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A Review of Models for Dose Assessment Employed by SKB in the Renewed Safety Assessment for SFR 1

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TITLE/ TITEL: A Review of Models for Dose Assessment Employed by SKB in the Renewed Safety Assessment for SFR 1/Granskning av modeller för dosberäkningar i SKB:s förnyade säkerhetsanalys för SFR 1.

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SUMMARY: This document provides a critical review, on behalf of SSI, of the models employed by the Swedish Nuclear Fuel and Waste Management Co (SKB) for dose assessment in the renewed safety assessment for the final repository for radioactive operational waste (SFR 1) in Forsmark, Sweden.

The main objective of the review is to examine the models used by SKB for radiological dose assessment in a series of evolving biotopes in the vicinity of the Forsmark repository within a time frame beginning in 3000 AD and extending beyond 7500 AD. Five biosphere models (for coasts, lakes, agriculture, mires and wells) are described in Report TR-01-04. The principal consideration of the review is to determine whether these models are fit for the purpose of dose evaluation over the time frames involved and in the evolving sequence of biotopes specified. As well as providing general observations and comments on the modelling approach taken, six specific questions are addressed, as follows.

- Are the assumptions underlying the models justifiable ?
- Are all reasonably foreseeable environmental processes considered ?
- Has parameter uncertainty been sufficiently and reasonably addressed?
- Have sufficient models been used to address all reasonably foreseeable biotopes ?
- Are the transitions between biotopes modelled adequately (specifically, are initial conditions for developing biotopes adequately specified by calculations for subsiding biotopes) ?
- Have all critical radionuclides been identified ?

It is concluded that, in general, the assumptions underlying most of the models are justifiable. The exceptions are a) the rather simplistic approach taken in the Coastal Model and b) the lack of consideration of Ôwild' foods and age-dependence when calculating exposures of humans to radionuclides via dietary pathways. Most foreseeable processes appear to have been accounted for within the constraints of the models used, although it is recommended that attention be paid to future climate states when considering these processes. Parameter uncertainty has been addressed in detail for the existing models but numerous detailed recommendations are made for the improvement of several specific parameter selections. It is also recommended that two semi-natural ecosystem models (for forest and dry meadows) are included in the study – this would require further parameter identification and collection. Transitions between developing biotopes need more careful explanation and reasoning and EDFs (Ecosystem Dose Factors) for all ecosystem types should be presented to demonstrate more clearly that all critical radionuclides have been identified.

SAMMANFATTNING: Denna rapport redovisar en kritisk granskning, som utförts på uppdrag av SSI, av de modeller SKB använt för dosberäkningar i den förnyade säkerhetsanalysen för slutförvaret för radioaktivt driftavfall i Forsmark, SFR 1. I rapporten granskas de fem biosfärsmodeller (kust, sjö, jordbruksmark, myrmark och brunn) som SKB använt för att beskriva successionen av olika biotoper i Forsmarksområdet och beräkna radiologiska doser under en tidsperiod som sträcker sig bortom 5500 år i framtiden. Granskningen har koncentrerats på att bestämma om

modellerna är tillräckliga för sitt syfte att beräkna doser över dessa tidsperioder och för att beskriva den specificerade tidsutvecklingen av olika biotoper. Följande specifika frågor har särskilt beaktats:

- Är alla antaganden i de underliggande modellerna tillräckligt motiverade ?
- Har alla rimligt förutsägbara miljöprocesser tagits i beaktande ?
- Har osäkerheter i olika parametrar utvärderats så långt det är rimligt ?
- Är modellerna tillräckliga för att beskriva alla rimligt förutsägbara biotoper ?
- Är övergångarna (i tiden) mellan olika biotoper adekvat beskrivna i modellerna ?
- Har alla kritiska radionuklider identifierats ?

Författarens slutsats är att de antaganden som ligger till grund för de flesta av modellerna överlag kan rättfärdigas. Undantagen är a) de relativt stora förenklingarna i kustmodellen och b) att man inte tagit hänsyn till naturlig föda (t.ex. vilt, bär, och svamp) och åldersberoende i beräkningarna av exponering till människor via födointag. Rimlig hänsyn tas till förutsägbara processer med hänsyn till de begränsningar som finns i modellerna. SKB rekommenderas dock att ta hänsyn till framtida klimatförhållanden när dessa processer beaktas. Parameterosäkerhet har hanterats utförligt i de använda modellerna. I rapporten ges dock ett antal rekommendationer på hur valet av specifika parametrar kan förbättras. Vidare rekommenderas att två seminaturliga ekosystemmodeller (för skog och torr ängsmark) bör inkluderas i analyserna, vilket skulle kräva ytterligare identifiering av parametrar och insamling av data. Hanteringen av övergångar mellan olika biotoper behöver förklaras och motiveras bättre och EDFs (ekosystemspecifika dosomvandlingsfaktorer) bör presenteras för alla ekosystem för att tydliggöra att alla kritiska radionuklider har identifierats.

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 vart 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 konsultgranskningar av SKB:s säkerhetsredovisning för SFR 1, som utförts på uppdrag av SSI. Rapporten redovisar en fördjupad granskning av de modeller som SKB använt för att beskriva exponeringsvägar för radionuklider i olika ekosystem, och för beräkningar av vilka doser dessa radionuklider skulle kunna ge till människor. Detta är frågor som SSI har att ta ställning till bl.a. vid bedömningen av hur väl SKB:s säkerhetsredovisning för SFR 1 uppfyller SSI:s föreskrifter om slutligt omhändertagande av använt kärnbränsle och kärnavfall (SSI FS 1998:1).

Arbetet har utförts av George Shaw på Imperial College of Science Technology and Medicine i England, på uppdrag av Björn Dverstorp, avdelningen för avfall och miljö, SSI. Författaren svarar själv 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

1.1 Background and objectives of review

This document provides a critical review, on behalf of SSI, of SKB Report TR-01-04 (Models for Dose Assessments – Models Adapted to the SFR Area, Sweden) produced for SKB and authored by S. Karlsson, U. Bergström and M. Meili (Karlsson et al., 2001).

The main objective of the review, based on a job description supplied by SSI in December 2001, is to examine the models used by SKB for radiological dose assessment in a series of evolving biotopes in the vicinity of the Forsmark repository within a time frame beginning in 3000 AD and extending beyond 7500 AD. Five relevant biosphere models (for coasts, lakes, agriculture, mires and wells) are described in Report TR-01-04. The principal consideration of this review is to determine whether these models are fit for the purpose of radiological dose evaluation over the time frames involved and in the evolving sequence of biotopes specified.

The six specific questions addressed are as follows.

- Are the assumptions underlying the models justifiable?
- Are all reasonably foreseeable environmental processes considered?
- Has parameter uncertainty been sufficiently and reasonably addressed?
- Have sufficient models been used to address all reasonably foreseeable biotopes?
- Are the transitions between biotopes modelled adequately (specifically, are initial conditions for developing biotopes adequately specified by calculations for subsiding biotopes)?
- Have all critical radionuclides been identified?

A specific review is also made of the comparison of sorption properties and contaminant pathways described in Chapter 10 of TR-01-04. A review of the methods of dose calculation was considered from the outset to be of secondary importance as these are based on conventional techniques. However, as requested, the question of whether reasonable ranges of parameter values have been used in the calculations is addressed.

1.2 Structure of review

The review begins (Chapter 3) with some general observations and comments on the modelling approach taken in Report TR-01-04, together with some general recommendations for the improvement of the clarity of presentation of the report. Chapter 4 summarises and describes the content of each of the chapters of TR-01-04 and provides general comments, where appropriate, on the specific assumptions, parameters and methods used in each chapter. Chapter 5 provides a general discussion of the report and considers, specifically, whether each of the six specific questions, above, have been addressed satisfactorily. Finally, Chapter 6 makes specific point-by-point recommendations for the general improvement of the report.

2 Comments on the modelling approach used in the report

2.1 General comments

The key problem in modelling radionuclide transfers, and the consequent radiological exposures of man, in ecosystems is the difficulty in finding an appropriate balance between model realism and model simplicity. The degree to which real-world processes are simplified within a model is usually dictated by the end use to which the model will be put. In other words, so long as a model can be demonstrated to be fit for purpose then it can be considered to be adequate. Usually, it is necessary to carry out some form of model validation before it can be judged whether a model is, indeed, fit for purpose. In the context of the SFR assessment the validation of any model over the extremely long (1,000 to 10,000 year) assessment period is clearly impossible. Therefore, the next best strategy in demonstrating the general applicability of a model applied over this time scale is to ensure that model conceptualisation and parameter selection have both been rigorous. For model conceptualisation, this means that all reasonably foreseeable states of the environment and radionuclide transfer processes should have been identified and included in the model, or suite of models, to be used for the assessment. For parameter selection, both the absolute values and known or assumed uncertainties of parameters should be shown to be reasonable, based on existing information. These two considerations should both be key objectives for TR-01-04.

