



Working Report 2006-110

Review of Geosphere-Biosphere Interface Processes and their Handling in the Safety Case of Posiva

Anne-Maj Lahdenperä

December 2006

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Review of Geosphere-Biosphere Interface Processes and their Handling in the Safety Case of Posiva

ABSTRACT

The report describes list of databases of the Features, Events and Processes (FEPs) on the basis of the current knowledge and ranks them for their potential importance of radionuclide transport in the Safety Case. Due to vast amount of FEPs, only those assessed as potentially significant for the geosphere-biosphere interface zone (GBIZ) are described in detail. However, for scientific understanding also general main FEPs in the GBIZ are incorporated whether they affect directly radionuclide transport or not.

The geosphere-biosphere interface zone, or the boundaries between the geosphere and biosphere modelling domains of the safety assessment, has been raised to an important issue but, according to the reports, it has so far taken into account rather poorly or not at all. Thus, it is acknowledged that a genuine site-specific treatment and incorporation of (deeper) overburden and aquifers into the biosphere models are needed to cover all relevant FEPs and to treat properly the zone in the modeling chain of groundwater flow and geosphere and biosphere transport of radionuclides.

The principal variability in the GBIZ, especially in the biosphere, is driven by climatic change. The change from bedrock groundwater to bioavailable region takes place without gaps in the top bedrock to the overburden. However, it is important to recognise that there are regions in GBIZ that overlap the geosphere and biosphere model domains

Problems envisaged with the treatment of the GBIZ are associated with defining the boundary conditions for both far field and biosphere models. The GBIZ is not a separate modelling domain and the processes and events affecting the transport of radionuclides within the GBIZ should not be considered to be unidirectional.

The biosphere is a diverse system under continuous development and impossible to model accurately. Thus, some inherent uncertainty already in the conceptual level of modelling has to be accepted. In addition of needs to handle spatial and temporal variations, transport models in the GBIZ should be complex, non-linear, and include a number of input parameters that are usually time- and space-dependent, associated with large uncertainties and often correlate to each other, even though actual radionuclide assessment models might be more simplified.

Assessing the impacts of releases of radioactivity into the environment rely on a great variety of factors. Important among these is an effectively justified level of understanding of radionuclide behaviour in the environment, the associated migration pathways, the processes that contribute to radionuclide accumulation and dispersion among and within specific environmental media.

Keywords: Geosphere-biosphere interface zone, FEPs, radionuclides, Safety Case

Selvitys geosfääri-biosfäärirajapintaan liittyvistä prosesseista ja niiden käsittelystä Posivan turvallisuustodisteissa

TIIVISTELMÄ

Raportissa kuvataan Olkiluotoon sijoitettavien ydinjätteiden loppusijoitukseen liittyviä turvallisuustodisteita (Safety Case), niihin vaikuttavia tekijöitä, tapahtumia ja prosesseja (Features, Events and Processes; FEPs) sekä kuvataan niiden potentiaalista merkitystä radionuklidien kulkeutumiseen geosfäärin ja biosfäärin rajapinnalla (GBIZ). Erilaisten prosessien ja vaikuttavien tekijöiden huomattavasta määrästä johtuen ainoastaan merkittävimmät on kuvattu yksityiskohtaisesti. Kuitenkin turvallisuustodisteiden kannalta myös muut potentiaaliset prosessit on kuvattu/listattu raportissa.

Ydinjätteiden sijoittamiseen liittyvien turvallisuustodisteisiin vaikuttavat tekijät ja prosessit geosfääri-biosfäärirajapinnalla voivat vaikuttaa olennaisesti radionuklidien kulkeutumiseen, vaikkakaan niitä ei ole yleensä huomioitu varsinkaan raportoinnissa riittävästi tai ei ole tunnistettu ollenkaan. Siten on tärkeää, että kaikki prosessit ja tekijät, jotka vaikuttavat syvemmillä maa- ja kallioperässä geosfääri-biosfäärirajapintaan sekä päinvastoin tulee ottaa huomioon radionuklidien kulkeutumisessa ja niihin vaikuttavien tekijöiden mallintamisessa. On otettava huomioon myös, että geosfääri-biosfäärirajapinnalla esiintyy alueita, joissa geosfäärin ja biosfäärin mallit lomittuvat.

Erityisesti biosfääri on huomattavan muuttuva ja monimuotoinen kokonaisuus, mistä johtuen kaikkien geosfääri-biosfäärirajapintaan vaikuttavien tekijöiden huomioiminen mallinnuksessa on jossain määrin epätarkkaa. Ilmaston vaikutus ja sen aiheuttamat muutokset ovat tärkeä tekijä geosfääri-biosfäärirajapinnalla tapahtuviin muutoksiin, erityisesti biosfäärin puolella.

Spatiaaliset ja temporaaliset vaihtelut radionuklidien kulkeutumisessa geosfääri-biosfäärirajapinnalla ovat kompleksisia ja epälineaarisia. Turvallisuustodisteiden kannalta on erityisen tärkeää ymmärtää eri radionuklidien kulkeutuminen ja niihin liittyvät prosessit erilaisissa muuttuvissa ympäristöissä, vaikkakin varsinainen kulkeutumismallinnus olisi yksinkertaistettumpaa.

Avainsanat: Geosfääri-biosfäärirajapinta, FEP-lista, radionuklidit, turvallisuustodisteet

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1 INTRODUCTION

The KBS-3 concept for spent fuel disposal in crystalline bedrock at Olkiluoto has been developed and investigated by Posiva well over 20 years. The KBS-3 concept aims at long-term isolation and containment of spent fuel assemblies within copper-iron canister to prevent any releases of radionuclides from the repository into geosphere as well as into biosphere for 100 000 years, at least. If barriers would fail, anyhow, it is important to show that the consequences for the environment are acceptable. In Finland and Sweden the same basic concept of design of the repository, KBS-3 is given priority (Vieno & Ikonen 2005). The safety concept as well as the functions and the required and desired properties of the barriers of the disposal system have been latest discussed in Posiva (2000, 2003, 2005, 2006), Vieno & Ikonen (2005), and SKB (2004, 2006).

The geosphere-biosphere interface zone (GBIZ) has been raised to an important issue (e.g. Egan et al. 2004, BIOPROTA 2005). The change from bedrock groundwater to bioavailable region takes place without gaps in the top bedrock, the overburden (both mineral and organic soil) and aquatic sediments. However, it is more appropriate to recognise that there is a region of space that should overlap the geosphere and biosphere model domains. Thus, it is acknowledged that a genuine site-specific treatment and incorporation of deeper overburden and aquifers into the biosphere models are needed to cover all relevant FEPs (Features, Events and Processes) and to treat properly the zone in the modelling chain of groundwater flow, geosphere and biosphere transport of radionuclides (Vieno & Ikonen 2005).

Problems envisaged with the treatment of the GBIZ are associated with defining the boundary conditions for both far-field and biosphere models and derivation of the source term for biosphere modelling from the far field modelling. The GBIZ is not a separate modelling domain and the processes and events affecting the transport of radionuclides within the GBIZ should not be considered to be unidirectional; for example climate change or changes in land-use, originally appearing in the biosphere domain, will also have an effect on the (upper) geosphere. There is a requirement for making existing models more robust for the treatment of the GBIZ whilst ensuring that a greater artificial block between geosphere and biosphere models is not created. This may require the development of current models to take account of appropriate spatial and temporal scales (BIOPROTA 2005).

Numerous FEPs are important to the GBIZ, but many are poorly understood. Not all FEPs can be considered and it is therefore important to identify those that are of greatest importance to the GBIZ. However, numbers of uncertainties and issues in the treatment of the GBIZ have also been highlighted.

The areas over which radionuclides enter aquifers from the geosphere are a key parameter in determining the additional radionuclide dilution produced by the aquifer. The area can vary greatly depending on which kind of media the geosphere flow is through and for a wide variety of other reasons, such as variations in topography, and contrasts in the hydraulic conductivity of rocks. The importance of this area arises due to degree of dilution which can occur, and nature of the aquifer which can influence the extent of the surface environment receiving contamination. The most important factor determining the transport of radionuclides is the assumed water balance of the system (BIOPROTA 2005).

Discharge areas near the shoreline have been predicted using the far-field model of TILA-99 (Löfman 1999, Vieno & Nordman 1999). However, due to the uncertainty of the presence and connectivity of major fracture zones actual discharge areas could be different from those initially predicted. A number of discharge points could occur from the repository and therefore multiple discharge areas need to be considered in the Safety Case; GBIZ is the conceptual gap between modelling domains and needs to be covered by consistent boundary conditions.

2 SCENARIOS FOR GEOSPHERE-BIOSPHERE INTERFACE

2.1 This report

This report presents a summary of geosphere-biosphere interface features, events and processes (FEPs). The geosphere-biosphere interface zone (GBIZ) is a region of site at the boundaries between the geosphere and biosphere modelling domains of the safety assessment that has been so far taken into account rather poorly or not at all. Thus, it is acknowledged that a genuine site-specific treatment and incorporation of deeper overburden and aquifers into the biosphere models are needed to cover all relevant FEPs and to treat properly the zone in the modelling chain of groundwater flow, geosphere and biosphere transport of radionuclides (Figure 1) (Vieno & Ikonen 2005).

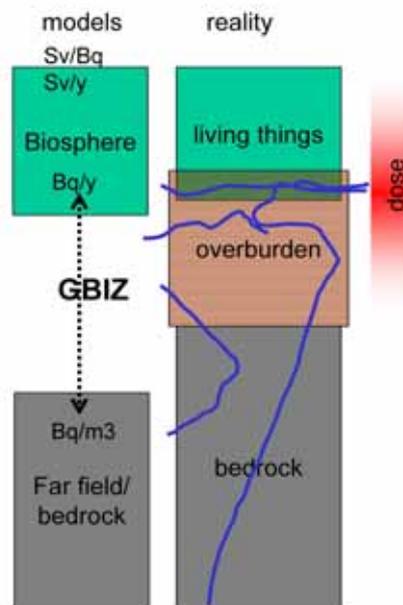


Figure 1. The difference between the concepts of traditional safety assessment approach and the reality (modified by Ari Ikonen, Posiva Oy 2005).

