lake. A full model representation of each was included, as a result of conceptual description arising from the use of radionuclide transfer interaction matrices[3]. The knowledge base that described the BIOMASS habitats was not as detailed as the full ecological description of similar model entities in Project SAFE. However, the BIOMASS knowledge base focused on the necessary and sufficient details for PA modelling.

The habitats in ERB2B were not only described as systems in their own right, but also in terms of how human exposures might arise as a result of radionuclide accumulation in them. Furthermore, review of potential exposure routes also allowed the description of key aspects of human behaviour which, in turn, fed into the characterisation of the candidate critical groups. The key is the interaction between the human groups and the modelled system. A detailed ecological understanding of the system, such as that provided by SKB in Project SAFE, helps to enhance confidence in the description of exposure pathways relevant to the different ecosystems in terms of what may be realistically assumed about human society's interaction with, and exploitation of, local resources.

By linking the ERB 'habitats' into the system description, BIOMASS also provided a description of radionuclide transfers through the combined system. In ERB2B the inter-habitat transfer of radionuclides was found to be important in determining dose to candidate critical groups. This finding suggests that the approach taken in SAFE, where the ecosystems were treated as independent model entities, may not be appropriate[4].

An approach that linked biosphere models together in this way would make it much easier, in the modelled system, to describe the spatio-temporal fate of radionuclides released from the repository system.

3.2 Definition of exposure pathways

Exposure pathways are treated in a standard way, compared with assessments elsewhere (e.g., applications of the vintage of BIOMOVS II [1996]). For example, although there are detailed ecosystem-level concepts on the leading diagonal of the biosphere matrix, there is no discussion of how these translate to elements of the exposure pathway models. *Primary producers*, *decomposers*, *filter feeders*, *herbivores*, *carnivores* and *humans* in the IM [SKB, 2001b] become *fish*, *crops*, *beef* and *humans* in the NAMs with no detailed reasoning and justification of the approximations necessary along the way.

There is no clear link between the system characterised by the SAFE IM and the routes by which exposure comes about. The NAMs used in SAFE give the impression that the modules available from earlier assessments (transport, accumulation and exposure pathways) were used in SAFE because the biosphere NAMs were simply those available from the biosphere modelling toolbox.

The multi-habitat approach employed in BIOMASS ERB2B allows a much more broadly based and inclusive description of exposure routes and suitable candidate critical groups.

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[3] It is also of interest to note that it was necessary to included the woodland area in the BIOMASS ERB2B model despite the woodland area not interacting directly with radionuclides in the system. The woodland area played a role in the water and solid material balance calculations for the modelled system.

[4] The key feature in ERB2B is that radionuclides are transported from parts of the system at higher elevations to accumulate in lower levels. For example, deeper rooting species may interact with contaminated groundwater, so accumulating activity. Detritus (as leaf litter, etc.) then moves through the system to accumulate in lower parts of the system, for example in mires. As mires already play an important role in the SAFE assessment because of the strong interaction with contaminated groundwater, the mechanism of detritus transfer across ecosystem boundaries is relevant to Swedish biosphere modelling.

3.3 System evolution and the geosphere-biosphere interface

SKB has chosen to evaluate doses and environmental impact in the calculated discharge area that follows the shoreline as it moves away eastward (regresses) from the repository. However, the treatment of the geosphere-biosphere interface in the assessment is rather simplistic. It appears to fit the requirements and capabilities of the biospheres NAMs rather than to have evolved from a detailed consideration of the biosphere interaction matrix and its interactions with the geosphere matrix. Local conditions at the discharge zone (as a function of time and space) are therefore not well represented.

There is a great deal of information in the supporting documentation to have enabled a more comprehensive treatment of the geosphere-biosphere interface. However, the basis for the decisions is not documented. Had a more rigorous procedure been pursued it is likely that different NAM structures would have resulted. As has been noted in Section 3.1, a sequential map of the *modelled interface* as a function of time would have greatly benefited the analysis.

SKB assumes that the highest consequences will be found in the discharge area at all times. To demonstrate this assumption satisfactorily would require supporting calculations as part of the system description and justification phase. Without such calculations, one can only say that the discharge area has the highest input at any given time. Consequences elsewhere might be higher depending on local factors. Treatment of system evolution, the extent to which memory of past releases is taken into account, and the extent to which inter-ecosystem transfers are included, are all relevant factors. At present the modelled system is too discretised and spatially disjoint. A broader and more integrated set of modules is probably necessary. BIOMASS ERB2B provides a worked example.

The treatment of the geosphere-biosphere interface, particularly at early times when the Öregrundsgrepen covers the repository and groundwater discharge area, is set out in such a way as to discount the potential for accumulation in media around the geosphere-biosphere interface. As a consequence, a number of assumptions are made in defining biosphere NAMs in order to arrive at what is claimed to be a pessimistic estimation of dose. Section 3.4 below discusses the consequences of the breakdown of the audit trail in more detail.

Contaminants leaving the model domain will predominantly be in solution and so, in the Baltic, very much more dilute than the concentrations in the local model area. An estimate of the potential for accumulation in the littoral zone as the land continues to rise might be possible (as there might be feedback to the bay ecosystem before widespread usage of the land is possible). Accumulations in the littoral zone are likely to be of less significance than the accumulation and retention of residual radionuclides in the geosphere-biosphere interface as the system evolves in the local model area.