The general modelling approach taken throughout the assessment study is simple, though completely consistent from one ecosystem to the next. Thus, all problems of radionuclide migration in marine, freshwater, and terrestrial ecosystems are conceptualised as transfers from one discrete compartment to the next with transfers being quantified as first order (i.e., time- and concentration-independent) processes. More complex, physically based, modelling methods are available for each of the ecosystems addressed in the study. However, it would be difficult to defend the use of a mechanistic and highly site-specific modelling approach when the data requirements of such models are usually very demanding and the uncertainties surrounding the site itself (particularly when considering its future state) are considerable.

So, the basic modelling approach taken in TR-01-04 should be at least adequate for the purpose of the study if

- the way in which the models are conceived and applied is made clear (e.g., underlying assumptions, definition of inputs and sequence of calculations) and
- the selection and use of parameters is fully explained and justified.

In order to meet these two criteria it is essential that any caveats associated with either model configuration or parameters is made clear. The reader of the report should be provided with sufficient information to be able to decide, finally, whether the conclusions reached are reasonable and defensible. Above all, clarity of presentation of ideas and modelling operations is essential.

Before addressing each chapter of the report specifically, a few general comments and suggestions will be made which are intended to improve the clarity of chapters describing both the general characteristics of the model system and the individual models.

2.2 Suggestions for the improvement of clarity of modelling descriptions

The primary problem to be addressed by the system of models proposed is that it should be able to simulate radionuclide transfers in a continuously changing sequence of ecosystems. This evolutionary sequence of biotopes is explained in Section 2.2 yet, considering the importance of this sequence, this section is rather short. In Section 2.4.1 of Lindgren *et al.* [2001, SKB Report R-01-18] a schematic description of the 'reasonable biosphere development' for SFR is shown as a diagram (Figure 2-2, page 17). It would be beneficial to include this diagram in report TR-01-04 to aid the description of scenarios as described in Section 2.2. Furthermore, a flow diagram should be added to show the sequence of model calculations in relation to the sequence of ecosystem evolution. A modified version of Figure 2-2 [R-01-18] could be drawn in which the stages in the evolutionary sequence in which the individual models are used is clearly indicated. In particular, the points at which one model ceases to be used and another begins should be shown. It could be that the boundaries between one modelling scenario and the next are not distinct but 'fuzzy', in which case there would be periods during which two models need to be used side-by-side. In any case, it is very important to show how the outputs of one model provide an input to another – again, for clarity; this should be incorporated in a general flow diagram somewhere near the beginning of the report.

At the beginning of each chapter in which a model or sub-model is described (Chapters 3, 4, 5, 6, 7 and 8) it would be useful to have all the parameters listed together with their symbols and units. This would avoid confusion. For example, the terms 'transfer coefficient' and 'rate constant' are used interchangeably within the report. In the first Paragraph of Section 3.1 (page 16) the term 'rate constant' is used, but in the first equation following this Paragraph the symbol TC is used to denote 'transfer coefficient'. This is confusing and possibly misleading. Also missing are any equation numbers that makes it difficult to refer to a specific equation. The adoption of a system of equation numbers based on the section in which the equation appears is recommended – e.g., the first equation in Chapter 3 would have the number 3.1.1.

In the individual diagrams of the models at the beginning of Chapters 3, 4, 5, 6 and 8 the arrows should be labelled to indicate which parameters are used to represent the fluxes between compartments. The use of transfer coefficients is described in general terms in Chapter 2. However, at present it is difficult to determine which equations in each chapter refer to each arrow (flux) in the model flow diagrams. Each transfer coefficient is, at present, simply referred to as 'TC', which makes it impossible to distinguish between individual transfer coefficients. Subscripts should therefore be used to give a unique identity to each transfer coefficient. For example, for the transfer coefficient representing movement of water from the Model Area to 'Grepen' in Chapter 3, the identity could be denoted as TC_{15}, representing flow of water from compartment 1 to 5. This might seem cumbersome but it would avoid potentially confusing statements such as 'The water inflow to Grepen from the Baltic Sea is obtained from the same expression but the values for the Model Area are replaced by those for Grepen and the values for Grepen by those for the Baltic' (page 16).

As far as general terminology is concerned, it would be less ambiguous to use the term 'activity concentration' rather than just concentration. Similarly, there are many points throughout the report at which either radionuclides or elements are referred to when, in most cases, these terms are being used interchangeably. Since the report deals with radionuclides this term should be used in preference to elements.

The report is generally very well referenced but the presentation of references in the text could be improved by removing the solidus before and after the reference – this is probably due to the use of an automatic referencing system such as Endnote, but it should be corrected.

3 Review of assumptions, parameters and methods used in each chapter

3.1 Chapter 1 – Introduction

The primary objective of TR-01-04, is set out in Section 1. It is made clear that the purpose of the document is to provide a description of a model system developed to predict radiation doses to the most exposed individuals resulting from the long-term release of radionuclides from the SFR facility. The general geographical setting and history of the SFR facility at Forsmark is briefly described and the requirement of the operational license for renewed safety assessments every ten years, which is catered for by the SAFE project, is explained. This is useful since an obvious question, which might be posed by a reader unfamiliar with the SFR facility, is why safety assessments are being carried out after the beginning of the operation of the repository.

Background studies on the biosphere within the area of the SFR facility are described on page 7, though these appear to be solely concerned with coastal processes such as shore level rise and sedimentation. It is not immediately clear from this part of the report how 'this material has been used for developing a model system for the area' since this information only appears to relate to the Coastal Model described in Chapter 3.

It would also be helpful to state more clearly in the first section of the Introduction (page 7) that sub-objectives of Report TR-01-04 are

- to describe the types of biosphere addressed in the study (see comments in Section 3.1, above) and
- to investigate the effects of different sorption properties on radionuclide pathways in coastal, lake and agricultural ecosystems.

It would be useful to state at the outset why the second of these objectives was necessary – for example, is it because sorption (K_d) is such a universally sensitive parameter in all the models developed? In its current form the introductory chapter gives no indication why only the effects of sorption on model outputs were explored and not the effects of any of the other parameters.

Section 1.1 provides a more detailed description of the characteristics of the coastal area near Forsmark. Given the present-day coastal conditions at the site it is reasonable that this description should focus on these features. However, a brief description is also given on page 9 of the expected evolution of Öregrundsgrepen over the next 2,000 to 5,000 years. At the bottom of page 8 it is stated that 'No agricultural areas occur in the near vicinity of the repository area and the amount of agricultural land is low in general (less than 10 % …)'. This is further emphasised at the top of page 9 where it is stated that 'Large scale farming does not occur in this part of the region'. In view of these statements it is surprising that emphasis has been given to an agricultural scenario while forests have not been considered even though, in the present day, they cover 70 % of the land (see also detailed comments on Chapter 5, Section 4.5). Since, over the assessment period of 1,000 to 10,000 years, the study area will evolve from a coastal to a terrestrial environment that is likely to be dominated by semi-natural ecosystems, it would seem reasonable that more emphasis should be given to this type of biotope.

The major shortcoming of the description of the study area is the lack of any mention of climate change that is likely to occur in parallel with the evolution of the land surface over a period of 1,000 to 10,000 years from the present day. In developing a defensible system of models for future ecosystem states this information, even though it may be subject to large uncertainties, is extremely important.

3.2 Chapter 2 – General characteristics of the model system

Chapter 2 describes, in general terms, the characteristics of the models developed to carry out radiological assessments of radionuclides emerging from the SFR repository into the local biosphere. It is stated at the beginning that these models are based on those developed by Bergström *et al*. [1999] for safety assessment SR 97 and this gives the impression that the authors assume the reader of TR-01-04 will be familiar with this document. Since many readers will not be familiar with previous models developed for assessment of the SFR facility it would be useful if the authors started from this assumption and provided a clearer introduction to the models actually described in TR-01-04. This might be achieved by listing or tabulating the models actually used (Coastal, Lake, etc.) together with their common and individual features.

The description of the use of transfer coefficients and bioaccumulation factors for different model components might be made clearer for the non-expert reader if a generic model structure were proposed and described. This generic model structure should refer to the description of the long-term geochemical processes and shorter-term biological processes as currently described in the text, but the definitions and units of transfer coefficients and bioaccumulation factors should be given. For example, a generic model might consider sorption and desorption of radionuclides between solid and liquid (physical) phases followed by biological uptake from the soluble phase, see Figure 1.