Due to vast amount of geosphere-biosphere FEPs, only those assessed as potentially significant are described in detail. However, for scientific understanding also general main FEPs in the GBIZ are described whether they affect directly radionuclide transport or not (Appendix 1). This report describes the FEPs on the basis of the current knowledge and ranks them for their potential importance of radionuclide transport in a following manner:

- The review of FEP databases in earlier assessments over 20 years time span
- Classification of the FEPs to the variety of external (e.g. glaciation, climate change, shore migration), internal (e.g. topography, overburden, aquatic ecosystems, ecological communities), and transport (e.g. atmospheric, water-born) processes

- Classification of the relevant FEPs (physical, hydrological, geochemical and biological) according to their significance in GBIZ
- Classification of FEPs according to their probability
- Estimation of level of understanding of the key processes (e.g. spatial and temporal scale, transport pathways)
- Listing available site data on key processes and their consistency
- Review current interfaces of geosphere - biosphere domains and cross-domains (e.g. source term definitions)
- Effects of geosphere systems in biosphere and *vice versa*
- Radionuclides of most interest based on recent models
- Level of consistency between modelling domains (e.g. emission routes, chemical processes, climate change, biotic influences)
- Scenarios for geosphere-biosphere interface (e.g. in SR-Can, Safety Case of Posiva, recommended scenarios)
- List of FEPs by FEPs according to their importance in biosphere, geosphere and geosphere-biosphere interface zone. However, the most of the FEPs overlap and could be categorized in the other way, in this report the emphasis is on GBIZ (Appendix 1). The FEPs which are also relevant in the other categories (e.g. far-field) are not mention in the list.

2.2 Regulatory guidelines

The regulatory requirements are set forth in the Government Decision on the strategy of the disposal of spent nuclear fuel (STUK 1999) and, in more detail, in the regulatory GUIDE YVL 8.4 issued by STUK (2001). The regulatory emphasizes the aim at complete containment by stating that the repository design shall effectively hinder the release of disposal radioactive substances into the host rock for several thousands years. For the quantitative safety assessment calculations, the regulatory requirements for a period that shall be extended to at least several thousands years after the closure of the repository area presented in Table 1.

The regulations give guidance on potential exposure environments and pathways that shall be considered in the safety assessment. According to the regulatory Guide YVL 8.4: “The scenario analysis shall cover both the expected evolutions of the disposal system and unlikely disruptive events affecting long-term safety. The scenarios shall be composed systematically from features, events and processes, which are potentially significant to long-term safety and may arise from:

- Mechanical, thermal, hydrological and chemical processes and interactions occurring inside the disposal system
- External events and processes, such as climate changes, geological processes and human actions”

The Guide YVL 8.4 gives also guidance on the potential exposure environments and pathways to be considered. The biosphere assessment, in general, is to be based on similar type of climate, human habits, nutritional needs and metabolism to the current ones, but to take account reasonably predictable changes in the environment, e.g. the land uplift and subsequent emergence of new land area. At least the following exposure pathways shall be considered (STUK 2001):

- Use of contaminated water as household water
- Use of contaminated water for irrigation of plants and watering animals
- Use of contaminated watercourses and relictions

The most exposed individuals live in a self-sustaining family or small village community in the vicinity of the disposal site, where the highest radiation exposure arises through the pathways mentioned above. In the environs of the community, a small lake and shallow well is assumed to exist. The other members of the public are defined to live at the regional lake or at a coast site and to be exposed to the constraint is set, but the acceptability of the doses depends on the number of exposed people, and they shall not exceed values from hundredth to on tenth of the constraints for the most exposed individuals (STUK 2001).

Disposal of spent fuel shall not affect detrimentally to species of fauna and flora. This shall be demonstrated by assessing the typical radiation exposures of terrestrial and aquatic populations in the disposal site environment, assuming the present kind of living populations. These exposures shall remain clear below the levels which, on the basis of best available scientific knowledge, but would cause decline in biodiversity or other significant detriment to any living population. Moreover, rare animals and plants as well as domestic animals shall not be exposed detrimentally as individuals (Vieno & Ikonen 2005).

Table 1. Safety assessment endpoints stated in the Finnish regulations (STUK 2001) for a time period of at least several thousands years from the closure of the repository.

| Endpoint | Criterion |
|---|---------------------------|
| Annual effective dose to the <i>most exposed members of the public</i> | Less than 0.1 mSv |
| Average annual effective dose to the <i>other members of the public</i> | Insignificantly low |
| Biodiversity of currently <i>living populations</i> | No decline |
| Effects on populations of <i>fauna and flora</i> | No significant detriments |
| Effects on individuals of <i>domestic animals and rare plants and animals</i> | No detrimental effects |

Arising from the regulatory requirements and needs of the overall Safety Case, the geosphere and biosphere assessment needs to include detailed description and quantitative analysis, for the next several thousand years, on:

- Radionuclide transport processes and pathways
- Exposure environments and cases based on the expected evolution of the site conditions and on the regulatory requirements
- Radiation doses: dose conversion factors (converting release rates into biosphere to dose rates)
- Effects on non-human biota

In the long term, after several thousand years, the quantitative regulatory criteria are based on constraints on release rates of long-lived radionuclides from the geosphere into the biosphere. The nuclide-specific constraints are set in the guide YVL 8.4. These constraints shall be defined so that:

- At their maximum, the radiation impacts arising from disposal can be comparable to those arising from natural radioactive substances
- On a large scale, the radiation impacts remain insignificantly low

Guide YVL 8.4 specifies nuclide specific constraints for the activity releases to the environment area as follows:

- 0.03 GBq/a for the long-lived, alpha emitting radium, thorium, protactinium, plutonium, americium and curium isotopes
- 0.1 GBq/a for the nuclides Se-79, I-129 and Np-237
- 0.3 GBq/a for the nuclides C-14, Cl-36 and Cs-135 and for the long-lived uranium isotopes
- 1 GBq/a for Nb-94 and Sn-126
- 3 GBq/a for the nuclide Tc-99
- 10 GBq/a for the nuclide Zr-93
- 30 GBq/a for the nuclide Ni-59
- 100 GB/a for the nuclides Pd-107 and Sm-151

These constraints are based partly on biosphere analyses (e.g. Karlsson & Bergström 2000), where SR 97's biosphere models have been applied at Olkiluoto and partially on comparisons with natural long-lived radionuclides. These constraints apply to activity release which arises from the expected evolution scenarios and which may enter the environment first after several thousands of years. These activity releases can be averaged over 1 000 years at most. The sum of the ratios between the nuclide specific activity releases and the respective constraints shall be less than one (Hautojärvi & Vieno 2002).

The importance to long-term safety of unlike disruptive events shall be assessed and, whenever practicable, the acceptability of the consequences and expectancies of radiation impacts caused by such events shall be evaluated in relation to the dose and release rate constraints. The unlikely disruptive events considered shall include at least (Vieno & Ikonen 2005):

- Boring a deep water well at the disposal site
- Core-drilling hitting a waste canister
- A substantial rock movement occurring in the environs of the repository

The models and data employed in the safety assessment shall be selected on the basis that the results, with high degree of certainty, overestimate the radiation exposure and radioactive release likely to occur. Simplification of models as well as the determination of input data for them shall be based on the principle that the performance of any barrier will not be overestimated but neither underestimated. The various models and input data shall be mutually consistent, apart from cases where just the simplifications in modelling or the aim of avoiding the overestimation of the performance of barriers implies apparent inconsistency (Vieno & Ikonen 2005).

In a very long term, after several hundred thousands or one million years, no rigorous quantitative safety assessment is required but the judgment of safety could be based on more qualitative considerations, such as bounding analyses with simplified methods, comparison with natural analogues and observations of the geological history of the site (Ruokola 2002).

The safety regulations imply that in the Safety Case the main emphasis shall be put on the isolation and containment capacity of the disposal system. For the quantitative safety assessment, there are three periods with different emphases:

- Until several thousand years after the closure of the repository, when the dose rate constraints apply. Biosphere transport and dose assessments need to be performed only for those radionuclides which are released into the biosphere during this period.
- From several thousand to several hundred thousand years, when the release rate constraints apply. No biosphere analyses are needed, and dilution plays no role in the fulfilment of the regulatory constraints.
- After several hundred thousand years the safety assessment can increasingly be based on qualitative considerations.

The safety regulations and guidance are expected to be updated periodically (Vieno & Ikonen 2005).

2.3 Tentative GBIZ Scenarios

Assessments of the impacts of radioactivity into the environment rely on a variety of factors. Important among these is an effectively justified level on understanding of radionuclide behaviour in the environment and the associated migration consequences for the environment and human health. It has been recognized that in some cases data for these assessments are sparse. Particular difficulties arise in case of long-lived radionuclides, due to the difficulty of setting up long-term monitoring and experimental programmes. The biosphere systems themselves will also change over the relevant periods, due to natural processes and the high potential for interference by mankind (BIOPROTA 2005).

The importance of individual processes controlling radionuclide transfer to the geosphere-biosphere interface is dependent on the characteristics of the site, in terms of the geology, hydrogeology, topography, soil system, climate and vegetation (Hooker et al. 2002). As such, radionuclide transfer processes are site and system specific. However, there remains considerable uncertainty with regard to:

- Which processes are significant for radionuclide migration behavior, and the nature of the interactions that occur between processes
- The rates of the transport and retardation processes that control radionuclide migration behavior

The continued shore-line displacement will influence the local and regional biosphere and eventually result in a situation where Olkiluoto is located inland rather than at the coast. This will in turn significantly influence the position of the potential discharge areas for radionuclides. The development of the shore-line will include changes of the internal biosphere conditions, such as biosphere succession (mire and forest development) and sediment redistribution (sedimentation and resuspension/erosion) (Posiva 2003, 2006, Vieno & Ikonen 2005, Mäkiäho 2005).