3.4 Documentation and traceability

3.4.1 LINK BETWEEN CONCEPTUAL AND NUMERICAL ASSESSMENT MODELS

The material documenting the system description is of high quality. The descriptions of ecosystem-specific properties of the system are more detailed than those found anywhere else in comparable models for use in long-term radiological performance assessment. As noted above, however, it is not clear how all of this material is used in the definition of the PA system. It is difficult to be certain whether the conceptual model description (including the scenario analysis) supported the structures adopted in the NAMs or whether, conversely, the NAMs defined the corresponding parts of the conceptual model description.

The former approach corresponds to the logic trail followed by BIOMASS, since no parts of conceptual model space are *a priori* discounted and those relevant to the PA are carried forward to the NAM stage. In the latter case, only those concepts already addressed in *pre-existing* NAMs are considered. Gaps in the conceptual understanding of the PA system then arise and modelling capabilities are not progressed from earlier forms.

The lack of a suitably detailed audit trail is most apparent where elements of the system description or conceptual model contradict, or are contradicted by the details used in the NAMs. This problem occurs throughout the transition from conceptual to numerical model. In several instances, alternative interpretations, based on the current state of knowledge, are possible. Two examples are presented below.

3.4.2 SEDIMENTATION AND BED SEDIMENTS IN ÖREGRUNDSGREPEN AT EARLY TIMES

Knowledge of the physical reality of bay bed sediments is presented on page 48 of Kautsky [2001]:

> *On the mainland side, Öregrundsgrepen has a shallow archipelago with a rocky bottom, partly covered with coarse moraine.* The finer fractions of the moraine top layer have been flushed and transported away by waves and currents leaving sand, gravel, stones and boulders**.** *In some places there are* spots of glacial clay remaining*, usually covered with a thin layer of sand. … Erosion and transport bottoms dominate in the area and* sedimentation is therefore very small*. Except for isolated spots, accumulation bottoms are only found in the groove along Gräsö, in parts of the Forsmarksfjärden west of the Biotest basin and in the shallowest, and less exposed bays. These are described as 'soft bottoms' below.* (Emphasis added)

In the corresponding numerical assessment model [Karlsson *et al*., 2001], the coastal model has the structure shown in Figure 5. Sedimentation rates are low in the region and the modelling assumption is that the thickness of the upper sediment is 0.02 m (ranging from 0.5 cm to 5 cm in sensitivity studies). The lower 'Sediment' has an undefined thickness because it is used as a sink compartment. Sediment accumulates at a rate of 0.01 m y^{-1}, effectively transporting material to the deeper sediment compartment by burial. Thus, because the radionuclides enter the water column from the geosphere, the NAM assumes that there is sedimentation throughout the model area, when in fact it is only in limited areas in the Öregrundsgrepen (Figure 6-1 of Kautsky [2001]). The reason for this assumption is that there is need to accumulate radionuclides in the modelled system in order to provide a conservative assessment of radiological impact.

Release of contaminated groundwaters is likely to be *through* the bay sediments. Without a discussion of what underlies the sand, gravel, stones and boulders of the rocky bottom, it is not possible to say if it is reasonable to assume that discharge is effectively to the water column as a consequence of low sorption on large-scale material at the sediment-water column interface. Neither is it possible to evaluate the potential for accumulation of radionuclides at the bottom of the bay. It is also important to recognise that retardation and retention of radionuclides on boulders might be different to that on sand. It seems inconsistent then to assume that the lower sediment can accumulate radionuclides through burial but contaminated groundwaters flowing through them are assumed not to interact.

There may be very good reasons for the system to be modelled in the way it is but documentation of the possibilities and alternatives is not given. The potential for accumulation in the system is therefore overlooked.