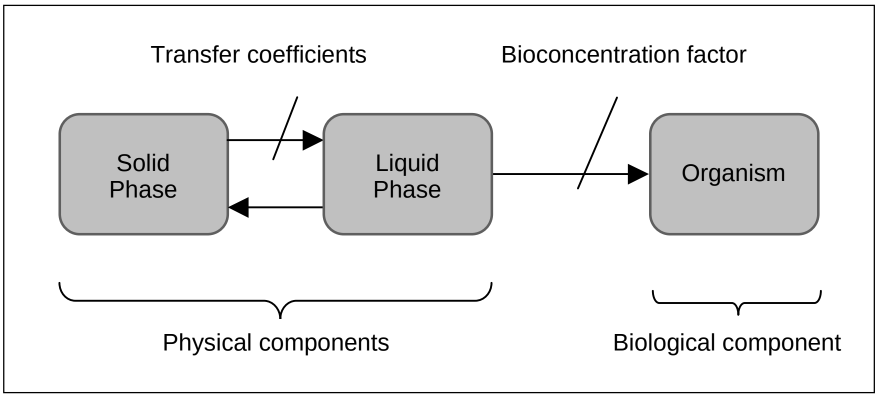

Figure 1
Suggested diagrammatic description of a generic model structure to aid understanding of the detailed model structures described in Chapters 3 to 8.

The basic symbol and definition of the transfer coefficient should be given, for example:

$$TC = \frac{\text{Radionuclide activity moving from liquid phase to solid phase during one year}}{\text{Average radionuclide activity contained in liquid phase during that year}}$$

and the units given:

$$TC = \frac{\text{Bq y}^{-1}}{\text{Bq}} = \text{y}^{-1}.$$

Thus, when more complex derivations of transfer coefficients are shown in specific modelling chapters (Chapters 3 to 8) the non-expert reader should understand that the dimension of the TC should be y^{-1} and that TCs are dynamic parameters. Similarly, the basic symbol and definition of the bioaccumulation factor should be given:

$$\text{BCF} = \frac{\text{Average radionuclide activity concentration in organism or part of organism}}{\text{Average radionuclide activity concentration in liquid phase}}$$

and the units given:

$$\text{BCF} = \frac{\text{Bq kg}^{-1}}{\text{Bq kg}^{-1}} \text{ (dimensionless)} .$$

Thus, the non-expert reader should understand that the BCF is a non-dynamic parameter, which assumes very rapid establishment of equilibrium of radionuclide activity concentrations between an organism and its environment.

Given the similarity in model structure between many of the models proposed in TR-01-04 the description of the generic 'building blocks' of the models should be straightforward and would significantly improve the clarity of Chapter 2.

Also described in Chapter 2 are the biosphere scenarios which, it is assumed, will apply to the study area over a period up to 12 000 AD (i.e., 10,000 years from the present day). The description of these biosphere scenarios could be significantly improved to aid the reader's understanding of the system of biotopes being modelled. One way in which this could be achieved would be to show diagrammatically the predicted evolution of the site. In Section 3.1, above, it has already been suggested that Figure 2-2 within report R-01-18 could be adopted for use in TR-01-04. The reader's understanding of the applicability of each of the models to each phase in the biosphere evolution would be further strengthened if each stage in this figure indicated clearly which model was applicable at each evolutionary phase. This would be made simpler if, as suggested above, a single table of each model and its major attributes were presented at the beginning of Chapter 2. One of the key problems in using a suite of discrete models to evaluate radionuclide migration in each of the individual phases in the evolving biosphere is that transitions between phases are not easily represented. Some effort must, therefore, be made to show diagrammatically how the output from one model is used to represent the input to another model, as described verbally at the bottom of page 12 in TR-01-04.

Finally, justification of the well scenario, modelled in Chapter 7 of TR-01-04, needs to be improved. Is the granite/gneiss bedrock likely to be a useful aquifer and is the supply of water at the surface likely to be so limiting that a well is required to provide drinking and irrigation water? Such questions might be linked to considerations of future climate state but as previously stated; climate change has not been considered in the report.

3.3 Chapter 3 – Coastal model

The Coastal Model seeks to represent three interconnected, though distinct, water bodies of three markedly different scales, *viz*. the Model Area, Öregrundsgrepen and the Baltic Sea. Despite the very marked differences in scale of each of these water bodies the conceptual approach taken for each one is the same. Each sub-area within the Coastal Model comprises water and sediment compartments, with sediments being divided into suspended and upper and lower bottom sediments.

Table 1. *Physical characteristics of the three major compartments considered by the Coastal Model.*

	Area (km^2) *	Mean Depth (m) *	Volume (m^3) §	Factor
Model Area	11.2	9.5	1.06×10^6	1.0
Grepen	456	11.2	5.11×10^7	48.2
Baltic	377,400	56	2.07×10^{11}	1.96×10^5

* Best estimates taken from Table 3-2. § calculated values.

The relative volumes of each of the compartments are shown in Table 1. The Model Area is 'nested' in the centre of Öregrundsgrepen. The water volume within Öregrundsgrepen is 48 times greater than the volume within the Model Area. However, due to the location of the Model Area within Öregrundsgrepen it is reasonable to assume a continuous exchange of water between the two areas.

The representation of the Baltic Sea in the same conceptual way as the two much smaller areas, however, is questionable. One of the fundamental assumptions of the compartmental modelling approach used throughout the report is that instantaneous mixing of radionuclides will occur in each compartment. The total volume of the Baltic Sea, calculated from the best estimates of sea surface area and mean depth presented in Table 3-2 (2.07×10^{11} m^3), is almost 200,000 times greater than the Model Area itself and more than 4,000 times larger than Öregrundsgrepen.

A previously published model [Nielsen, 1995] treated the Baltic Sea as a series of horizontally and vertically stratified compartments. The region from Skagerrak in the west to the Belt Sea, south of Malmö, was treated as a series of five compartments (total volume 7.6×10^{12} m^3) while the main part of the Baltic, east and north of the Belt Sea, was treated as a series of eight compartments (total volume 2.1×10^{13} m^3). Even with this degree of compartmentalisation, Nielsen [1995] admitted that the assumption of instantaneous uniform mixing could be a problem, especially close to the point of discharge where steep gradients in activity concentrations of radionuclides would be expected. This is the kind of problem, which would be expected when considering exchange of waters between the Baltic Sea and Öregrundsgrepen where the 4,000-fold difference in water volume would result in a very steep gradient in activity concentrations between the two compartments.

As might be expected, the mean water retention times of each of the three water bodies considered are linearly related to the respective water volumes of the compartments (Figure 2). Thus, it would be expected that the radionuclide activity concentrations in the Model Area and Öregrundsgrepen would reach steady state much more quickly than those in the Baltic Sea.

These problems are alluded to on page 21 for the scenario 'Coast 2'. '… flux may be underestimated since the volume in the Baltic is too large and the water retention time may be too short'. It is also not clear which part of the Baltic Sea is being considered. Where does the boundary of the Baltic Sea and the 'Oceans' occur?

The problem of the comparative scaling of each of the three water bodies in the Coastal Model is perhaps best illustrated by Figure 10-1, Chapter 10, which shows that, at steady state, only a one to two order of magnitude difference in seawater activity concentrations is predicted between the Model Area and the Baltic Sea – in reality, surely a bigger discrepancy between *average* water activity concentrations in the Baltic Sea and Öregrundsgrepen would be expected? Perhaps these modelling results are realistic? However, of all of the models proposed in TR-01-04 the coastal model seems to be the least justifiable in terms of the level of simplification it uses (see general comments at the beginning of Chapter 2, above). If the authors feel that this level of simplification can be justified then they should provide this justification at the beginning of Chapter 3. If not, they could perhaps use the published model and parameters of Nielsen [1995] to improve the representation of the Baltic Sea in their model.