Also the erosion of overburden and accumulation of inorganic and organic materials will slowly change the topography and consequently the potential discharge areas of radionuclides. Spatial and temporal distribution of potential discharge locations as well as dilution during geosphere transport should be assessed on the basis of groundwater flow analyses (Ikonen et al. 2004, Vieno & Ikonen 2005).

3 GBIZ FEPS IN EARLIER ASSESSMENTS AND DATABASES

The concept of the geosphere-biosphere part of the assessments has changed over the years, e.g. TVO-82 (Anttila et al. 1982), TVO-85 (Vieno et al. 1985), TVO-92 (Vieno et al. 1992), TILA-96 (Vieno & Nordman 1996), TILA-99 (Vieno & Nordman 1999) and Posiva (Vieno & Ikonen 2005). TVO-82 and TVO-85 assessments were generic feasibility studies of the KBS-3 disposal concept and the site of the Olkiluoto nuclear power plant at the coast of the Baltic Sea was used as one of example sites.

In TVO-85 the basic principle, which was adopted for the analysis, was to employ conservative assumptions, models and data in each stage. From the comparison point of view, the most interesting scenarios of the TVO-85 safety analysis were the disturbed evolution scenario P1, where a canister was assumed to be initially defective, and the disruptive event scenario, where a large postglacial rock displacement was assumed to intersect the repository. In the disruptive event scenario, a large postglacial displacement breaking all 60 canisters in a disposal tunnel was assumed to intersect the repository after 30 000 years. The maximum dose rate was approximately 1 mSv/yr. It was caused mainly by Np-237 and occurs about three million years after the rock displacement. The oxidizing conditions were assumed to prevail everywhere in the near-field and the geosphere. The groundwater transit time from the repository into the biosphere was assumed to be 500 years (Vieno et al. 1992).

In TVO-85 FEPs were categorized mainly for the natural features and some human activities including: tectonics and volcanism, meteorites, ice ages/glaciations, earthquakes, erosion, land-uplift, sea-level uplift, atmosphere (carbon dioxide, acid rain), mineralogical changes and critical mass.

In TVO-92 a conservative variant of the biospheric part of the Swedish safety assessment (SKB-91) (Bergström & Nordlinder 1990a, 1990b) was used. The safety analyses was based on the site data from preliminary investigations at five candidate sites (Kivetty in Äänekoski, Olkiluoto in Eurajoki, Syyry in Sievi, Romuvaara in Kuhmo and Veitsivaara in Hyrynsalmi), as well as on the developments in technical plans and in supporting R&Ds. In the scenario of TVO-92, the maximum dose rate was about 1 mSv/yr, when a rock displacement is assumed to break 60 canisters at 10 000 years. The maximum dose rate occurs already about 10 000 years after the rock displacement and was caused mainly by Pu-239 and Pu-240. It was assumed due to the large amount of iron in Advanced Cold Process (ACP) canister that reducing conditions prevail in the canister outside the fuel surface. Reducing conditions in the source area have a strong effect on the release of neptunium. In TVO-92 the groundwater transit from the repository to the biosphere was assumed to be direct and very fast flow path, the groundwater transit time being no more than one year. The maximum dose rates in TVO-85 and TVO-92 were equal in magnitude, but were widely different due to time scale and different nuclides.

In TVO-92's scenario development was initially taken also approximately 50 FEPs of very low probability or negligible consequences. However, later, some phenomena and events (e.g. criticality, volcanism, meteorite impact) in the disruptive event analysis of the TVO-85 safety analysis were unheeded. A major part of the remaining FEPs were assigned to the "process system which comprises the complete set of non-stochastic chemical and physical processes that might influence the release of radionuclides from the repository into the biosphere. The phenomena in the process system were considered

basic in the central scenarios and their modelling was quite similar in the SKI Project-90 (SKI 1991) and SKB 91 (SKB 1992) safety analyses. On the basis of similar causes or consequences, the FEPs were grouped into 16 primary FEPs. Eleven of them were in principle, be combined with all the FEP's in developing of scenarios. The remaining five were so isolated that, for practical reasons they were treated as special cases. The main 16 FEPs included:

- Random canister defects – quality control
- Backfill material deficiencies
- Stray material left
- Unsealed boreholes and/or shafts
- Change in sea level
- Uplift and subsidence
- Human induced actions on groundwater recharge
- Altered water chemistry by humans
- Faulting
- Permafrost
- Glaciation
- Non-sealed repository (isolated)
- Accidents during operation (isolated)
- Waste retrieval, mining (isolated)
- Explosions, sabotage (isolated)
- Postclosure monitoring (isolated)

Systematic identification and screening of processes and events potentially affecting the long-term safety of nuclear waste disposal and compilation of FEP databases have had of great value. In TVO-92 it was reassuring to note that the exercises have not added very much completely new, significant FEPs to the lists of processes and events considered in the TVO-82 and the TVO-85 safety analyses. TILA-96 was a continuation and update of TVO-92. Three postulate canister defect scenarios were considered:

- An initial small (“pinpoint”, 5 mm²) hole through the copper overpack (Scenario SH: SH-ns50, SH-sal50)
- An initial large (“fingertip”, 1 cm²) hole through the copper overpack (Scenario LH: LH-ns50, LH-sal50)
- No physical contaminant (“disappearing canister”) after 10 000 years (Scenario DC:DC-ns50, DC-sal50)

(ns= non-saline, sal=saline, 50 = median flow and transport data)

In the TILA-96 report the transport analysis was performed under steady circumstances with no time-dependent evolution of the conditions. Redox conditions were assumed to be reducing except for the surface of the fuel where oxidizing conditions were assumed to prevail due to alpha radiolysis. The three scenarios differed only as concerns the defect in the canister and the associated conceptual modelling of the near-field transport. The data used in the release and transport analyses was so conservative that it was expected to cover most of the effects.

In the TILA-96, as concerns assessing the effect of glaciations on repository performance, there were two significant developments in Posiva's programme since TVO-92. Firstly, the new canister design with the cast insert provides better safety margins against elevated hydrostatic pressure during glaciation than the ACP canister (Advanced Cold Process). Secondly, the effects of glacial melt water on corrosion of copper were studied and noted that deep groundwater contains traces from glacial water (Ahonen & Vieno 1994). TVO-92's discussions and conclusions on human intrusion were still valid in TILA-96. Thus, the general structure of the TILA-96 set of scenarios was very similar to TVO-92.

The NEA International Database of Features, Events and Processes, relevant to the assessment of post-closure safety of radioactive waste repositories have been compiled by a working group within the Nuclear Energy Agency (NEA) of OECD (NEA 1997). The first version of the international database includes FEPs from seven national and international performance assessment projects (NEA 1999). The main part of the database is a master list of 150 generalised FEPs and the original project-specific database contain descriptions, comments and references on the FEPs. All FEPs are mapped to one or more of the FEPs in the master list (Vieno & Nordman 1999). The treatment of FEPs in the TVO-92 and TILA-96 safety assessments was audited against the international database (Vieno & Nordman 1997). The auditing was made against all the 1261 project-specific FEPs in the international database. The FEPs were considered one by one and were classified in fourteen groups (for example, "scenario", "model", "primary data", "excluded due to very low probability") on the basis of TVO-92 and TILA-96.

The exercise was instructive, but did not reveal anything substantially new from the previous assessments, nor did it provide much new for TILA-99. The strong sides as well as weak points of TVO-92 and TILA-96 were fairly well recognized and identified in the reports and in the regulatory reviews (Ruokola 1994, STUK 1997). In the auditing the most significant open issues (e.g. gas generation and release, saline groundwater, glaciation) fell into the "discussed" category. Most of the FEPs audited into the "not considered" category with the factors were not very important (Vieno & Nordman 1997).

The fact that a FEP is included in a database and is said to be "considered" or "modelled" in a performance assessments (PA), showed only that the authors of the PA were aware of it. It does not tell whether the treatment of the FEP was correct or adequate, which can be assessed only on the basis of the PA itself. FEP databases and formal scenario development methodologies often tend to deal with matters on fairly theoretical level without giving much practical guidance for the modelling of release and transport of radionuclides. The completeness and robustness of a performance assessments can be assessed only by considering the analysed scenarios, assumptions, models and data together (TILA-99). The international, TVO's, Posiva's and SKB's exercises have provided a broad background of features, events and processes which may affect disposal of spent fuel in copper-iron canisters in a KBS-3 type repository in the Svecofennian crystalline bedrock. In the Appendix 1 is presented the main FEPs listed according to their importance in biosphere, geosphere and geosphere-biosphere interface zone.

4 FEP ANALYSIS

4.1 Identification and description

The main geosphere-biosphere FEPs are categorized into external, internal and transport factors and further divided into sub-categories. The FEPs related not only to the biosphere are discussed in more detail in SKB process reports (SKB 2003, 2004, 2006) in Rasilainen (2004), Posiva's Evolution Report (Posiva 2006) and in the Posiva's Process Report (2007, in preparation).

4.1.1 External factors

Geomorphological processes and effects

A variety of processes of geosphere-biosphere origin have an impact on the future evolution of the process system relevant to radioactive waste disposal. Many of these are relevant primarily to the description of the geological environment and the potential effect on groundwater flow rates, release from near-field and contaminant transport pathways. However, certain processes may be responsible for landform change to the extent that they directly influence the characterization of the biosphere.

Particularly important at a coastal site, such as Olkiluoto, are those geological processes that may affect the position of the coastline. Sedimentation and erosion processes will occur on a spatial and temporal timescale. Coastal erosion may be significant for sites that are located close to the coast and therefore needs to be considered in developing an understanding of the future evolution of the site and its environment. The possibility of accelerated coastal erosion is considered in the context of sea-level raise (Posiva 2005, 2006, Lahdenperä et al. 2005).