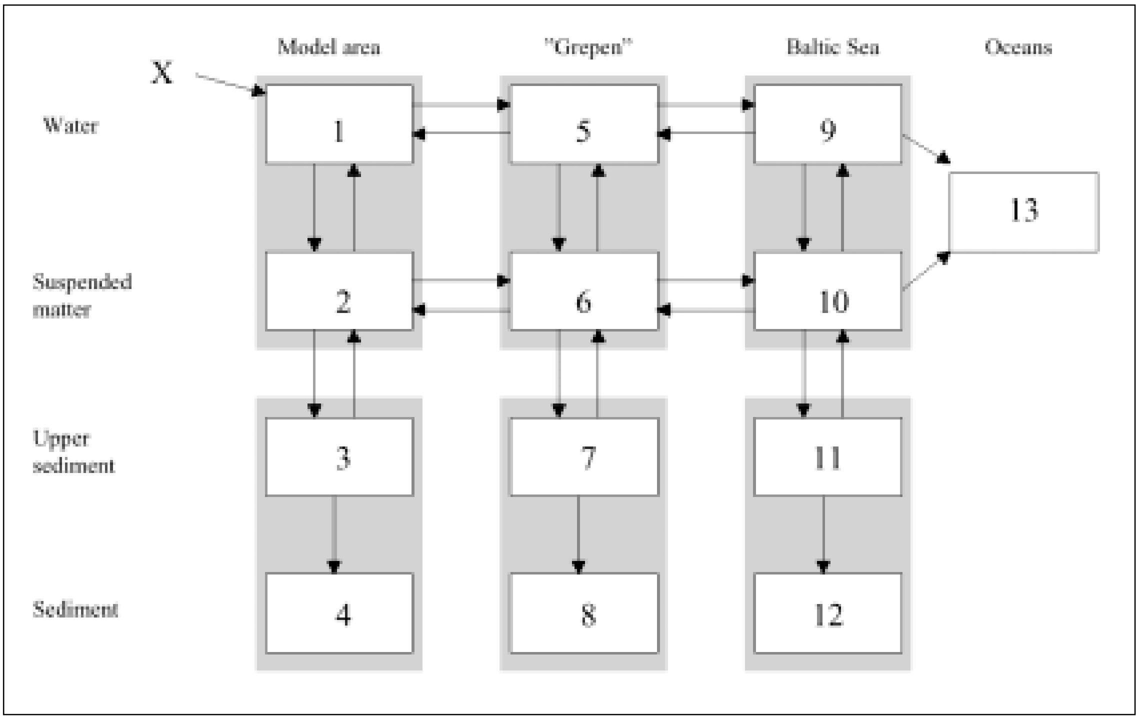

Figure 5
Structure of the coastal model used in the SAFE study. The 'X' denotes the compartment receiving radionuclides from the disposal system far-field. Transfers of radionuclides within the system are marked with arrows [Karlsson et al., 2001].

3.4.3 GROUNDWATER INTERACTION WITH LAKE BED SEDIMENTS

At different times there might also be a variety of different human activities associated with specific geographical locations (linked to the ecological succession) – for example, those involved in clearing bed sediment boulders to make way for farmland. The RBM Candidate Critical Group methodology would provide a more comprehensive quantitative and semi-quantitative description of the potential interactions.

A similar lack of attention to detail is found in the discussion of lakes, where the potential for accumulation and retention during release is again played down by SKB. The modelled structure of lakes is shown in Figure 6. Details of the ecology of the system are given in Kautsky [2001, page 112]:

> *The existing hardwater lakes in the Forsmark area can be characterised by the presence of three main key habitats: the sheltered littoral zone, the light-exposed soft-bottom sediments, and the open water. In relatively mature systems, the two former habitats are well developed, and there is reason to believe that both these components may have great influence on the* quality of the inflowing water before it reaches the pelagic zone*. The open-water habitat, on the other hand, is most likely of little importance to the production and turnover of carbon and nutrients in the system in this as well as in all other stages of succession. The reason for the low [ecological] importance of the pelagial is that the hardwater lakes typically have very limited drainage areas. As a consequence, most of the inflow is 'diffuse',* i.e. in the form of groundwater*, and this inflow passes through one or the other of the two bottom habitats.* Thus, any water entering: the pelagic zone [of] the lakes has been slowly prefiltered through a biological sieve, and thereby most likely cleared from biologically active substances. (Emphasis added)

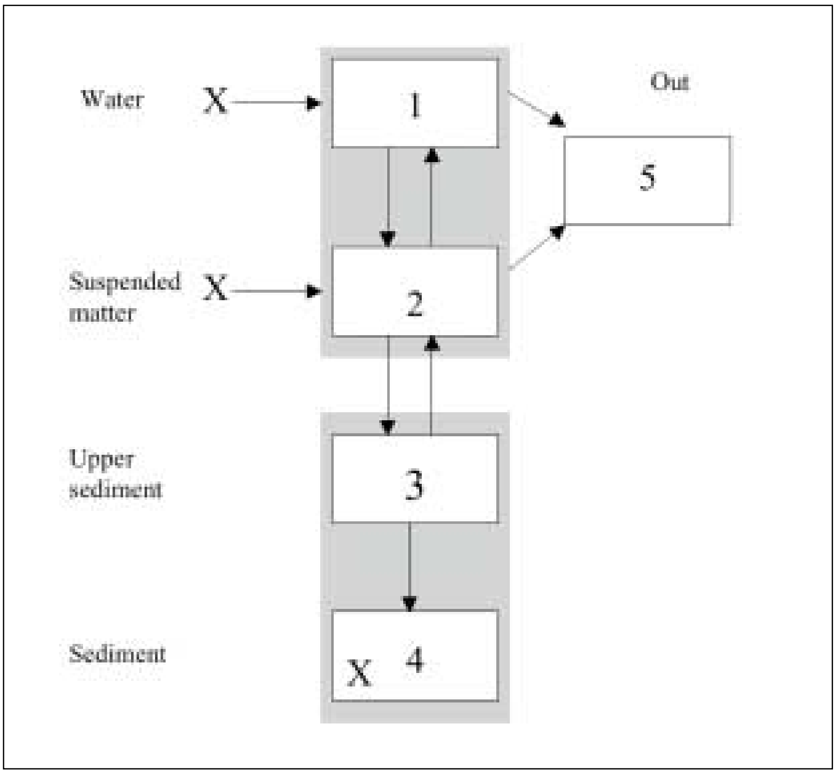

Figure 6
Structure of the lake model. Transfers of radionuclides within the system are marked with arrows. 'X' denotes input of radionuclides. Note that sediment may contain a memory of radionuclide accumulation at earlier times. Past accumulations in sediments and further accumulation in this model are used as the basis for contaminated farmland at future times in the model [Karlsson et al., 2001].