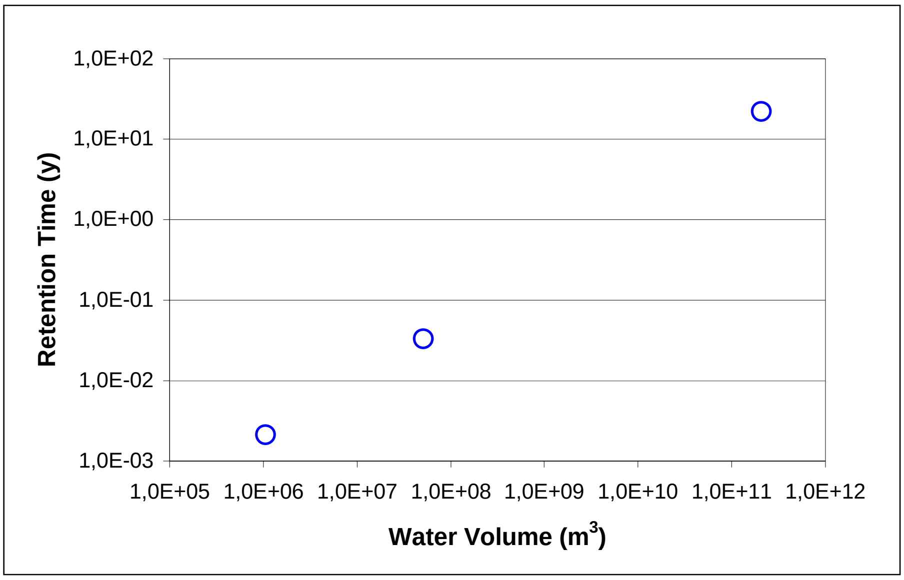

Figure 2
Water retention time versus water volume in each of the three areas represented in the Coastal Model.

All the equations in Chapter 3 have been examined and appear to be dimensionally consistent. However, as stated in Section 3.1, above, the equations need to be numbered consecutively and unique identities given to individual transfer coefficients.

All the parameter values used in the Coastal Model are shown clearly in Tables 3-2 and 3-3. These tables are both clearly presented and show parameter identifications, symbols, units and values (minima, best estimates and maxima). The system of footnotes used to identify the sources and to provide justification for the choices of individual parameter values is comprehensive although somewhat difficult to read. However, the use of detailed footnotes is good because it avoids the need for excessive cross-referencing of data sources in the main text of the chapter. One general criticism of these tables is that no key is given to identify the codes used to indicate the types of parameter distributions (Probability Density Functions) used.

The only parameter value, which appears open to question, is the maximum value for the depth of the upper sediment (D_s, 5 cm). From the text on page 18 this appears to represent the maximum depth of mixing by bioturbation as obtained from the reference by Eckhell *et al*. [2000]. Though not an expert in this specific field I would have considered that organisms such as marine worms routinely burrowed below such depths and this might warrant a small discussion by the authors.

Related to the depth of mixing, as described on page 18 of TR-01-04, is the term ‘accumulation bottoms’ which is not sufficiently well defined for the non-expert reader to understand. This term should be defined more rigorously.

In summary, Chapter 3 presents a highly simplified model description of three water bodies of considerably different volumes and characteristics, but in each of which similar processes of sediment transport and radionuclide partitioning between solid and liquid phases can be expected to occur. The simplicity of the conceptual model means that the selection of parameter values is made relatively straightforward and the selected parameters are evidently based on a sound body of site-specific studies which the authors have documented using detailed annotated footnotes. The major conceptual problem remains that the ‘Baltic Sea’ is represented as a single compartment when at least *one* previous study has represented the same sea area as a series of between 5–8 compartments. If the authors consider this level of simplification to be reasonable then a stronger justification is required, perhaps involving representative calculations using the Coastal Model in its current configuration.

3.4 Chapter 4 – Lake model

Conceptually, the Lake Model is identical to each of the three sub-components of the Coastal Model with water, suspended sediment, upper and lower bottom sediments being represented as discrete compartments. Inputs (X) and outputs of radionuclides are considered to occur directly into/from the water and suspended sediment compartments only.

In the first and second paragraphs of Chapter 4 it is stated that radionuclides may be present in the lake sediments due to deposition when the lake area was under marine conditions. However, a more explicit explanation of the transition from the Coastal Model to the Lake Model needs to be given. For example, how do the inputs 'X' into the water and suspended sediment compartments in Figure 4-1 relate to a) preceding contamination (especially of sediment) and b) current leakage from SFR? The relationship between outputs from the Coastal Model and inputs to the Lake Model could be explained using a general flow diagram, as suggested in Section 3.1, explaining the sequence of evolution of the biosphere above SFR and the way in which each model is used to address each successive phase in this evolution.

All the equations in Chapter 4 appear to be dimensionally consistent. However, they need to be numbered consecutively and unique identities given to individual transfer coefficients. Essentially, the lake model is identical to each part of the Coastal Model representing a discrete water body. Consequently, the equations describing the transfer coefficients for the Lake Model are identical to those describing the transfer coefficients for the Coastal Model and the descriptions of each of the equations and parameters are very similar. Much of the model description in Chapter 4 could be considered redundant, therefore, unless the transfer coefficients are given unique identities as suggested in Section 3.1, above.

The main difference between Chapters 3 and 4 is the choice of parameter values. As in Chapter 3, many of the parameter values selected have been obtained from site-specific studies which are directly relevant to the SFR study area. An exception to this, however, is the choice of solid-liquid K_d values that are tabulated in Appendix 9. Of these values the ranges adopted are all drawn from respected sources and it would be difficult to criticise these values. For Cs and Pu, however, I would suggest that the current maximum values (10^2 and 10^3, respectively) each be increased by one order of magnitude to 10^3 and 10^4. For Tc, the probability that chemical reduction of this element will occur in anoxic bottom sediments dictates that a maximum K_d of the order of 10^2 should be considered under these circumstances.

Table 4-1 is clearly presented and, as in Chapter 3, the system of footnotes is comprehensive. However, Table 4-1 needs a key to identify the codes used to indicate the types of parameter distributions (Probability Density Functions) used.

The bioaccumulation factors (BAFs) shown in Table A-13 are drawn from a variety of sources, most of which appear to be internationally recognised [e.g., IAEA, 1994]. It is curious that values for BAFs for palladium for fish are based on an assumption of the similarity of uptake of nickel and palladium during plant root uptake. Some justification is given for this assumption in footnote 5 of Table A-13, but if palladium proves to be a critical radionuclide then these BAF values need more careful scrutiny. It is also noteworthy that the BAF values for crustaceans (Table A-15) are drawn from one source only [Thompson *et al.*, 1972]. If consumption of crustaceans proves to be a significant exposure pathway then it would be wise examine the literature for further sources of information on appropriate BAFs.

Finally, crop translocation factors are used when considering irrigation of crops with contaminated lake water. These translocation factors are shown in Table A-6 and, for most elements considered, are drawn from respected sources. It would be interesting to know the original origin of the translocation factor for Tc, however, as the review by Coughtrey *et al.* [1985] is a secondary source – a recent survey by ANDRA (pers. comm.) found no measured values for the Tc translocation factor in the literature.

3.5 Chapter 5 – Agricultural land model

The first impression of the structure of the soil model is its similarity to the aquatic models. Conceptually, this is reasonable, however, since it can be argued that both soils and aquatic (water/sediment) systems are similar to solid-liquid systems but with different ratios of solid to liquid components. Perhaps the most curious aspect of the Agricultural Land Model, however, is that it has been included in the study at all! In the first paragraph of Chapter 5 it is stated that ‘there will most probably not be any large areas suitable for cultivation of crops in the future’. This could be interpreted to mean that agriculture will be almost insignificant in the SFR area in future. In an area in which agriculture is almost insignificant it would be expected that any existing agriculture would be primitive, so the assumptions made about practices such as tile drainage on page 31 need to be justified.

As in the case of the Lake Model, a weak point in the general description of the Agricultural Land Model is the lack of any detailed explanation of how the predictions of the Coastal and Lake Models are used to provide inputs to the soil. A general statement that ‘Radionuclides accumulated in the sediments during the coastal and lake stage(s) are present within the soil as a secondary source’ is made (page 31) but more detail is required for clarity. Paragraph 3, page 31, states that ‘The fraction accumulated during the lake stage is present in the top soil layer whereas those from the coastal stages are added to the deep soil and the solid fraction of the saturated zone’. This is useful but a more explicit (e.g., diagrammatic) description of how one model’s output values provide input values into a subsequent model would greatly facilitate the reader’s understanding of the way in which the *system* of models operates.

Another important issue concerning the Agricultural Land Model concerns agricultural practices. A lake sediment does not immediately become a cultivable soil for agriculture when the lake is drained and a major question is what effect the practice of preparing the soil for cultivation (e.g., ditch or tile drainage as mentioned on page 31) is likely to have on the radionuclide pool within the soil? Another question concerns direct inputs from the SFR facility into the groundwater and, ultimately, the topsoil. Paragraph 2 on page 31 suggests that the major sources of soil contamination with radionuclides will be the remains of contaminated lake sediments, as mentioned above, but it is also stated that ‘inflow of radionuclides with groundwater may also be simulated’. Such questions need to be addressed to improve the credibility of the model simulations.