Global climate change

The Quaternary period has been characterized by climate cycling on a global scale between glacial and interglacial periods. Such global changes are understood to be caused by long-term changes in the seasonal and latitudinal distribution of solar insolation, due to periodic variations in the Earth's orbit around the Sun (Milankovich 1920, 1930, 1941). The interaction between anthropogenic greenhouse gas emissions and other factors affecting global climate is not yet well enough understood; however, it is thought that global warming may delay the onset of next global ice age (Egan et al. 2001, IPCC 2001, BIOCLIM 2001, 2003, 2004, Posiva 2006). The principal effects of global climate change in the context of geosphere-biosphere for geological disposal are:

- Impact on local and regional climate characteristics
- Changes in eustatic sea level as a result of thermal expansion and contraction and growth and decay of ice sheets
- Impacts on surface hydrology

The effects of the local climate on the surface environment are direct. Many aspects of the natural and human environments in Finland are affected by seasonal variations in temperature and precipitation. For example, cold weather and freezing reduced surface

water flows while spring thaws can result in substantial runoff, which can hold or flush contaminants into surface waters. The most important effect on a repository is likely modification of the rate of surface water infiltration, which could influence the rate and composition of groundwater flow around the repository (Posiva 2005).

Glaciation

During the last million years, glaciations and warmer periods have followed each other. The length of glacial phases have been on average about 100 000 years and warmer interglacial phase have been an average 10 000 years (e.g. Forström 1999). Glaciation will bring massive changes to geosphere and biosphere. The most reliable evidence for the impact of glacial advances in Scandinavia is obtained from the most recent glaciations, especially the Weichselian (Korhola et al. 2000, Petit et al. 1999, Holmgren & Karlén 1998, Ehlers & Gibbard 2003).

Estimates of Fennoscandian ice sheet thickness during the last ice age range widely; few hundreds to thousands and over 2000 of meters (e.g. Koivisto 2004, Eronen & Olander 1990). This uncertainty is seen in difficulties to determine the basal temperatures of the ice sheet. Maximum ice thickness over Olkiluoto is estimated to have been about 2 km during the last glacial maximum (Lambeck et al. 1998).

The pressure of ice mass on the landscape will cause a wide-spread depression of the regional crystal plate. The weight of the ice sheet will change the stress fields around the glacier. In particular, advance or retreat of ice sheet may be accompanied by reactivation of faults and fractures, and the occurrence of earthquakes (e.g. Kotilainen & Hutri 2003).

The presence of ice sheets will change hydraulic heads directly, possibly imposing an additional head equivalent to the height of ice sheet. During and after the glaciation, surface topography will change, and new underground fractures might form or old fractures will open or close. Consequently groundwater flow paths may change. In addition, erosional processes associated with glacial movement and with glacial melt water beneath the ice mass and its margins, will change the topography. Due to large amounts of melt water and relatively rapid unloading of the crust, the impacts are likely to be most severe during a melting phase (SKB 2004).

The average recharge rate of groundwater during the glacial cycle will be obviously smaller than in the present interglacial phase. In the tundra and glacial climate, precipitation is estimated to be lower than today. Melting of glaciers simply releases the precipitation accumulated in them over the glacial period. During the glacial climax, there may be areas with a layer of free, pressurized water in the bottom of the glacier. The amount of water possibly infiltrating from the bottom of the glacier into the bedrock is estimated to be of the same order or less than the present infiltration rate (Ahlblom et al. 1991). In the melting phase there may be strong fluctuations in the flow of groundwater.

Besides the large amounts of melt water, also the gradients caused by the glacier and tilting of the Earth's crust, and the potential permafrost may play a significant role in the flow of groundwater. This kind of transient phase can be dealt with the "short-circuit" groundwater scenario, where the groundwater transit time from the repository into the biosphere is no more than one year. In the glacial melting phase, the consequences of an increased groundwater flow are compensated by the fact that the amount of surface

water diluting the releases is greatly increased. Melt waters also form large lakes in front of the glaciers. Furthermore, the sea level rises because the influence of the melt water is more significant at the beginning than the land uplift (e.g. Forström 1999).

Glacial melt waters are oxidizing, non-saline and have a low content of humic substances. Most of the oxygen is consumed in the surface layers of the bedrock and today only minor changes in bedrock chemistry can be directly/indirectly related to penetration of oxidizing melt waters of past glaciations deep into the bedrock (Brandberg et al. 1993, Pitkänen et al. 2004).

Glacial erosion

The main soil type at Olkiluoto, till is formed from bedrock, preglacial sediments and “in situ” weathered bedrock when the slowly flowing glacial ice dislodged, crushed and ground the mineral matter. The melt waters from glaciers and flowing waters have abraded, rounded and sorted the sediments during transport, and accumulated them in glaciofluvial deposits. The finest material is carried in suspension and, as the flow decreases, is deposited as silt and clay at the bottom of water basins.

A study by Pässe (2004) indicates that erosion of the bedrock in Scandinavia over an last ice age was approximately 1 m with a maximal erosion of 4 m. Erosion due to wind and water of the Canadian Shield has been estimated to be about 2 m/100 ka, whereas erosion associated with glaciation has been 20-35 m/100 ka (McMurry et al. 2003). Thus, erosion will not be a threat to the integrity of the repository, but will change the biosphere and the GBI-zone in the long-term.

Permafrost

Physical processes in cold but ice-free environment include the potential for large-scale water movements associated with seasonal thaws. Permafrost will restrict such movements to the surface environment, while potentially serving to isolate deep (possible contaminated) groundwater from the surface hydrological regime. Regional groundwater flow may become focused at localized unfrozen zones, under lakes, large rivers or at regions of groundwater discharge.

Continuous permafrost of over 500 m depth requires tens and even hundreds of thousands of years to develop. For deep continuous permafrost to develop in Finland, both mean annual precipitation and temperature would have to decrease considerably (Ahonen 2001, Hartikainen 2006). To be able to assess the depth and extent of permafrost development at the Olkiluoto area, we need to know (Cedercreutz 2004):

- If Olkiluoto will be under water, under ice or free of ice and water cover
- For how long the climate in question will last

The most reasonable scenario is that permafrost will indeed develop during the advance of ice sheets, but Olkiluoto will never be long enough without ice or water cover for permafrost to develop to repository depths. This conclusion is supported by the reports of Vallander & Erenius (1991) and SKB (2004). Hartikainen (2006) has made numerical modelling of the permafrost depths at Olkiluoto. The development of permafrost and perennially frozen subsurface are described more detailed in

consideration of vegetation cover or no vegetation cover in Cedercreutz (2004) and Posiva (2007, preparation).

The presence of permafrost would have important effects on the hydrogeological regime and could therefore be important in modifying the release and dispersion of radionuclides from a repository. Permafrost will also reduce the recharge of groundwater (McEwen & de Marsily 1991).

Shore-line migration: land uplift and changes in sea level

The one main important feature of a future climate-induced change will be a large landward and/or ocean-ward migration of the Fennoscandian shoreline. The relation between land uplift, eustatic sea level and the water balance of the Baltic Sea determine, whether the sea level is generally rising, maintaining stable or lowering the present coastlines (Johansson et al. 2001). More subtle changes include the present day tilting of large inland lakes and sea shorelines and the vertical and horizontal displacements of the Earth's crust with the associated changes in crustal stress (Lambeck & Purcell 2003).

In the past, the isostatic component has been greater than the eustatic component leaving large parts of Baltic Sea countries under sea level. After the last glaciation the Fennoscandian lithosphere is still undergoing postglacial rebound and the rebound still has about 20 000 years to run (Påsse 1996). At present the uplift rate is highest in the Bothnian Bay (Milne et al. 2001) where the ice sheet was thickest. The current uplift rate at Olkiluoto of about 6.8 mm/a can be considered constant for the next few centuries but will eventually slow down (Johansson et al. 2002, Kahma et al. 2001, Eronen et al. 1995). What is unclear is how long the uplift rate will be about constant and what will the boundary be (Ekman 1996). According to Löfman (1999) Olkiluoto will rise about 40 m during the next 10 000.

The shoreline models are based on empirical data and include no physical description of the land evolution processes (Påsse 1997) (Figure 2). Empirical data from which the course of glacio-isostatic uplift has been estimated is e.g. from investigations of lake tilting (e.g. Påsse 1990b, 1996b, 1998a).

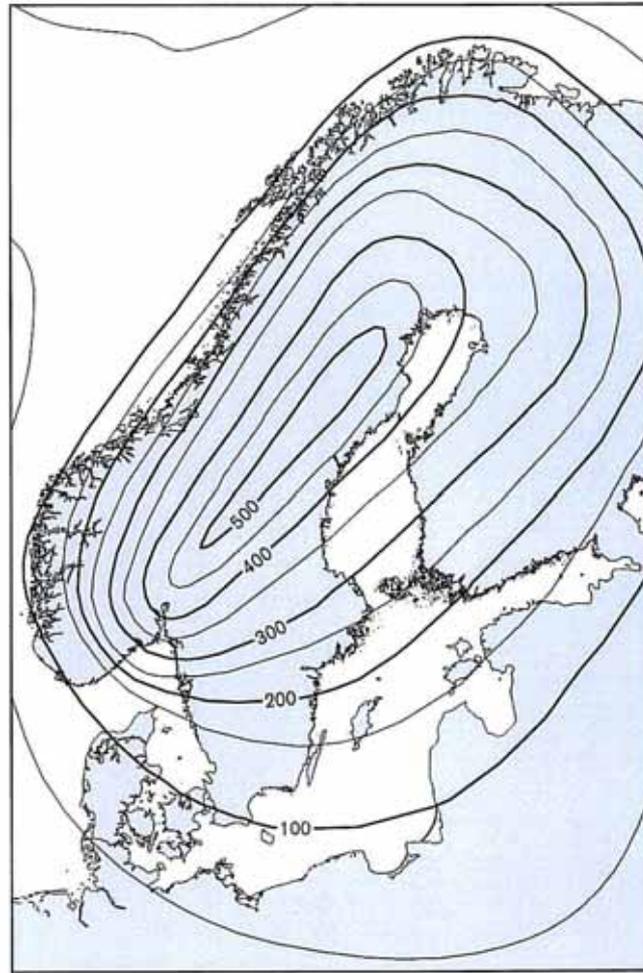


Figure 2. *Isobases for the uplift at 12 500 BP (Morén & Pässe 2001).*

Eronen et al. (1995) have studied the shore level changes of the Baltic Sea and the land uplift process in south-western Finland during the last 8 000 years time span. The empirical data obtained by studies on sediments in small lakes is consistent with the model by Pässe (1996). However, during the ice age continental environments existed to the east and to the south of a Scandinavian ice sheet and oceanic coast conditions prevailed to the west and to the north. These environmental differences make the modelling of shore level displacement in Fennoscandia quite a complex issue (Morén & Pässe 2001).