It is therefore clear that the flow of groundwater *through* the bed sediment layers of lakes is an important feature in lakes. The review in Kautsky [2001] goes on to discuss the dike theory, where the sediments are impermeable, as well as the sieve theory. The sieve theory has clear implications for the filtering and accumulation of waterborne contaminants[5]. No discussion of the potential implications is found in the description of the NAM. The input of radionuclides to the lake is via solution and suspended solid material from outside the system, see Figure 6.

The description of the leading diagonal elements of the biosphere interaction matrix is not sufficient to take this kind of material into account. The analysis would be clearer were SKB to provide a further level of interaction matrix, concerned with radionuclide transport.

The biosphere interaction matrix in SKB [2001b] shows that the geosphere interacts directly with quaternary deposits (solid and water), surface water and humans, and via heat transport. This level of discussion does not provide the justification for the treatment of the geosphere-biosphere interface in the biosphere models, as shown in Figures 5 and 6.

There are other examples where the audit trail breaks down but these two serve to illustrate the problems.

[5] Even if sieving is not the relevant concept for dissolved radionuclides, it is clear that there is the potential for interaction between the sphagnum layer and groundwaters.

4 Review of risk issues in Project SAFE

4.1 Scenario selection

There appear to be contradictory arguments put forward for determining the basis of the basic scenario. In particular, changes in the position of the shoreline arising from continued land uplift, and consequent changes in ecosystems, are included in this scenario, but changes in climate are not. SKB states that the uncertainties as to how the climate will change are much greater than the uncertainties over movement of the shoreline. However, rather than take account of these uncertainties in the analysis of the base scenario, SKB selects one set of climate conditions (present-day) and uses these for the whole analysis. This may allow information to be gained as to the sensitivity of the system to ecosystem changes, but it does not fulfil SKB's requirement of being 'plausible'.

SKB also implies that a distinction can be drawn between climate change brought about by natural processes and change caused by human influences (greenhouse gases). Again, although neglecting the human influence on climate might help in building an understanding of system behaviour, assessment calculations that do not account for these effects, with the associated uncertainties, cannot be regarded as plausible.

4.2 Assessment of risk

SKB discusses the assessment of risk in general terms in Section 5.3.5, and presents two possible approaches. As described, the only difference between the approaches is in the treatment of parameter uncertainty, and both approaches use the same method of accounting for scenario uncertainty. The descriptions do not make these similarities particularly clear, and seem to imply that there are greater methodological differences than is in fact the case. Also, there is no mention of the dose-risk factor in the description of how risk is determined.

One issue in particular, that is not clearly described, is the difference between different measures of consequence. The result of any calculation, be it a deterministic calculation or one simulation within a probabilistic calculation, is usually dose. This is a *conditional* dose, conditional upon the occurrence of the scenario being assessed, and the particular set of parameter values selected. This dose can be converted into a conditional risk by multiplying by the dose-risk factor. In the case of a probabilistic approach to parameter uncertainty, the results from all of the simulations can be averaged to give a conditional dose or risk for the scenario. To combine conditional risks into an overall risk, the probability of all of the scenarios must be determined, and the overall risk is then the probability-weighted sum of the conditional risks.
In summary:

For a probabilistic approach, the conditional risk for a particular scenario s is given by:

$$R_s = \frac{1}{n}\sum_{i=1}^{n}\gamma D_i$$

where

D_i is the conditional dose for simulation i,
n is the number of simulations, and
γ is the dose-risk conversion factor.

For a deterministic calculation, the conditional risk for a particular scenario s is given by:

$$R_s = \gamma D_s$$

where

D_s is the conditional dose for scenario s.

In both cases, the overall risk is given by:

$$R = \sum_{j=1}^{N} R_j P_j$$

where

N is the number of scenarios,
R_j is the conditional risk of scenario j, and
P_j is the probability of scenario j.

This description of the calculation of risk assumes that the scenarios identified form an exclusive and exhaustive set. This means that the sum of the scenario probabilities must be equal to one. If pessimistic values are assigned for one or more scenarios, then the overall probability will be greater than one. In practice, however, not all scenario probabilities need be estimated and the probability of the most likely scenario can be calculated as one minus the sum of the other scenario probabilities.

In the discussion of how scenarios are combined (Section 5.8.1), SKB assigns a probability of one to the basic scenario, and acknowledges that this probability should be reduced as significant scenarios (i.e., those with consequences greater than those from the basic scenario) are added to the set of scenarios that contribute to the overall risk. Because the probabilities of these other scenarios are considered to be small in comparison with the basic scenario, SKB has not reduced the probability of the basic scenario from unity. This leads to a total scenario probability of greater than one, but the extent of the error, and the fact that it leads to an over-estimation of risk, mean that it is not significant in terms of the other uncertainties inherent in the analysis.