The equations have been checked for dimensional consistency and appear to be correct. It is interesting that, unlike the Coastal and Lake models, the number of site-specific parameter values available for the Agricultural Land Model is rather limited. Despite the fact that the parameter values selected are from a wide variety of sources, the choices of values seem generally judicious and are well justified. One potentially questionable value is the area assumed to be subject to agricultural use. A best estimate of 530,000 m^2 is based on the assumption that half the area of Lake 4, as described in Chapter 4, is used for agriculture. Given the rather low percentage of land currently used for agriculture in the Forsmark area (less than 10 % according to Brunberg and Blomqvist [1998]) it would be useful to calculate the percentage of the assessment area which 530,000 m^2 represents. If this is substantially more than 10 % of the total area it could be considered that the calculations of exposure *via* agriculture are unnecessarily pessimistic.

The effects on root uptake of crop species, soil type, climate and cultivation practices described on page 38 should be taken into account by the ranges of root uptake factors (RUFs) presented in tables A2 to A5 for pasture, cereals, root crops and vegetables, respectively. The RUFs presented in these tables are well referenced and appear to be, in general, from internationally recognised sources. It would have been useful, however, to have stated which soil type has been assumed for the agricultural scenario. This can have a significant effect on the choice of RUF, but it is impossible to determine from the information provided whether this factor has been taken into account explicitly.

3.6 Chapter 6 – Mire model

As stated by the authors at the beginning of Chapter 6, the Mire Model is very simple – perhaps surprisingly so. Within the proposed model structure no account is taken of the process of peat formation and growth, which will be highly significant during the 1,000 to 10,000 years considered in the assessment study. This leads to a problem because it is stated that 'it can be assumed that the radionuclides are present within the peat at the start of modelling as a consequence of earlier accumulation in sediments'. The authors appear to be confusing peat with sediment: in fact, they are two entirely different materials with different modes of formation. Since peat is formed from organic matter, largely derived from atmospheric carbon, any radionuclides originally incorporated in the 'peat' will be successively diluted as peat accumulation proceeds. This dilution may be balanced by further radionuclide accumulation in inflowing water (which is accounted for in the existing model) but the model would be more credible if it were to account for peat growth. A simple peat accumulation rate (kg DW m^{-2} y^{-1}) could be adopted for this purpose using values that are applicable to present day and future climate conditions in Sweden.

Again, the existing equations appear dimensionally consistent and assumed correlations between parameters appear reasonable. The authors admit that the ranges of parameter values adopted are generally wide and that they 'should be seen as rough estimates'. Given this general limitation to the parameter estimates the ranges of values selected seem reasonable. K_d values appropriate to organic soils are given in Table A-8. It is strongly recommend that values obtained from source 4 [IAEA, 1994] are re-checked by the authors. Several of the maximum values quoted in Table A-8 are substantially below the values recommended for organic soils by the IAEA [1994]. For example, the maximum value recommended in Table A-8 for Pu is 20, while the corresponding maximum value suggested by the IAEA is 3.3×10^5. The authors of TR-01-04 may have good reasons for selecting lower values but these need to be justified.

In Section 6.4 of TR-01-04 it is stated that 'the same root uptake factors (RUFs) as in the agricultural land model' are used within the Mire Model to calculate root uptake of radionuclides by crops consumed by both humans and cattle. In Section 4.5, above, it was pointed out that soil type is important when selecting ranges of RUFs and, therefore, that a stronger justification should be given for the selection of RUFs in Tables A-2 to A-5 based on soil type. In my opinion, it is incorrect to assume that the soil types in the agricultural land scenario and the mire scenario are the same. Mire soils (peats) are likely to have more substantially organic matter contents than typical agricultural soils, even if the agricultural soil is derived from lake bottom sediments as assumed in Chapter 5 of TR-01-04. Therefore, RUF values for use in the Mire Model should be selected for predominantly organic soils – such value are available from sources such as IAEA [1994].

3.7 Chapter 7 – Well model

The major question which can be asked of Chapter 7 is the realism of a scenario in which a well is sunk into granite/gneiss bedrock (a very poor aquifer, which, presumably, is one of the main reasons why the SFR facility has been sited here) to provide irrigation water in a geographical area which is never likely to experience any significant limitation of the surface water supply.

No model structure is shown since the model consists of only one compartment. Parameter values are presented, however, and these are open to question. The main criticism of the selection of parameter values is that no initial justification is given as to the assumed lifestyle of people extracting and using the well water. The assumptions about personal water use and the use of water for animals and a garden plot appear to be based on present day practices. These assumption are acceptable if they are stated clearly at the outset but, at present, Chapter 7 makes no attempt to describe the type of domestic and/or farming system expected to be making use of well water. Future climate states will have a marked effect on this issue so the discussion of the well model parameters should be linked to a discussion of future climate (see comments in Section 4.1, above).

Well abstraction and irrigation scenarios generally lead to pessimistic predictions of exposures to sub-surface sources of radionuclide and, for this reason, they are often included in assessment calculations. If the primary reason for including the well water abstraction scenario in the SFR assessment is for the sake of pessimism then this should be stated.

3.8 Chapter 8 – Sub-model irrigation

The closing remarks in Section 4.7, above, apply equally to Chapter 8 in TR-01-04, which is devoted to the Irrigation Sub-Model. The main criticism of this chapter is that no justification is given for the inclusion of this sub-model. The use of the model in the assessment study needs to be justified in relation to likely domestic practices foreseen for the area, most probably based on current practices (it is stated on page 45 of TR-01-04 that irrigation of fields is not considered). It would be helpful at the outset of Chapter 8 to indicate whether irrigation of either agriculture or garden plots is a significant practice in the Forsmark area in the present day. If this is not the case then it seems unlikely that it will become a significant practice in future unless a future drier climate state is foreseen. This further emphasises the point, originally made in Section 4.1 above, that some prognosis or assumption of future climate states in the area is required in order to base the biosphere scenarios developed on a firmer footing. It is stated on page 45 that 'The need for irrigation is, of course, governed by the water need of the vegetation and the annual precipitation'. This implies a close link with climate, but this needs to be stated formally.

The equations presented to describe irrigation and turnover in the soil are appropriate and dimensionally consistent. It is stated on page 48 that 'few site-specific data is used' and that parameter values from Bergström *et al*. [1999] have been adopted. Presumably these parameter values are generic. In general the parameter values presented in Table 8-1 are reasonable and well documented with references and footnotes. However, I would question the initial retention of irrigation water on plant surfaces as described in Section 8.2. It is stated on page 46 that a 3 mm layer of water is assumed to be retained on a plant surface after an irrigation event. This is the product of a 0.5 mm storage capacity and a leaf area index (LAI) of 6. The LAI of 6 might be applicable to a small tree but it is possibly a factor of 5 times too high for a crop canopy – thus, the model probably overestimates significantly the importance of the direct contamination of crop foliage when calculating radiation exposure. Similarly, the area assumed to be irrigated (530,000 m^2, in other words half the area of 'Lake 4') is extremely large for a garden plot. This is the same area assumed for the Agricultural Land Model as described in Section 4.5, above. Since the assumption made at the beginning of Chapter 8 is that irrigation to garden plots only is considered then it should be expected that the area affected should be significantly smaller than the area considered in an agricultural scenario.

In summary, the consistency of the application of each of the models could be improved by clearer development of scenarios – this is demonstrated particularly by the Irrigation Sub-Model, which needs to be based on firmer and more explicit assumptions.

3.9 Chapter 9 – Methods for calculation of doses to humans

It is not the purpose of this review to comment in detail on the methods used in TR-01-04 to calculate doses to humans since these methods are commonly used and accepted in assessments of this kind. The main requirement is to comment on the parameter values adopted for use in these calculations.

First, however, it is clear that Chapter 9 does not develop calculations solely for exposure to inhalation, ingestion and external sources. Sections 9.1.1, 9.1.2 and 9.1.3 (pages 54 to 58) actually describe calculations of radionuclide contamination of animal, crop products and aquatic food products, respectively, rather than addressing directly the dose calculations *via* these products. It would be better to include the descriptions of these calculations as part of the relevant sections in the preceding modelling chapters since the endpoints of ecosystem models should be radionuclide activity concentrations in compartments or food substances which can result in exposure of humans. Chapter 9 should deal with the exposure calculations (i.e., the application of appropriate dose coefficients) only.