The ice thickness is of great importance for the amount of isostatic depression. However, the viscous flow mechanism also implies that the duration of the glacial load is very important for the depression. A thick ice existing during a short period may produce a small depression, while a thinner ice existing during a long period may produce a similar or even bigger depression (Morén & Pässe 2001).

Currently it is widely agreed that the Earth's climate is warming up and that the sea level is rising. The mean sea-level, which appears to have been steady for the last 3 000-4 000 years, has shown a linear rise of between 1 to 2 mm per year over the last 100 years (IPCC 2001, Johansson et al. 2001). According to ICCP (2001), global average sea level will rise 0.11-0.77 m in the next century. Factors taken into account in this

estimate were: thermal expansion (0.09-0.37 m), glaciers and ice caps, Greenland and Antarctic ice sheets, thawing of permafrost and the effects of sedimentation. A rise of the sea level could have strong impacts on the spatial development of coastal regions, e.g.:

- Lowland inundation and wetland displacement
- Shoreline erosion
- More severe storm-surge flooding
- Saltwater intrusion into estuaries and freshwater aquifers
- Altered tidal range in rivers and bays
- Changes in sedimentation patterns

According to the most radical scenario, the melting of the Greenland ice sheet would cause a sea level rise of 6 m in the next 1000 years. Antarctic temperatures are too low for the ice sheet to significantly melt; an increase in temperature 10-20 °C would be required, which is beyond all present climate-change scenarios (ICCP 2001). The maximum estimate of sea-level rise due to thermal expansion is 4 m. So, at most the sea level will rise 10 m in the course of the next 1000 years. This will put Olkiluoto 1 m above water (mean current elevation = 5 m, uplift rate = 6.8 mm/a) (Cedercreutz 2004). Most estimates suggest a much slower sea-level scenarios (slower than the land uplift at Olkiluoto), which implies a retreat of the shoreline (Ruosteenoja 2003)

Due to postglacial uplift and shallow coast areas sea bottom sediments are emerged from the sea continuously which increase primary succession along Olkiluoto shores. When comparing the situation at Olkiluoto thousand of years ago to the situation 500 years ago and further to the situation today, it can be seen that already the change in land area has been fast. According to Mäkiäho (2005) Olkiluoto will become a part of the Finnish continent during the next decades.

At Olkiluoto, the discharge areas are in today's conditions near the shoreline (Löfman 1999a, b). As the land rise proceeds discharge areas will move further away from the repository and, when the sea retreats, it comes more likely that discharge will take place in water basins separated from the sea or at dried-areas. At the same time, the previous discharge areas will be revealed from under the sea. It thus seems that in the long term, after some thousands of years, various freshwater, forest, peat land, agricultural and even industrial/urban environments will be represented among the possible discharge environments at Olkiluoto (Vieno & Nordman 1999, Vieno & Ikonen 2005).

It is assumed that lakes shallower than 2 m are transformed to mires after 1 000 years and the new lakes are continuously being formed at the coast (Posiva 2006). On the shallow shores of Olkiluoto, especially in geolittoral regions (between the mean and highest sea level), the amounts of common reed are increasing naturally, resulting in paludification of coves and accumulation of organic matter in shallow and nearly-stagnant water. Locally this results in a faster apparent shoreline displacement than mere land uplift or changes in sea-level would yield. In addition, eutrophication of Baltic Sea speeds up the process (Miettinen & Haapanen 2002).

Future human actions and effects

Human impact on the atmosphere has made our current climate significantly different from any past one, so that temperature decline at the end of the last interglacial cannot be taken as a direct analogue of near-future developments (Kukla et al. 2002). In the view of Loutre & Berger (2000), future climate predictions should take into account the inevitable increase in human induced greenhouse gases. They concluded that owing to the warming effect of greenhouse gases, a future glaciation will be delayed and probably be milder. The atmospheric concentration of CO₂ has increased by 31 % since 1750, with a rate of increase of about 1.5 ppm (0.4 %) per year over the past two decades. The concentration of methane (CH₄) in the atmosphere has increased by 151 % and that of nitrous oxide (N₂O) by 17 % since 1750. Also the concentrations of halocarbon gases and their substitute compounds have increased. The radiative forcing due to greenhouse gases, from 1750 to 2000, is estimated to 4.86 W/m², in total (IPCC 2001). Thus neither present nor near-future atmospheric conditions resemble those in the last ice age.

Aerosols include sulphates, nitrates, organics, soot, dust and fly ash. Some aerosol particles occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation and sea spray. About 10 % of aerosols derive from human activities, such as the burning of fossil fuels and alteration of natural surface cover. Aerosols are one of the least understood influences on global climate. It is unclear whether the net effect of aerosols is to warm or cool our planet (IPCC 2001), although the common opinion is the latter.

The near-waters of Olkiluoto are influenced by industry; there is a nuclear power plant and a harbour on the island, both having part of their navigable passages artificially deepened. In front of the cooling water outlet of the power plant, the currents are strong for some distance offshore (Posiva 2003). The effects of the cooling water intake and discharge are significant only in close vicinity of the intake and discharge sites. However, possible constructions and operation of the third nuclear reactor unit at Olkiluoto nuclear power plant could affect temperature and icing of the near sea as well as biological production and water quality (Ikonen et al. 2003a). In addition, there are number of other FEPs related to the future human actions, but their handling, however requires more detailed discussion than is the scope of this report (SKB 2004).

4.1.2 Internal factors

Topography and morphology

Topography defines surface water flows, the location of groundwater recharge and discharge locations, and the magnitude of hydraulic heads that drive local and regional groundwater flows. Features such as slope or depression affect the amounts of moisture and soil that are retained locally, which in turn influences plant and animal communities.

Regional and local changes can occur from processes such as lake infilling, river course meandering, river erosion, wind erosion, soil subsidence, landscape subsidence (possibly caused by the repository excavation), uplift (e.g. from previous ice ages) and construction of dams. Some such changes could affect temperature and local climate.

Important components of the topographical and morphological description of the biosphere system domain include those features that relate to the “margins” between major environmental features. In particular, a time-dependent description of the margins between land areas and surface waters is essential in long-term dynamics.

The average elevation of Olkiluoto is about +5 m above sea level. The highest points are around 12-17 m. The bedrock surface can vary locally rather much, but the ground surface is still quite even at places where the bedrock surface abruptly changes: the depressions of rock surface are filled with thicker layer of till and the outcrops stick through the modest soil layers. The overburden is mainly fine-textured sandy till. The thickness of the overburden is usually 2-4 meters, although even up to 12-16 meter thick layers have been observed (Posiva 2003). More detailed description is presented in the reports of Posiva (2003, 2005) and Lahdenperä et al. (2005).

Surface soils

Surface soils are considered to be those within a few meters of the surface. Typically the top around 0.3-0.5 m is the most active surface soil region which contains the bulk of soil flora and fauna, e.g. the plant roots. It is also the area which is most directly affected by external and internal factors (Kähkönen 1996).

In order to characterize adequately the geosphere-biosphere system, it is necessary to identify different soil horizons, with different characteristics, as well as possible variations over the spatial domain of the system. The extent to which such descriptions are required as a basis for assessment modelling will depend on the geosphere-biosphere interface and other basic assumptions regarding potential pathways of environmental contaminants. Contaminant mobility and transport in soils and their pore waters is dependent on various soil properties and contaminant redistribution can lead to a number of different exposure pathways (Egan et al. 2001). Another important property is the distance between the soil surface down to the ground water table which can vary from centimetres to meters and can change rapidly in response to surface water infiltration and runoff.

The soil types, till, sand, gravel, clay and organic matter can be roughly characterized by parameters such as particle size distribution, moisture, stoniness, organic matter content etc. These have different physical, chemical and biological characteristics (e.g. weathering and erosion rates, water percolation rates, pH, organic content and microbiological populations), different land management properties (e.g. irrigation and fertilization needs, crop yields) and different contaminant properties (e.g. sorption).

The properties of soils will evolve because of natural weathering processes that include hydration and dehydration, freeze-thaw cycles, dissolution and leaching, oxidation, acid hydrolysis and complexation. Podsol soil type, typical in Finland, tends to be acidic due to iron and aluminium oxides, and leaching of alkalis and alkaline earth metals from surface to deeper horizons (Kähkönen 1996). Soils also evolve because of erosion that could be driven by water and wind, and initially by land management practices. Important impacts are how these changes might affect local ecosystems and the net consequences to groundwater and radionuclide movement. The detailed results of the surface soils at Olkiluoto are presented in reports of Posiva (2003, 2005) and Lahdenperä et al. (2005).

Overburden

The intermediate zone is called as defined in this report, overburden, typically comprised of an unconsolidated mixture of rock and mineral particulates. Fine till soils as is the case at Olkiluoto, are quite heterogeneous in chemical, physical and mineralogical properties (Lahdenperä et al. 2005). The transition from surface soil to overburden and from overburden to bedrock and *vice versa*, are not abrupt. Similarly, a layer of unconsolidated rock mineral material may exist between sediments deposited at the bottom of underlying bedrock. Depending on the depositional history, overburden may include alternating layers with greater amounts of clay and organic matter.