The overall approach adopted by SKB of assessing a high probability ‘normal evolution’ scenario and a number of low probability ‘disturbed evolution’ scenarios is common practice in assessment programmes and is a reasonable approach, even if scenario probabilities are treated pessimistically. However, SKB’s application of this approach is flawed, because the basic scenario does not account for climate change, and therefore has an extremely low probability of actually occurring.

It is not entirely clear from the descriptions of the scenarios and the assessment calculations whether the scenarios identified by SKB fulfil the criterion of being exclusive. In particular, the way in which the well scenario is described suggests that it is not treated as a ‘full’ scenario, but rather as an additional event. In other words, the consequences calculated for the well scenario are restricted to those arising from drinking water from a well drilled through a specific region. This scenario can therefore occur in addition to the basic scenario, rather than instead of it.

This approach to defining scenarios is not unreasonable in assessments where there are no consequences if the ‘event’ does not take place. For example, in assessing the risk of a chemical plant exploding, the consequences of it not exploding are zero and hence the risk can be calculated from the probability of the explosion. In radiological risk assessments, however, there is generally a dose associated with the normal evolution scenario, and this dose should be added to that of any additional ‘event’ to determine the risk of the scenario.

In this specific example, let the conditional dose for the basic scenario be D_b, the dose from drinking water from the well D_w, and the probability of drilling the well P_w.

The approach reported by SKB is equivalent to:

$$R = \gamma(D_b + D_w P_w)$$

whereas the overall risk should be calculated as:

$$R = \gamma(D_b(1 - P_w) + (D_w + D_b)P_w)$$

assuming that drilling the well does not change concentrations and hence doses from other parts of the system, which may not be a reasonable assumption.

If D_b and P_w are both small, the differences between these calculations will be small, and the overall assessment by SKB is a reasonable indication of system performance. However, the interpretation of the risk assessment results would be eased if there were a clearer presentation of the risk calculations and the assumptions involved.

A similar criticism applies to the treatment of scenarios with low consequences. According to the ‘principles’ presented in Section 5.8.1, SKB does not take ‘credit’ for scenarios that have consequences less than those for the basic scenario. Effectively, these scenarios are assumed to have the same consequences as the basic scenario, and their probabilities of occurrence are included within the probability of the basic scenario, which is given a value of one. In fact, none of the scenarios analysed appear to give doses less than those for the basic scenario, and this principle is not used. In general, however, it would be useful in terms of system understanding if the results of all of the scenarios analysed were reported in the same manner, without a distinction based on the level of the consequences.

4.3 Probability of the well scenario

In the description of the well scenario, SKB uses the current well density in the region (0.5 wells per km^2) and the area of the region with a sufficiently high concentration of radionuclides (< 0.2 km^2) to derive a probability. SKB describes this as the (annual) probability of a well being drilled within the area of concern, but this is only the case if the lifetime of a well is one year, and the well density is maintained at the current level. The important assumption is the constant well density. Figure 4-14 shows the number of wells in the region, but this figure is not easy to interpret in terms of how well density may change with time, and hence how the probability of extracting water from a particular region might vary with time.

4.4 Risks from the well scenario

SKB calculates a risk of up to 4×10^{-6} for the well scenario, which exceeds the SSI risk criterion for a representative member of a group exposed to the greatest risk. SKB argues that the group exposed to this risk (a family running a small farm) does not meet the definition of the critical group, or potentially exposed group, and that a larger group of individuals should be considered. Because the water demands of a larger group would be greater, abstraction from the well would be greater, leading to more dilution, lower concentrations and lower risks.

In assessment of existing facilities, the group exposed to the greatest risk can generally be identified and is referred to as the critical group. There is no absolute limit (upper or lower) on the size of the critical group. However, guidance from the ICRP [ICRP 1977; 1985] specifies the following criteria:

- Size – The critical group should be small in number and typically include a few to a few tens of persons.
- Homogeneity among members of the critical group – There should be a relatively small difference between those receiving the highest and the lowest doses. It is recommended that the range between the low and high doses not differ by more than a factor of ten or a factor of about three on either side of the critical group average.

In the case of potential exposures, the most exposed group cannot be identified *a priori*, and a series of potentially exposed groups must be considered instead. The criteria above can be used to determine such groups. BIOMASS [2001] illustrates a practical method for identifying such candidate groups.

It is unclear why SKB consider that a family running a small farm does not meet the ICRP criteria. In section 5.1.2, SKB states that '… SSI mentions the population in an area where it is theoretically possible to site ten different deep repositories'. There is no reference in the regulations to such a definition. In the background documentation, the potential impacts from a number of sources (not only repositories) is mentioned as a reason for requiring that the risk criterion is lower than that for existing facilities. A similar approach is taken by the Environment Agencies in the UK.

4.5 Timescale of the assessment

SKB notes in their introduction that forthcoming SKI regulations will require an assessment for *at least* 10,000 years, and there is no time limit for assessments given in the SSI regulation or background material. The onus should therefore be on SKB to justify the selected timescale. There are several ways in which an assessment timescale could be determined:

- Decay of inventory to insignificant levels.
- Time of peak dose passed as radionuclides dispersed into groundwater and/or sea.
- Loss of repository through erosion, and dispersal of radionuclides over a wide area.
- Level of uncertainty about characteristics of disposal system increases to a level at which calculations are meaningless.