The first major assumption in Chapter 9 is that all food products consumed by inhabitants of the study area are obtained from the local area. This is conservative, based on current Swedish habits, as explained by the authors, but it is reasonable since no assumptions are made about lifestyle habits of the local population over the next 1,000 to 10,000 years (see Section 4.7, above). Figure 9-1 shows the accepted pathways of human exposure to radionuclides in the environment and food products, but it could be improved by the addition of arrows that indicate that the various food products shown represent exposure *via* the dietary pathway. Also, a rather obvious feature of Figure 9-1 is that it shows ‘wild’ food products in the form of mushrooms and game, although these items are very clearly omitted from the assessment calculations described in Chapter 9. These items should either be omitted from Figure 9-1 or, preferably, they should be included as food products in the assessment of dietary exposure. This would, of course, necessitate the addition of models of semi-natural ecosystems to the suite of models already developed (see Section 5.4, below).

In terms of the pathways considered in the study, Table 9-1 is very useful as it clearly shows the individual exposure pathways relevant to each modelling scenario. This is a good example of how simple explanatory tables and figures can be used to improve the clarity of understanding, especially for non-expert readers, as discussed in Section 3.2, above.

Section 9.1.3 (page 58) provides a much better explanation of the applicability of bioaccumulation factors than currently given earlier in the report in Chapter 2 (page 11). It has already been suggested, in Section 4.2 above, that the description and definition of the bioaccumulation factor should be improved in Chapter 2.

As in previous chapters, the tabulated parameter values in Chapter 9 (Tables 9-2 to 9-5) are clearly set out and justified by extensive cross-referencing to published literature sources. The main question that arises concerning parameter value selections concerns Table 9-3 which shows parameters connected with human exposure. The first concern is that age-dependence of a) exposure and b) dose conversion coefficients is not mentioned. The authors need to specify which age group (or groups) they have considered in their study and adjust their choices of parameter values accordingly. For instance, food, water and soil consumption rates by humans are all highly age-dependent. The authors state at footnote 2 of Table 9-3 that ‘No extreme diets are considered in this study so a relatively narrow range (i.e., a standard deviation of 10 % on all dietary consumption parameters) is used’. The assumption of ‘no extreme diets’ does not take into account the well known age-related range of dietary intakes, nor does it account for the consumption of ‘wild’ foods, as described above. Indeed, individuals consuming ‘wild’ foods often represent critical groups when considering environmental exposures to radionuclides. In view of the statement on line 2 of page 7 of TR-01-04 that the objective of the study is to ‘predict dose rates to the most exposed individuals' it is therefore necessary to include such food products in the assessment calculations.

Another problem with the assumption of a 10 % standard deviation in Table 9-3 is that many ingestion rates, e.g., the ingestion of soil by children, are positively skewed and cannot be described by the adoption of a normal distribution – in fact a log-normal distribution is probably the best model. In a study by Stanek *et al*. [2001] it was shown that soil ingestion by children could be described by a log-normal distribution with a median value of 13 mg d^{-1}. The current best estimate for soil ingestion in Table 9-3 (100 g y^{-1}) is 21 times higher than the median value determined by Stanek *et al*. [2001] – this is pessimistic, but possibly unreasonably high.

Finally, on the question of age-dependence of dose parameters for dose calculations, it is not stated in Table A-1 to which age group(s) the dose conversion coefficients shown refer. If an assumption has been made by the authors to select a representative age group for the study, or if average dose conversion coefficient values have been calculated, then this should be stated clearly at the beginning of Chapter 9.

3.10 Chapter 10 – Effects of different sorption properties and contamination pathways

Chapter 10 is the only chapter in Report TR-01-04 in which model simulations are shown. The first observation that can be made of these simulations is that they are all deterministic whereas it was previously described (page 12) that probabilistic model calculations (1,000 realizations) were to be made using the ranges and distributions of parameter values presented in the tables in each modelling chapter. For the purposes of Chapter 10, which is an analysis of the sensitivity of the models to solid-liquid K_d values, it may be the case that deterministic calculations are more informative. However, it would also be useful to show at least some examples of the outputs from probabilistic calculations in which K_d values are sampled from a continuous distribution of values.

The second observation concerns the use of a constant release of 10 kBq y^{-1} over a period of 1,000 years (page 63) when using the Coastal Model. Although it is not essential to the analysis of the effect of K_d (because the models all assume linear, concentration independent behaviour) it would be useful to know on what basis this release rate was selected. Is it, for instance, based on a calculated release that may have been published in a previous report?

The general result achieved using the Coastal Model, as described in paragraph 2 on page 63, is reasonable. Can the results of these model simulations be supported by referring to real data, such as the experience in the Irish Sea in which Pu isotopes released from Sellafield have remained largely contained in the bottom sediments but from which Tc-99 has been largely lost to the North Atlantic and arctic seas? While this would not provide a direct validation of the Coastal Model it would indicate whether, broadly, the simulations were reasonable. Such a qualitative demonstration of the applicability of the Coastal Model is particularly desirable in the light of the criticism concerning the model's simplicity as described in Section 4.3, above. It is stated in paragraph 2 on page 63 of TR-01-04 that 'Even after reaching a steady state, the concentration of these elements will decrease with the distance from the outflow point due to dilution with clean waters and suspended matter entering the Baltic'. This is an important point because the gradient of concentration away from the release point will drive migration of radionuclides away from the study area. However, in its current configuration it could be argued that the Coastal Model does not simulate this gradient sufficiently because it treats the entire Baltic Sea as one mixed compartment.

The important transition between the marine phase and the terrestrial phase is dealt with in the final paragraph on page 63. Here it is stated that 'Elements with a strong tendency to sorb to solid matter in the marine environment can be expected to show the same behaviour in soil'. This is questionable since the ionic strength of sea water is so much greater than that of an average soil solution that de-sorption of elements such as Cs would be expected to be much greater in sea water [Assinder *et al*., 1985].

The results of the sensitivity analysis are clearly shown in Figures 10-2 to 10-4 that indicate that the K_d is, indeed, a very important parameter in the Coastal Model. It would have been useful, however, to state at the beginning of Chapter 10 why this sensitivity analysis was so important that it requires a complete chapter. This shortcoming was identified in Section 4.1, above, and the reason for devoting Chapter 10 to this sensitivity analysis should, perhaps, be explained at the beginning of the report (i.e., Chapter 1).

The sensitivity analysis of the Lake Model is somewhat simpler since the model only comprise one third of the compartments, which make up the Coastal Model. The same release scenario of 10 kBq y^{-1} over a period of 1,000 years has been adopted as in the Coastal Model, but the release is assumed to take place directly into the lake water. Again, the rationale for this scenario should be explained, even if it is not based on a calculated release from the SFR repository.

The results of the sensitivity analysis are clearly shown in Figures 10-6 to 10-8 that indicate that the K_d is also a very important parameter in the Lake Model. It is stated in paragraph 1 on page 69 of TR-01-04 that 'The fraction of radionuclides sorbing to suspended matter increased with increasing K_d and as a consequence the fraction of the radionuclides leaving the lake sorbed to particles compared to those leaving with the water also increased. With a K_d-value of 1,000 m^3/kg the outflowing fraction associated with suspended matter is about twice the size of the dissolved fraction leaving the system'. However, as K_d increases, the *total* activity of radionuclides (soluble plus sorbed) leaving the lake decreases from 99 % to 23 % – this should also be pointed out in the text.

In the final paragraph on page 69 the discussion concerning the effect of irrigation in transferring radionuclides from the lake to the soil is interesting but a simulation 'was not included since the fraction removed is very small and insignificant'. However, it is later stated that 'the levels of radionuclides in soils should increase due to a continuous build-up'. If continuous irrigation over a period of 1,000 years is, indeed, a likely scenario (see Section 4.8, above) then a continuous build-up of radioactivity in the soil could be significant over such a long period. For this reason it would be useful to include a simulation of this build-up as part of Section 10.2 in the report.

Section 10.2.1 is an important part of the report since it deals with the transition of one biosphere model to another, which is probably the most difficult, and least well-explained aspect of the modelling study. From page 72 to page 75 a detailed argument is developed to test the hypothesis that radionuclides in deep sediments, originating under marine conditions, can diffuse upwards into lake water and increase the activity concentration in the lake water significantly. At the top of page 75 it is concluded that, even though this process occurs, it is not significant in terms of elevating the activity concentration in lake water so 'Instead, radionuclides accumulated in the sediments during the lake stage were added to the pool which was used as a source in the agricultural land model'. It is useful that the authors have considered in such detail the transition from marine to lake sediment, but it would also be useful if they were to consider the transition from lake sediment to soil in similar detail. Such a consideration might, in particular, take into account any agricultural practices that are employed to convert lake sediment into cultivable soil, as pointed out in Section 4.5, above.