The changes in overburden with time are driven by natural weathering processes. However, changes may also be driven by hydrothermal reactions with groundwater. Human activities such as excavation can affect the overburden. The overburden/sediment also has a potential to affect the groundwater flow field in the near-surface geosphere. The groundwater discharge from the repository passes in most cases through the overburden before entering the biosphere. Since radionuclides can be absorbed in the overburden, it affects the concentrations of radionuclides in the groundwater discharging into the biosphere. The detailed results of overburden at Olkiluoto are presented in reports of Posiva (2003, 2005) and Lahdenperä et al. (2005).

Aquatic sediments

Of all the geochemical boundaries, the sediment-water interface exert the greatest control on the cycling of many elements in shallow aquatic environments such as lakes, rivers, estuaries and coastal embayment and, to a lesser extent in the deep sea. Across this interface, the gradients in physical properties (i.e. density), in chemical conditions (i.e. pH, Eh, ligand concentrations), and biota abundance (i.e. fauna and flora living near the interface) are large, thus producing potentially variable diversity.

Aquatic sediments are generally composed of fine-grained sand, clays, gyttja and organic matter. "Mixed sediments" refers usually to relatively recent and often quite shallow deposits that are susceptible to resuspension. Mixed sediments are treated as part of the biosphere model, respectively. "Compacted sediments" refers to the underlying older and are usually thicker. They can affect the groundwater flow in the geosphere near a lake as well as radionuclide concentrations in the groundwater discharging into the lake from the repository. Suspended solids in the lakes are deposited into the mixed sediment compartment. In the nuclide transport calculations it is assumed that radionuclides in the groundwater discharging into the lake and sea are not sorbed by the mixed sediments.

It is customary to include the characterization of suspended solids within the description of the surface water bodies themselves. Relevant characteristics of surface water bodies therefore include their shape, hydrochemistry, flow characteristics, suspended solid composition, suspended solid load and sedimentation rate. Aquatic sediments related contaminant transport in sediments through sorption processes. Contaminant sorption onto suspended solids can remove contaminants from aqueous environment, but can also contribute to exposure routes involving contaminated sediments (Garisto et al. 2004). The detailed results of sea bed stratigraphy and sediments at Olkiluoto are presented in reports of Rantataro (2001, 2002) and Lahdenperä (2006).

Wetlands

Organic matter accumulates as peat in bogs through humification of moss, sedge and grass and as humus in soil and in bottom sediments in water basins. Owing to the cool climate of Finland, these remains accumulate more rapidly than decompose. The process, often called paludification, has continued throughout postglacial time and is enhanced by the silica-rich granitoid bedrock prevalent in Finland and by the general acidity of soils and waters (Koljonen 1992). The main factors affecting the peat formation are (SKB 2003):

- Climate; the precipitation and evapotranspiration are the major factors in peat forming, generally precipitation is greater than evapotranspiration
- Relief; peat formation is enhanced by glacial landscapes with low permeable thin soil layers, glacial-lake beds and kettle-hole topography, gently sloping topographies with blocked drainage.
- Geology; igneous silica-rich rocks generally have lower permeability and they are more acidic than sedimentary rocks
- Biota; peat forming vegetation, especially at coastal areas
- Time since glaciation or emersion out of sea

Most of the peat lands in western Finland are initiated on land uplift shores (Aario 1932, Brandt 1948, Huikari 1956). The uplift will also segregate bays, which will develop to lakes. Part of them are converted to peat lands filling-in and overgrown by mire vegetation. The primary mire formation and the overgrowth are the starting points of larger mire areas, which will reach their later scale by expanding over adjacent forests (Ikonen et al. 2005).

The general trend in the vegetation succession of the mires has been from minerotrophic sedge-dominated communities to ombrotrophic Sphagnum-dominated communities (Aartolahti 1965, Tolonen 1967, Elina 1985, Heikkilä et al. 2001). This can be found out in several bogs in the Satakunta region, e.g. the Häädetkeidas bog (initiated on land uplift shore about 9 100 BP) in Parkano, 80 km east from the sea coast and about 110 km northeast from the Olkiluoto site. When forecasting the coming vegetation types at the Olkiluoto Island the logical supposition is that at the moment prevailing types will be the prevalent ones also in the future, as also proposed in the regulatory guidance (STUK 2001).

Wetlands may be discharge areas for deep groundwaters. The passage of water through multiple layers of organic material may serve as a biochemical filter to concentrate heavy metals such as uranium and halides such as iodine (SKB 2004).

At Olkiluoto, the relative area of mires is less than on average in south-western Finland. About 10 % of the total area of the Olkiluoto Island has been drained and undrained mires cover 17 ha (Saramäki & Korhonen 2005). The detailed results of mires at Olkiluoto are presented in Ikonen (2003) and Lahdenperä et al. (2005).

Lakes

Lakes have numerous features in addition to lake type, such as catchment area, inflow, outflow, nutrient content, dissolved oxygen, pollutants, sedimentation and other chemical, physical and biological features. The change in level of a lake is controlled by the difference between the sources of inflow and outflow, compared to the total volume of the lake. The significant input sources are precipitation onto the lake, runoff carried by streams and channels, groundwater channels and aquifers and artificial sources. Output sources are evaporation from the lake, groundwater flows and any extraction of lake water by humans. Climate conditions have a greatly influence, e.g. in fluctuation. Most of the Finnish lakes are not very deep. Finland's lakes and coastal waters are so shallow because the rocks in this geologically stable region of Europe have been gradually evened out by erosion over millions of years, and during successive recent ice ages. Compartment model for the lake model is adopted without changes from & Bergstöm (2000) presented in Ekström & Broed (2006) (Figure 3).

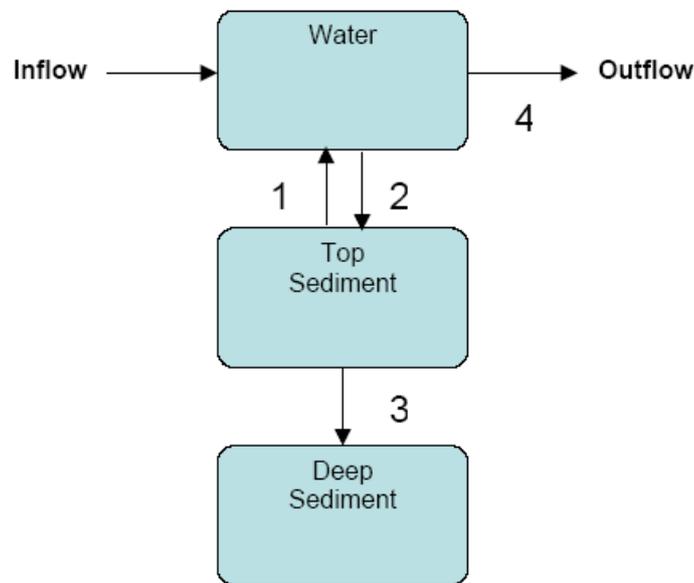


Figure 3. *Compartment model for the lake model (Ekström & Broed 2006).*

The model of Ekström & Broed (2006) describes the future ecosystem development at Olkiluoto on the basis of sea depth data and on the approximation that 2 000 years after present there will be a land uplift of 10 meters above the current depth and elevation values (Rautio et al. 2005). The succession of linked biosphere models was identified from maps of the terrain and will also involve lakes, rivers and coastal areas, as illustrated in Figure 4. From the depressions remaining under the sea level, locations of lakes can be estimated. Likely some of the lakes will be larger or smaller than the depression, but for testing the tools and modelling methods these estimates were judged to be adequate.

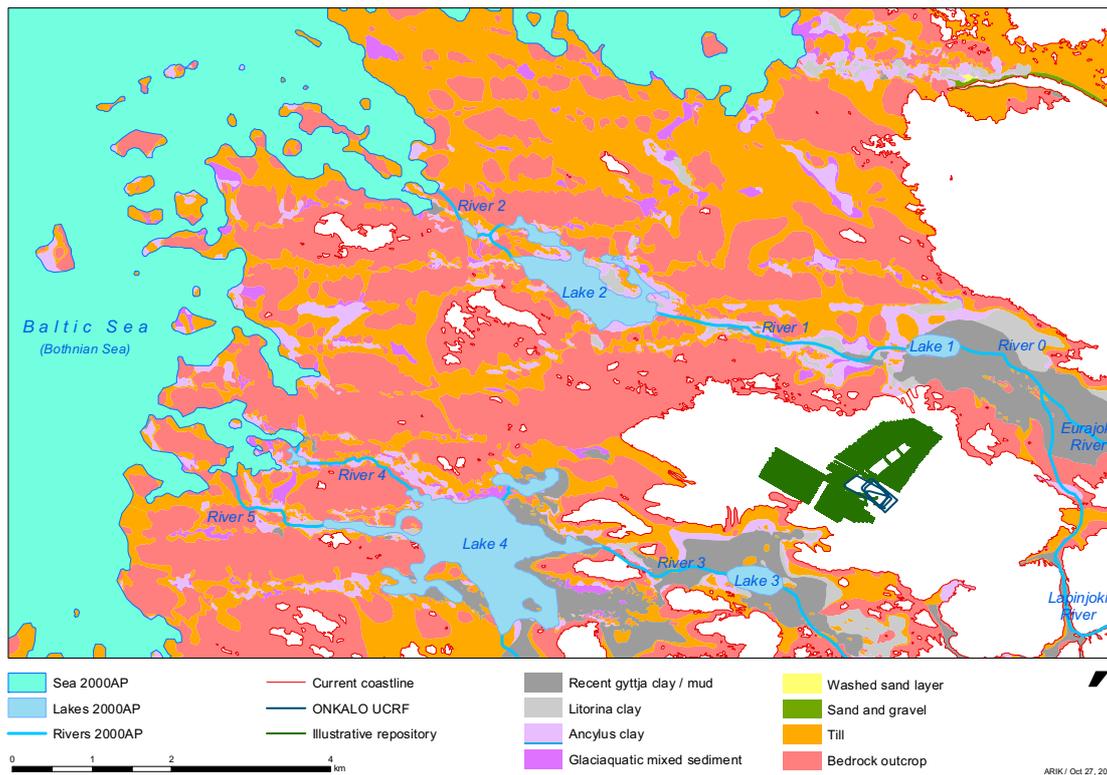


Figure 4. Surroundings of Olkiluoto at about 2000 AP (modified from Rautio et al. 2005 in Ekström & Broed 2006).