In the case of the last two, although quantitative calculations might not be conducted beyond the limit, qualitative reasoning would be required to demonstrate that the dispersed radionuclides would not pose significant risks.

The documents presented do not provide justification for limiting the assessment to 10,000 years. Figure 7-3 [Lindgren *et al.*, 2001] indicates that, for the 'reasonable' biosphere, doses are decreasing by 10,000 years, but for some of the other biosphere assumptions, the peak dose may not have been reached. Figure 6-9 [Lindgren *et al.*, 2001] also shows that, for some radionuclides, the release rate from the Silo is increasing at 10,000 years, suggesting that there is still a significant inventory present at this time.

The only process that could erode sufficient material as to directly affect the repository is glacial erosion, and SKB's analysis of climate change (Section 5.4.5) indicates that continental ice is not expected near the Forsmark area until at least 20,000 years.

Finally, there is no structured approach to assessing the level of uncertainty in the characteristics of the disposal system, and no event or process is conjectured to take place at 10,000 years that would markedly increase this uncertainty.

5 Review conclusions

5.1 Project SAFE biosphere system

5.1.1 BIOSPHERE MODELS

Given that the assessment context requires both numerical results (for assessing risk to future human populations) and a more qualitative approach to address the consequences to the environment in general, the relative balance between these two aspects of performance estimate is not clear. If the qualitative results are more important than the numerical results, then the relatively low level of justification for the numerical assessment models is more understandable than if equal weight is assigned to both, or if greater reliance were placed on the numerical results.

As identified in the BIOMASS RBM, model definition requires system identification, description and justification. This three-stage approach should be applied to both the conceptual model definition *and* the numerical assessment model definition. In the current SAFE documentation, the level of detail supporting the conceptual model is strong (particularly with respect to the understanding of system ecology), but the corresponding support for the NAMs is weak.

The biosphere interaction matrix is comprehensive and detailed but there is a gap between the knowledge summarised within it and the details in the numerical assessment models. Documentation to fill the gap would provide the identification, justification and description of the numerical models. A good knowledge base exists but, in SAFE, demonstration of its use is poorly documented, so that it is unclear how much of it has been used. A more detailed discussion of how numerical assessment models arise from the conceptual understanding of the system would help to resolve what aspects of the overall knowledge base are relevant to the assessment. Emphasis needs to be on what is necessary and sufficient for the performance assessment.

The BIOMASS RBM would, if applied, have important benefits to the definition of models for assessment purposes. In particular, the translation of conceptual model to assessment model is greatly facilitated by the use of second-stage interaction matrices which describe radionuclide input, transport and accumulation and output from spatially and temporally well-defined assessment model domains. The RBM provides a clear audit trail linking conceptual model to numerical model and helps to identify data requirements.

In a spatially distributed system that allows for temporal evolution, the fate of radionuclides in the system can be tracked as a function of time, and the RBM allows for a consistent description of candidate critical groups, the character of which might be expected to change in time.
Application of the RBM would significantly improve SKB's PA audit trail.

5.1.2 TREATMENT OF THE GEOSPHERE-BIOSPHERE INTERFACE

Treatment of the geosphere-biosphere interface is a specific area where additional review might be considered. The conceptual description and the numerical assessment models show significant dislocation in Project SAFE.

Interaction of radionuclide-bearing groundwater with bay sediments and, particularly, lake sediments could lead to radionuclide accumulation with significantly higher concentrations than have been accounted for in the assessment models used in SAFE. As the system evolves, these sediments may become agricultural soils (as modelled in SAFE), so giving rise to higher doses and risks than have been calculated.

Such accumulation has been calculated in alternative interpretations of the geosphere-biosphere interface [Maul and Robinson, 2002] but analysis of radiological consequences in terms of dose from the full set of SAFE agricultural pathways was not carried out. Effort to carry out such an analysis would bring benefits in terms of understanding the necessary and sufficient (from a PA model perspective) representation of features, events and processes acting in the geosphere-biosphere interface in numerical assessment models. Comparison with Project SAFE (both with and without groundwater – bed sediment interactions) and with the model set out by Maul and Robinson [2002] is suggested, employing the full set of agricultural pathways defined in Karlsson *et al*. [2001].

5.2 Risk assessment methodology

Our main conclusions from review of the risk assessment methodology used by SKB for Project SAFE are as follows:

- The basic scenario should take account of climate change and the associated uncertainties, or a better basis for omitting these changes should be provided.
- A more structured approach to risk assessment, with a clearer distinction between conditional and overall risks and between the risks from scenarios and those from isolated events, would be beneficial.
- The risk arising from the well scenario is strongly dependent on the size of the exposed group considered. SKB appears to make unreasonable assumptions regarding the size of this group so as to reduce the risk to acceptable levels. Further guidance from the regulators may be of value in clarifying this issue.
- SKB needs to justify the limitation of the assessment to 10,000 years.