In the description of the sensitivity analysis of the Agricultural Land Model (Section 10.3) the same release rate is used as for the previous two scenarios (i.e., 10 kBq y^{-1}) but in this case over a period of 10,000 years, with the radionuclide input entering the soil system *via* the groundwater. Again, this choice of input rate needs some justification or explanation. In lines 4 and 5 of

Section 10.2 it is stated that 'Lower K_d-values were used compared to the tests with the coastal and lake models since soil K_d is typically lower than sediment K_d'. This is a highly contentious statement since the K_d in soil is highly dependent on *soil type*. In lines 13–15 of page 77 it is stated that '…the masses of the different compartments in the model are different from what is gained when using the figures in Table 5-1…'. The reason for this should be explained, or if it is because 'The calculations presented in this chapter were performed before the values of all parameters were finally decided', as the text goes on to say, then this should be more clearly stated.

In Figure 10-12 the very high values for radionuclide transfers between the solid and liquid phases in the groundwater are evident. The legend states that 'The large figures for the transfers between the solid matter and groundwater in the saturated zone is a consequence of the large number of time steps used when solving the differential equations…'. Surely, it is not the large number of time steps *per se* but the fact that the sorption and desorption rates are relatively fast which gives rise to the very large interchange of radionuclides between soluble and sorbed phases over the end of a 10,000 year period? For instance, interchange of radionuclides between the saturated zone and the deep soil is calculated using the same number of time steps but the overall transfers are much lower.

On page 79, lines 4 to 5 state 'This is an example of a non-linear response to a gradual parameter change, which may be difficult to predict without the use of complex and dynamic models'. This is an interesting point concerning the use of relatively simple linear models for long-term predictions. In view of this effect it would be useful if the authors were to discuss the possible shortcomings of the linear compartmental modelling approach when modelling systems that are inevitably subject to non-linear processes such as diffusion (see general comments concerning the general modelling approach used, Section 3.1, above).

Finally, it is interesting that the Agricultural Soil Model had not reached equilibrium even after a simulation period of 10,000 years. A comment from the authors on whether this would be expected in reality, even if the agricultural soil ecosystem were to remain constant over the simulation period, would be appropriate. Indeed, based on the site-specific studies [e.g., Kautsky, 2001] cited by the authors on the long-term development of biotopes in the vicinity of the SFR facility it would be useful if the authors were to comment on the applicability of the time-scales (1,000 and 10,000 years, respectively) examined in the sensitivity analyses described in Chapter 10.

3.11 Chapter 11 – Summary and discussion

The test simulations reported in Chapter 10 are summarised in the first paragraph of Chapter 11. One of the key conclusions is that 'most of the radionuclides leave the Model Area and Öregrundsgrepen quickly as a result of the fast water turnover'. This is not unexpected since the neighbouring water body, the major part of he Baltic Sea, is a large mass of water that provides a considerable sink for radionuclides emanating from the study area. Nevertheless, with the Coastal Model in its current configuration the results from the simulations are open to question because of the rather simplistic representation of the Baltic Sea as a single large compartment.

In Section 11.1 the authors describe the parameters used in the biosphere models based on the general categories to which they belong (geometrical, physical/chemical, etc.). It would have been useful to have described and categorised the nature of the parameters much earlier in the report, preferably when the general characteristics of the model system were described in Chapter 2. It is suggested in Section 4.2, above, that a generic model structure (e.g., Figure 1, above) is presented to facilitate the general description of the modelling approach used throughout the study. It would be most appropriate to discuss the general nature of parameters, and how they relate to such a generic model structure, at this point in the report.

The discussion comparing the relative uncertainties of each parameter type is very useful. It would also be useful to rank the parameter types based on their uncertainties, as follows.

radiological<geometrical<physical/chemical<biological<living habits

This is informative because it immediately alerts the reader to the fact that it is most probably the least technical data (i.e., living habits) that are subject to the greatest uncertainty while many of the more technical parameters can be quantified with greater certainty. It could be argued that, if present day living habits are assumed, these are not subject to such great uncertainty. However, it is noticeable that the authors have not made any comment about the likely foreseeable living habits of people or agricultural animals over the 1,000 to 10,000 year assessment period. It would be useful in Chapter 11 for the authors to address this question in more detail.

Section 11.2 compares, briefly, the results of the study reported in TR-01-04 with two previous studies, both conducted by at least one of the authors of the current report. At this point the concept of the ecosystem-specific dose factor is introduced. This is referred to as the Ecosystem Dose Factor (EDF) in both SR 97 and TR-01-04 and the EDFs calculated using the Coastal Model in TR-01-04 are presented in Appendix B. The Coastal Model EDFs are presented to facilitate comparison of the present study with the former studies, but it would also have been useful to present EDFs for the other models in the present study. Since EDFs are, by definition, ecosystem-specific, significant differences would be expected between EDFs calculated for different ecosystems!

It seems curious that EDFs for Co-60 and Cs-137 are discussed in the context of an assessment study lasting between 1,000 and 10,000 years since the short radioactive half lives of these radionuclides would ensure that effectively complete radioactive decay would have occurred within 50 and 300 years, respectively. EDFs for the Lake Model are referred to on page 85 although no EDF values for this model are actually tabulated anywhere in the report. It would be useful to tabulate all EDFs calculated using each of the models.

The comparison of EDFs calculated using the different models used in TR-01-04 and SR 97 is interesting from the point of view not only of parameter uncertainty but of model uncertainty. In paragraph 2 of page 85 it is stated that 'The main difference between the two (lake) models … is how sedimentation and resuspension processes are described…'. This statement makes it clear that model uncertainty contributes significantly to uncertainty in the EDF values obtained. This is fully to be expected but it is something which must be identified and discussed clearly when summarizing the results of this study.

Finally, on page 85 it would be most useful to have a clear concluding summary of the study, perhaps using bullet points to identify the key achievements of this study. The final paragraph of Chapter 11, which discusses the ecosystem based modelling approach developed by Kumblad [2001], is useful and interesting but it does not adequately conclude the main content of TR-01-04 which is the development and application of scenarios and models for assessment of the full range of possible biotopes which are expected to evolve around the SFR study area. It is arguable that the ecosystem based modelling approach could not be used for this full range of scenarios and biotopes so its use in future assessments may have to be carefully targeted at specific scenarios.

4 Discussion

The following general discussion of report TR-01-04 is organised around the six principal questions originally posed in the Introduction (Chapter 2, above).

Are the assumptions underlying the models justifiable?

Since the general approach taken by each of the models used in TR-01-04 is the same, the assumptions are broadly similar for each model. The most important assumption in each of the models is that the linear compartmental approach can be applied successfully to each of the ecosystems modelled. In Section 3.1, above, the compromise between model simplicity and model realism is discussed. Over the time scales of interest in this study (1,000 to 10,000 years) it would be very difficult to justify the use of more complex models based on a more mechanistic approach to environmental transfer of radionuclides because such models are usually much more demanding in terms of the input information they require. One of the key features of the current modelling study is the use of ranges of parameter values sampled in multiple realizations of each of the models (although the full results of these probabilistic simulations are not shown in this report). This kind of modelling approach (i.e., simple models in which parameter uncertainties are combined and propagated to produce a final distribution of possible predictions) is ideally suited to the scenarios addressed in this study in which uncertainties on individual parameters are often large.

A major assumption, which it would be difficult for the authors to defend, is the representation within the Coastal Model of the Baltic Sea as a single large compartment. The shortcomings of this assumption are discussed in Section 4.3, above, and these arguments will not be repeated here. The important concluding point from these arguments, however, is that, if the authors wish to retain the existing configuration of the Coastal Model, they should at least demonstrate that their assumption that a single, large, well-mixed control volume can represent the Baltic Sea adequately is valid, perhaps by comparison with another more detailed model such as that proposed by Nielsen [1995].

Another questionable assumption concerns the human exposure parameters shown in Table 9-3. Age-dependence of both dose coefficients and consumption rates (food, water and soil) need to be addressed and the consumption of wild foods (which can lead to 'extreme diet' exposures) needs to be considered.

Are all reasonably foreseeable environmental processes considered?

The models developed to address the series of scenarios which is identified in Section 2.2 of TR-01-04 appear to represent in general each of the major environmental processes to be expected within each scenario. One specific process that is not addressed is peat formation, which should be considered as an intrinsic part of the Mire Model described in Chapter 6.

Another major question is whether all reasonably foreseeable scenarios have been addressed and this is considered below.

The major omission from TR-01-04 is the complete lack of consideration of future climate states, which over the assessment period of 1,000 to 10,000 years, are likely to change considerably. Arguably, climatic conditions should not strictly be categorised as 'processes' but climate will play a major role in controlling the type and extent of common environmental processes such as precipitation and evapotranspiration, as described in Chapter 8 when considering the requirement for irrigation. It may be that the authors have implicitly considered climate change when considering the evolution of biotopes in the study area, but it would improve the clarity of the scenario development if the likely climatic conditions expected under any individual future scenario were to be described explicitly.