Rivers

The river conducts water by constantly flowing perpendicular to the elevation curve of its bed, causing meandering. The river ecosystem is formed by the interaction between river biota and their hydrogeochemical environment. It is characterised by a continuous transport of various substances from the soils of the drainage basin to the river and from there, downstream with the flowing water. Nutrients transported to the river are important especially to macrophytes and to some extent to fungi and bacteria. Compartment model for the river model is adopted without changes from Jonsson & Elert (2005) presented in Ekström & Broed (2006) (Figure 5).

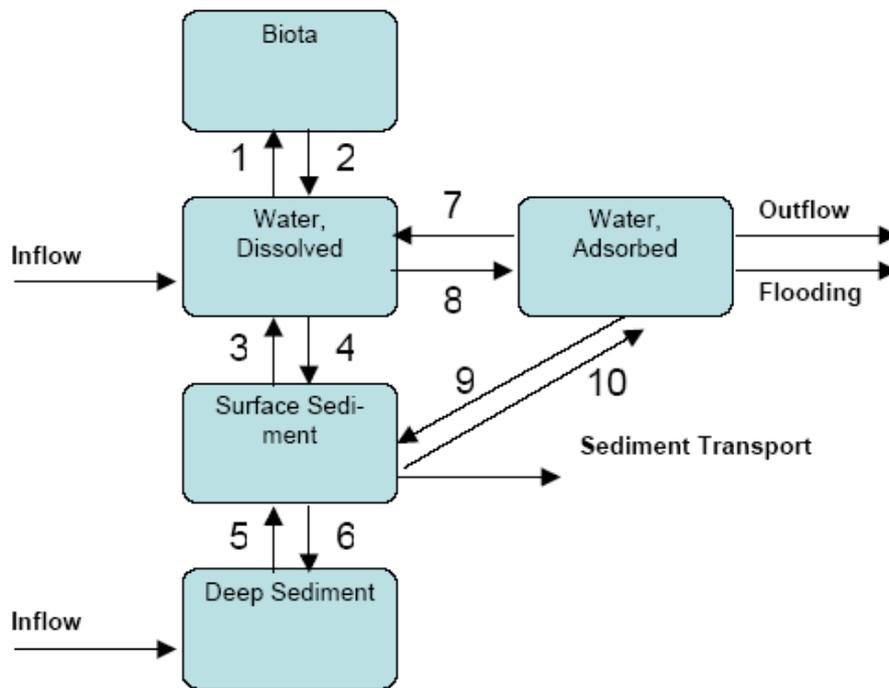


Figure 5. *Compartment model for the river model (Ekström & Broed 2006).*

The most significant forms of land use causing loading are agriculture, forestry and peat mining. As a result of different forms of land use in the drainage basin, various substances leach into the river, e.g. sediment, humic substances, certain metals (mainly iron and aluminium), nutrients (nitrogen and phosphorus) and locally also acidifying substances.

At the Olkiluoto area the quality and biological production of the water are affected by the loadings brought by the Eurajoki and Lapinjoki Rivers increasing the concentrations of solids and nutrients, especially at the river mouths. Irregular climatic variation also exerts a considerable influence on the nutrient economy and biological production of the area (Ikonen et al. 2003).

Springs and discharge zones

In springs and other discharge water table intersects the surface, allowing groundwaters to flow out onto surface as streams, wetlands and lakes. Discharge zones are often low-lying areas such as margins or bottoms of lakes and wetlands. Springs may also be found at various elevations depending on factors such as lithology and stratigraphy of the geosphere and the location of outcropping geological units. Discharge zones could be local or regional, in regional discharge results likely greater dispersion and needs longer travel times. Discharge zones can be affected by changes in the water table caused by local climate changes (e.g. seasonal rainy periods, climate swings with extremes in precipitation), human activities (e.g. diversion of surface water, pumping of groundwater from wells) or changes in topography (e.g. erosion of a new river channel).

Discharge locations for deep groundwater can also show measurable release rates of geosphere gases as radon and helium.

Climate changes can also bring about evolution of surface bodies and springs, such as flooding of land to create a lake or a new river bed. Springs can dry up, possibly as seasonal occurrence. Springs and discharge zones are required to explicitly link the geosphere to the biosphere. Groundwater discharges usually underlie a water body (wetland, lake, river), but can also underlie terrestrial areas (e.g. areas where the water table is below the surface and the land is suitable for agriculture).

At Olkiluoto the groundwater table follows the topography with a few exceptions. In the majority of the observation points the mean groundwater table is less than 2 m from the ground surface in the areas of elevation roughly between 3 and 10 m above sea level. If the groundwater table is so close to the surface, capillary raise is possible and the surface vegetation can use groundwater (Lahdenperä et al. 2005).

Coastal Features

Coastal features include headlands, bays, beaches, spits, cliffs and estuaries. The processes operating on these features e.g. along shore transport, may represent a significant mechanism for dilution or accumulation of materials, including radionuclides entering the system. Compartment model for the coast model is adopted without changes from Karlsson & Bergstöm (2000) presented in Ekström & Broed (2006) (Figure 6).

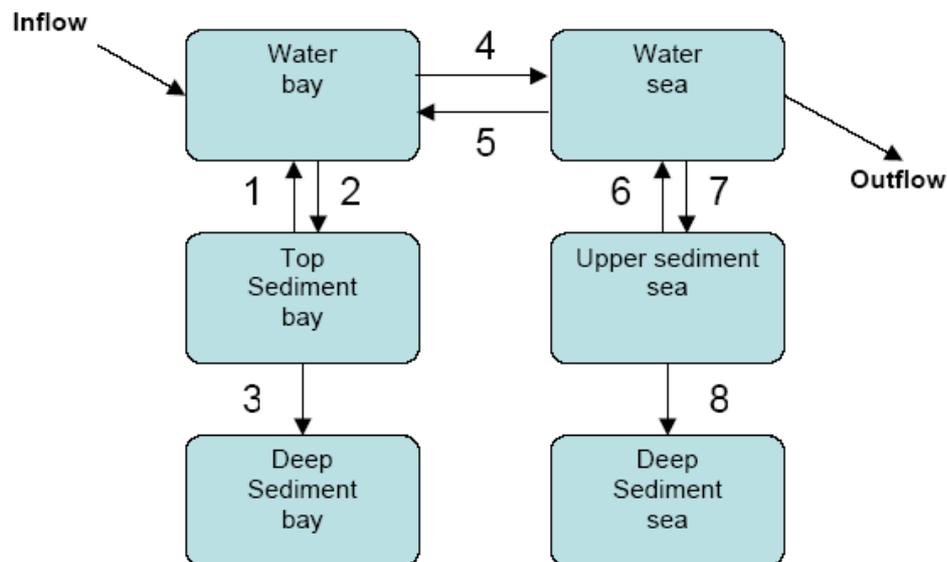


Figure 6. Compartment model for the coast model (Ekström & Broed 2006).

At Olkiluoto the shoreline migration has affected and will continue to affect subsurface conditions. For Olkiluoto the uplift rate is 6.8 mm/year (Kahma et al. 2001). Due to postglacial uplift and shallow coast areas of sea bottom sediments are emerged from the sea continuously. This in turn, makes primary succession along shores very fast. When comparing the situation at Olkiluoto thousand of years ago to the situation 500 years ago and further to the situation today, it can be seen that already the change in land area has been fast. Even though newly exposed shores are rapidly vegetated (wet land), succession can continue still for thousands of years (Rautio et al. 2004). The detailed results of the Olkiluoto offshore and coastal areas are presented in Rantataro (2001, 2002), Mäkiäho (2005), Lahdenperä (2006), Ikonen (2006), and Broed (2006 in preparation).

Marine features

In seas, features such as erosion, sedimentation, thermal stratification and salinity gradients may represent a significant mechanism for dilution or accumulation of materials, including radionuclides entering the system.

If radionuclides are released from the geosphere directly to the sea, individual dose rates will, at least in the short term, be significantly lower than via the well pathway (Bergström & Nordlinder 1991, Barrdahl 1996). The reasons for this are the effective dilution in the sea and the absence of drinking and other freshwater exposure pathways. This is illustrated by the seabio variant where the dose conversion factors of most nuclides are 1 000 times lower than in WELL-97 (Vieno & Nordman 1999). C-14, Se-79, Sn-126, Cs-135 and Cs-137, which have high enrichment factor in fish (Bergström & Nordlinder 1991), still have dose conversion factor 100 times lower than in WELL-97. It should, however, be noted that as a result of land rise the activity bound in sea sediments, may be later redistributed in the environment due to use of the former sea bottom (Vieno & Nordman 1999).

The geological history of the Baltic Sea history has been very diverse resulting in profound changes in the hydrographic conditions and subsequently also in chemical, physical and biological features of the sea and its catchment area. The future geosphere-biosphere states in the Baltic Sea are mostly determined by land uplift, sea level changes and future climate and climate related changes. Climate changes are caused by factors external to the climate system and by internal dynamics of climate system. In addition, to natural processes, human activities have been identified as potentially significant cause of climate alternations. Changes in climate and geological environment will have a significant effect on local and regional hydrological conditions, e.g. to groundwater flow, salinity, discharge and recharge areas as seen in the past. In the reports of Rantataro (2001, 2002), Mäkiäho (2006) and Lahdenperä (2006) are presented more detailed state of the Baltic Sea, and especially the Olkiluoto offshore.

Hydrogeochemistry

The characterisation, interpretation and understanding of groundwater geochemistry form an essential part of repository performance assessment and safety analysis of radioactive waste disposal. The performance of technical barriers and migration of possibly released radionuclides depend on chemical conditions. A prerequisite for understanding these factors is the ability to specify the water-rock interactions, which control chemical conditions in groundwater. The baseline hydrogeochemistry provides

the conditions for long-term geochemical stability, which is a requirement for safe long-term disposal of nuclear waste (Pitkänen et al. 2004).