6 References

BIOMASS (2001): BIOMASS Programme. Cd-rom version β2, BIOMASS Working Material, IAEA.

Brydsten L (1999a): Change in coastal sedimentation conditions due to positive shore displacement in Öregrundsgrepen. SKB Technical Report TR-99-37, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Brydsten L (1999b): Shore level displacement in Öregrundsgrepen. SKB Technical Report TR-99-16, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

BNFL (2000): Status Report on the Development of the 2002 Drigg Post-Closure Safety Case. BNFL, British Nuclear Fuels, Sellafield, UK.

Davis PA, Zach R, Stephens ME, Amiro BD, Bird GA, Reid JA, Sheppard MI, Sheppard SC and Stephenson M (1993): The Biosphere Model, BIOTRAC, for Postclosure Assessment of Canada's Nuclear Fuel Waste Management Concept. Atomic Energy of Canada Limited Report, AECL-10720, COG-93-10, Canada.

IAEA (2001a): 'Reference Biospheres' for Solid Radioactive Waste Disposal: Volume I – Overview, BIOMASS Theme 1: Final Output. IAEA Draft TecDoc BIOMASS THEME 1, November 2001.

IAEA (2001b): 'Reference Biospheres' for Solid Radioactive Waste Disposal. Volume II – BIOMASS Methodology for Creating Assessment and Reference Biospheres, BIOMASS Theme 1: Final Output. Version 3.0, November 2001.

IAEA (2001c): 'Reference Biospheres' for Solid Radioactive Waste Disposal: Volume III – Example Reference Biospheres, BIOMASS Theme 1: Examples. Version 3.0, November 2001.

ICRP (1977): International Commission on Radiological Protection, Recommendations of the ICRP. ICRP Publication 26, Pergamon Press, Oxford.

ICRP (1985): International Commission on Radiological Protection, Principles of Monitoring for the Radiation Protection of the Population. Publication 43, Annals of the ICRP 15(1), Pergamon Press.

Holmén JG and Stigsson M (2001): Modelling of Future Hydrogeological Conditions at SFR, Forsmark. SKB Report R-01-02, Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden.

Jerling L, Schiildt R, Isaeus M and Lanneck J (2001): The vegetation in the SFR-region: Yesterday–Today–Tomorrow. SKB Report R-01-09, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Karlsson S, Bergström U and Meili M (2001): Models for dose assessments. Models adapted to the SFR-area, Sweden. SKB Technical Report TR-01-04, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Kautsky U, ed (2001): The biosphere today and tomorrow in the SFR area: A summary of knowledge for the SAFE project. SKB Report R-01-27, Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden.

Kumblad L (1999): A carbon budget for the aquatic ecosystem above SFR in Öregrundsgrepen. SKB Report R-99-40, Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden.

Lindgren M, Pettersson M and Karlsson S (2001): Project SAFE – Radionuclide release and dose from the SFR repository. SKB Report R-01-18, Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden.

Nagra (1994a): The KRISTALLIN-I Performance Assessment Report. NAGRA Technical Report NTB 93-22, NAGRA, Wettingen, Switzerland.

Nagra (1994b): Bericht zur Langzeitsicherheit des Endlagers SMA am Standort Wellenberg. NAGRA Technical Report NTB 94-06, NAGRA, Wettingen, Switzerland.

Maul P and Robinson P (2002): Exploration of Important Issues for the Safety of SFR using Performance Assessment Calculations. Quintessa Report QRS-1067A-1. Quintessa, Henley-on-Thames, UK.

SKB (2001a): Project SAFE: Summary Report, Chapter 5 (biosphere). SKB draft report.

SKB (2001b): Project SAFE: Scenario and system analysis. SKB Report R-01-13, Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden.

SKB (2001c): Project SAFE: Compilation of data for radionuclide transport analysis. SKB Report R-01-14, Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden.

SSI (1998): The Swedish Radiation Protection Institute's Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste; decided on September 28, 1998.

Appendix A
Overview of the BIOMASS reference biospheres methodology

The key stages in the BIOMASS Reference Biospheres Methodology (RBM) are set out in Figure 2.

Assessment context

BIOMASS recognised the overriding importance of the assessment context in determining the content of the assessment model.

The Assessment Context sets purpose, endpoint and philosophy of the assessment. It identifies the type of repository system and sets the site context, including the source terms to the biosphere and the nature of the geosphere-biosphere interface. It sets out the relevant time frame over which the system is to be assessed. It also defines the societal context relevant to the system over the timescale.

The SAFE documentation reviewed did not present an explicit assessment context in the form employed in BIOMASS. However, Chapter 5 of SKB [2001a] sets out the corresponding details.

System identification, justification and description

These three stages essentially define the system which is translated into the conceptual model. BIOMASS took care to explicitly include decisions as to how the temporal evolution of the system would be represented. In Project SAFE, a similar process is apparent but it is not documented in such an explicit way (see Section 3.1).

The justification stage requires that the system as identified be audited against FEP lists (e.g., the BIOMOVS FEP list, the NEA FEP list). Those FEPs that do not fit the requirements of the assessment context may then be discarded. Within the framework of the RBM are a number of checklists that provide the scientific and technical basis on which to base the system description.