Such future climatic conditions are, inevitably, subject to great uncertainties but such uncertainties might be used to help justify the selection of parameter ranges. A good example would be the selection of parameters relating to human living habits that, as discussed in Section 4.11, above, are possibly subject to the greatest uncertainties of all the parameters used. Human (and domestic animal) living habits are extremely closely linked to climate that will influence such practices as agriculture and water use.

Has parameter uncertainty been sufficiently and reasonably addressed?

This study has addressed parameter uncertainty in a rigorous way. All parameters for which ranges of values are to be expected have been assigned values that are justified by referencing to published studies. As discussed in Chapter 11, some of these parameter values have fairly small uncertainties because they are based on detailed site-specific studies in the vicinity of the present day SFR facility. Other parameters are more generic and are, inevitably, subject to greater uncertainty. But, in general, the system of tabulated parameter values, showing maximum, minimum and best estimate values, is clear, consistent and well justified. Specific recommendations concerning the selection of parameter values are as follows.

In Chapter 3 the maximum depth of the upper sediment (D_s) assumed for the Coastal Model appears too small – if this represents the maximum depth of bioturbation it should be re-assessed.

In Chapter 4 the Lake Model K_d-values for Cs, Pu and Tc should be re-assessed. The current maximum values for the Cs and Pu K_ds should each be increased by one order of magnitude and the maximum K_d for Tc should be increased to 10^2 to account for anoxic sediments. If palladium proves to be a critical radionuclide then the bioaccumulation factor for this element needs more careful justification. Also, the current bioaccumulation factors for crustaceans should be drawn from more than one literature source if possible.

In Chapter 5 (Agricultural Land Model) the root uptake factors for crops should be selected on the basis of the soil type expected in the agricultural scenario. Similarly, in the Mire Model, in which crops are assumed to be grown on organic, peaty soil, root uptake factors for organic soils should be selected. The K_d-values currently selected for peat soils in the Mire Models should be re-checked with reference to IAEA [1994].

In Chapter 8 the range of leaf area index values should be re-checked. Currently the best estimate of 6 (expressed in Table 8-1 as an initial retention of irrigation water of 3 mm) is very high for an agricultural crop.

In Chapter 9 the parameters concerning human exposure rates (Table 9-3) should be re-assessed. Specifically, age-dependent parameter values for food, water and soil consumption should be given and the assumption of a normal distribution with a 10 % standard deviation should be re-assessed, especially for soil ingestion. In connection with Table 9-3, the dose conversion coefficients presented in Table A-1 should be shown for specified age classes.

Have sufficient models been used to address all reasonably foreseeable biotopes?

It is stated in Chapter 1 of TR-01-04 that, in the vicinity of the present day SFR facility, about 70 % of the land area is covered by forest, with wetlands and dry meadows also occurring. Moreover, it is also stated that 'No agricultural areas occur in the near vicinity of the repository area and the amount of agricultural land is low in general (less than 10 % …)'. This description of the study area suggests that, in the present day, semi-natural ecosystems are potentially important when considering radiation exposures through environmental pathways. The experience following the Chernobyl accident has emphasised the importance of such exposure pathways, particularly through the ingestion of 'wild' foods such as game, mushrooms and fruits. The current assumption within the modelling study appears to be that exposure *via* agricultural food products will be more important in the terrestrial environment than exposure *via* semi-natural pathways. This assumption would be justified if the authors made explicit assumptions about future living habits of people in the SFR area. However, no such assumptions are made and it would seem unreasonable not to consider semi-natural ecosystems as a potentially important source of radiation exposure.

Given the present day predominance of forest cover in the area, the inclusion of a forest model in the study is desirable. Also, because dry meadows are also reported to occur in the area and, in any case, usually form an important component of the mosaic of ecosystems in forested areas, a dry meadow model should also be included. The existing Mire Model is probably sufficient to address the wet meadow ecosystems described on page 8 of the report as long as it can be improved as described in Section 4.6, above.

Are the transitions between biotopes modelled adequately (specifically, are initial conditions for developing biotopes adequately specified by calculations for subsiding biotopes)?

The transitional phases between ecosystem types are probably the most difficult features of the evolving sequence of biotopes to model, yet these transitional periods are, arguably, one of the most important features of the scenarios considered. In its current form the document does not adequately explain how the transitions between ecosystems are considered conceptually. It is suggested in Section 3.2, above, that a diagrammatic representation of the evolutionary sequence of biotopes is included in Chapter 2 and that a flow diagram should be added to this to show the sequence of model calculations in relation to the sequence of ecosystem evolution. A suitable diagram is already shown in Section 2.4.1 of SKB Report R-01-18 (Figure 2-2, page 17) and this could be adopted for use in TR-01-04.

From the existing model descriptions in TR-01-04 it seems as if end points from one model are simply used as starting points for the next model in the biotope sequence. For example, the discussion in Section 10.2.1 (pages 72 to 77) considers the way in which radionuclides in deep marine sediment can act as a source of contamination to lake sediments deposited over the top of them. While the discussion about the possible secondary contamination of the lake sediments by upwards diffusion from the deeper marine sediments is very useful it seems as though the 'transition' between the coastal and lake systems is treated as a discrete junction rather than as a gradual transition, which it will be in reality. This might not be such a problem for the transition of one aquatic system to another, but the transition from the lake system into the agricultural system requires more careful consideration. It has already been described in Section 4.5, above, that lake sediment does not immediately become converted to cultivable agricultural soil once drainage of a lake has occurred. In the case of the agricultural scenario, manual cultivation of the sediment would be expected, possibly in connection with the application of animal and/or chemical fertilizers. This treatment would be expected to alter a) the vertical distribution of the radionuclides within the lake sediment (e.g., in the case of ploughing, this might increase or decrease the average activity concentration in the soil, depending on the initial vertical distribution in the sediment) and b) the chemical disposition (i.e., the degree of sorption) of the radionuclides in the newly developed soil. Over the overall timescale of the assessment, the length of time over which such transitional processes apply might be significant or not significant.

However, if such processes are considered by the authors to be potentially insignificant then this needs to be stated and justified explicitly.

Have all critical radionuclides been identified?

The use of Ecosystem Dose Factors (EDFs) is an excellent way to demonstrate and rank the likely dose contributions of the range of radionuclides considered in this study, especially when they are used to compare radiological impacts of the same radionuclides in different ecosystem types. However, in its current form the report only presents EDFs for the coastal ecosystem. A more comprehensive collection of tables of EDFs should be presented for each of the ecosystems considered.

Even if such a comprehensive series of tables of EDF values were to be presented it would still be difficult to judge whether all potentially important radionuclides had been considered. This is because there is no indication, anywhere in the report, of the range of potentially significant radionuclides expected to emerge from the SFR facility. This information is, no doubt, included in one of the reports that is referenced in TR-01-04, but it would be desirable to include a summary table of potentially significant radionuclides in the introductory report. If calculated EDFs for each of these radionuclides were then to be presented for each ecosystem it would be relatively straightforward for even the non-expert reader to conclude which were the critical radionuclides. A further suggestion would be to present the EDF values in ranked order to improve the clarity of the results even further.

5 Recommendations

The following list of major recommendations is based on major points raised in the preceding sections of this review and, specifically, in the Discussion section (Chapter 5, above).

- A table of all the radionuclides of potential concern in this study (i.e., those considered likely to migrate in significant quantities from the SFR facility into the biosphere over the assessment period) should be given in Chapter 1.
- Clear flow diagrams should be added to Chapter 2 to show the evolutionary sequence of biotope development and the complementary sequence of model calculations. As the basis for this Figure 2-2 from SKB Report R-01-18 could be used.
- If the output(s) from one model provide an input(s) to a succeeding model then this should be indicated in the flow diagram and an explanation given of how the transition between the two is modelled.
- At the beginning of each chapter in which a model or sub-model is described all the model parameters should be listed together with their symbols and units.
- In the diagrams of individual models, arrows should be labelled to indicate which parameters are used to represent the fluxes between compartments.
- Model equations should be numbered systematically to aid description and discussion of the models.
- The term ‘activity concentration’ should be used throughout the report in preference to just ‘concentration’ and ‘radionuclide’ should be used in preference to ‘element’.
- Two additional models should be included in the study to simulate radionuclide exposures in a) forests and b) dry meadows (i.e., both semi-natural ecosystems).
- Tables of EDF values for all potentially significant radionuclides should be presented for each ecosystem type modelled. EDF values should be ranked to aid in the identification of critical radionuclides.

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