The result is a conceptual model of the system that is consistent with the assessment context. In BIOMASS this stage was accompanied by the creation of a phenomenological interaction matrix. The purpose of this matrix was to summarise the types of interactions between system components that are required to adequately describe the system and its evolution. In terms of the types of knowledge necessary to describe the system, BIOMASS recognised the role played by external FEPs leading to the identification and description of initial conditions representing the system in a particular state in its evolution. It also recognised the need to represent the internal dynamics of the system in that state. The RBM was careful to distinguish between the system in its initial state and minor perturbations of that state that allow a condition of dynamic equilibrium to be assumed in further model refinement. This was tied into the treatment of system evolution.

A further level of conceptual description was found to be very important in the RBM. This involves the placing of *radionuclide transfers* in an interaction matrix. This procedure allows a much clearer link between the contents of the conceptual model and the numerical assessment models to be established and discussed. The lack of this stage was found to be a significant hindrance in relating the SAFE NAMs to the CM, to the extent that overall traceability of FEPs through the system was made very difficult, there being no conceptual hook on which to hang elements of the NAM. The identification, justification and description phases should be applied to both the conceptual model description and the numerical assessment models.

In this sense, the biosphere component of SAFE is similar to that found in many earlier assessments elsewhere [e.g., Davis *et al*., 1993; NAGRA, 1994a; 1994b]. It was precisely this lack of a structured approach to biosphere modelling that the RBM was intended to address. It is worth noting that other more recent assessments, most notably BNFL [2000], have applied a much more structured approach.

Identification and justification of candidate critical groups (CCGs)

Given the societal context provided by the assessment context, BIOMASS found that the biosphere system description could proceed without detailed reference to the critical groups. This separation of critical group issues from the system description was found to be useful in that it allowed the system to be defined before it was necessary to consider the detail of how critical group behaviour might be included in the PA modelling. The societal context, identified in the assessment context, ensures that appropriate types of human activities are included.

Project SAFE similarly decouples critical group definition from the system description, but the treatment is much more simplistic than in the case of BIOMASS. The BIOMASS Candidate Critical Group methodology uses the assessment context to systematically populate the model domain with appropriate population groups with well-characterised lifestyles, and then goes on to associate lifestyle with modes of exposure. Candidate Critical Groups are then defined by identifying higher rates of exposure with particular group activities. This systematisation provides an in-depth conceptualisation of the habits and behaviour of key groups within the system, and these can then be linked directly to numerical assumptions, for use in the numerical calculations.

In contrast, the SAFE approach employs a limited description of behaviour linked directly to release points on the assumption that the maximum consequences would be spatially associated with the release from the geosphere.

Numerical assessment model development and description

Detailed comment on the NAMs used in the biosphere calculations is outside the scope of this review. However, the link between the conceptual description of the biosphere and numerical representation is relevant in terms of traceability of reasoning.

The use of a second level of interaction matrices to describe radionuclide transfer (and accumulation) in the system is very valuable in this respect. In the BIOMASS Example Reference Biosphere (ERBs), the translation from this level of conceptual description to the numerical version and the parameters required was much more transparent than is the case in SAFE.

The *Calculation and Results* stage of the RBM is outside the scope of this review.

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SSI Rapport

Statens strålskyddsinstitut, SSI, är central tillsynsmyndighet på strålskyddsområdet. Myndighetens verksamhetsidé är att verka för ett gott strålskydd för människor och miljö nu och i framtiden.

SSI är ansvarig myndighet för det av riksdagen beslutade miljömålet *Säker strålmiljö*.

SSI sätter gränser för stråldoser till allmänheten och för dem som arbetar med strålning, utfärdar föreskrifter och kontrollerar att de efterlevs. Myndigheten inspekterar, informerar, utbildar och ger råd för att öka kunskaperna om strålning. SSI bedriver också egen forskning och stöder forskning vid universitet och högskolor.

SSI håller beredskap dygnet runt mot olyckor med strålning. En tidig varning om olyckor fås genom svenska och utländska mätstationer och genom internationella varnings- och informationssystem.

SSI medverkar i det internationella strålskyddssamarbetet och bidrar därigenom till förbättringar av strålskyddet i främst Baltikum och Ryssland.

Myndigheten har idag ca 110 anställda och är beläget i Stockholm.

The Swedish Radiation Protection Authority (SSI) is the government regulatory authority for radiation protection. Its task is to secure good radiation protection for people and the environment both today and in the future.

The Swedish parliament has appointed SSI to be in charge of the implementation of its environmental quality objective *Säker strålmiljö* ("A Safe Radiation Environment").

SSI sets radiation dose limits for the public and for workers exposed to radiation and regulates many other matters dealing with radiation. Compliance with the regulations is ensured through inspections.

SSI also provides information, education, and advice, carries out its own research and administers external research projects.

SSI maintains an around-the-clock preparedness for radiation accidents. Early warning is provided by Swedish and foreign monitoring stations and by international alarm and information systems.

The Authority collaborates with many national and international radiation protection endeavours. It actively supports the on-going improvements of radiation protection in Estonia, Latvia, Lithuania, and Russia.

SSI has about 110 employees and is located in Stockholm.

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