The groundwater chemistry at Olkiluoto has been studied since 1990s. The interpretation of hydrogeochemical data indicates that mixing of end-member waters controls the wide salinity variation in groundwaters at Olkiluoto. Changes in past climate and geological environment have left distinct chemical and isotopic signatures, and caused great variability in the hydrogeochemical data. Water-rock interaction, such as carbon and sulphur cycling and silicate reactions, buffer the pH and redox conditions (Figure 7) (Pitkänen et al. 2004).

The more detailed description of groundwater chemistry, evolution and monitoring is described more detailed e.g. in the reports of Pitkänen et al. (1992, 1994, 1996, 199a, 2001, 2004) and Ahokas et al. (2005).

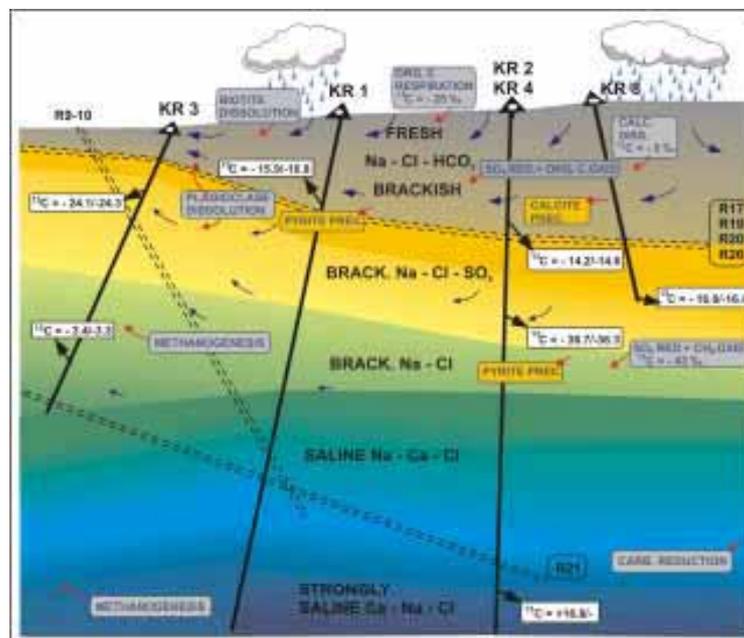


Figure 7. Illustrated west-east cross-section of hydrogeochemical and hydrogeological conditions in the bedrock of Olkiluoto based on interpretation of hydrogeochemistry. Changes in colour describe alteration in water type. Blue arrows represent flow directions. Rounded rectangles contain the main sources with estimated $\delta^{13}\text{C}$ data, and sinks affecting pH and redox conditions. Rectangles show measured/calculated $\delta^{13}\text{C}$ (DIC) of selected groundwater samples. Generalised fracture zones (coded by R) are combined on the basis of bedrock models by Vaittinen et al. (2001) and Saksa et al. (2002) (Pitkänen et al. 2004).

Terrestrial and aquatic fauna and flora

The identification and description of the characteristics of plants, animals and other organisms that are assumed to be present within the biosphere are critical elements of the overall system description. The overall food chain/food web structure, based on links between identified community components is also included in ecological community.

Vascular plants and trees can take up contaminants in soil via their roots or from airborne deposition onto their exposed surfaces. Surface vegetation, with large surface areas such as mosses and lichens, may be particularly sensitive to the deposition. The degree of uptake varies depending on factors that include the contaminant, soil, plant and the stage of the plant's growth cycle. Compartment model for the terrestrial/forest model is adopted without changes from Karlsson & Bergstöm (2000) presented in Ekström & Broed (2006) (Figure 8).

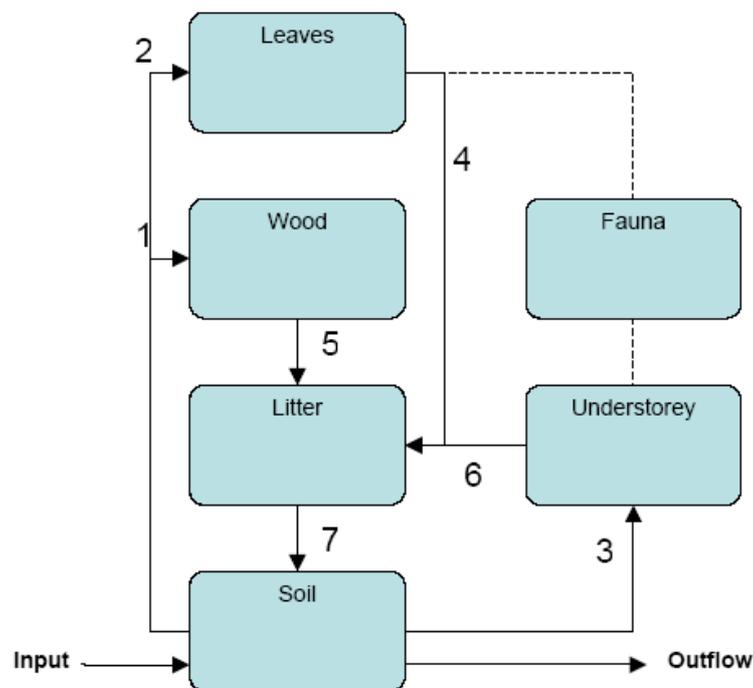


Figure 8. Compartment model for the terrestrial model (Ekström & Bored 2006).

The effects on vegetation should be considered with respect to possible changes to local conditions, such as moisture, groundwater flow, salinity and temperature. Vegetation will change with time, with consequent changes to their properties and their effects on contaminant transport and exposure routes. Local ecosystems will respond, often very quickly, in response to changes such as denudation caused by lumbering, the infilling of a lake and fluctuations in water tables in response to local climate variation.

Once in plants, contaminants can be passed into various food webs and lead to different exposure routes affecting humans and other biota. Contaminant accumulation in aquatic vegetation affects biota and the contaminant movement in surface waters.

One of the more important groups of animals is those that might serve as a source of food for local people. A large range of characteristics is possible and many could affect contaminant transport and exposure routes:

- Habitat can effect exposure routes, for instance burrowing animals may live extensively in contaminated soil
- Diet varies considerably between different animals
- Contaminants levels can increase when moving up to food chain (biomagnifications)
- Miscellaneous characteristics could be important

Animals can become exposed to radionuclides through the following pathways: soil ingestion, plant ingestion, water ingestion and external radiation exposure from, for example, ground and water contamination.

Potential relevant components of terrestrial and aquatic ecosystems include:

- Agricultural and native plants
- Domesticated and native animals
- Other organisms (fungi, algae, microbes)

For each of these, potentially relevant characteristics include:

- Net primary and secondary productivity
- Biomass/standing crop per unit area
- Cropping
- Population dynamics
- Vegetation canopy, root structure and nutrient absorption characteristics
- Animal diets and behavioral characteristics
- Chemical composition and chemical cycles
- Metabolism

The available data of flora and fauna is quite comprehensive, although the time span is not very long (e.g. Roivainen 2006, Oja & Oja 2006, Haapanen et al. 2006, in preparation, Huhta & Korpela 2006, Ranta et al. 2005, Saramäki & Korhonen 2005, Kinnunen & Oulasvirta 2004, Rautio et al. 2004, Miettinen & Haapanen 2002).

Microbiology

The analysis of microbiology is very important for proper understanding of the evolution of geochemical processes in and around the underground research facility ONKALO being constructed at Olkiluoto. Microbial populations in Finnish deep bedrock groundwaters have been studied since the late 1990s (Pitkänen et al. 2004, Rasilainen 2004, Pedersen 2006). There are several conclusions and hypotheses with respect to the microbiology that are of great importance for ONKALO and for the spent fuel repository. The following hypotheses have been drawn by Pedersen (2006):

- The transient between the shallow and deep biospheres occurs at a very shallow depth, typically within the first 15-25 m.
- The shallow biosphere is dominated by oxygen consuming micro-organisms that will block oxygen migration to deeper groundwater.
- The groundwater depression caused by construction of ONKALO will most probably move the borderline between the shallow and deep biosphere downwards.
- As the groundwater depression zone deepens, oxygen will intrude from above and microbial oxidation of ferrous iron and pyrite will occur with a concomitant decrease in pH and the deposition of ferric iron oxides in the aquifers. Later, when the repository is closed and the groundwater level is restored, those oxides will add to the radionuclide retention capacity of the rock.
- At present, a deep biosphere signature is found at relatively shallow depths in Olkiluoto compared to other sites investigated with the same methods (The SKB sites Forsmark, Oskarshamn and Äspö).

The subsurface biosphere on Earth appears to be far more expansive and metabolically and phylogenetically complex than previously thought. The main potential effects of micro organisms in the context of a KBS-3 type repository for spent fuel in the bedrock of Olkiluoto are (Pedersen 2006):

- Oxygen reduction and maintenance of anoxic and reduced conditions
- Bio-immobilisation and bio-mobilisation of radionuclides, and the effects from microbial metabolism on radionuclide mobility
- Sulphate reduction to sulphide and the potential for copper sulphide corrosion

Microbes, colloids and complexes

At Olkiluoto the samples has been studied by Haveman et al. (1998, 2000) including iron (IRB) and sulphur (SRB) reducing bacteria, heterotrophic and autotrophic acetogens and methanogens. Heterotrophic acetogens and methanogens (HA, HM) use organic carbon sources to produce acetate and methane, whereas their autotrophic responses (AA, AM) use inorganic carbon sources such as carbonate together with hydrogen. SRB and IRB metabolise simple organic compounds (e.g. acetate) in reducing sulphur and iron (Pitkänen et al. 2004). One very clear example of the importance of understanding the microbiological community structure is presented in Figure 9 illustrating the production of acetate from hydrogen and carbon dioxide by one group of microbes and the production of methane, sulphide or reduced iron by another group (SKB 2006).

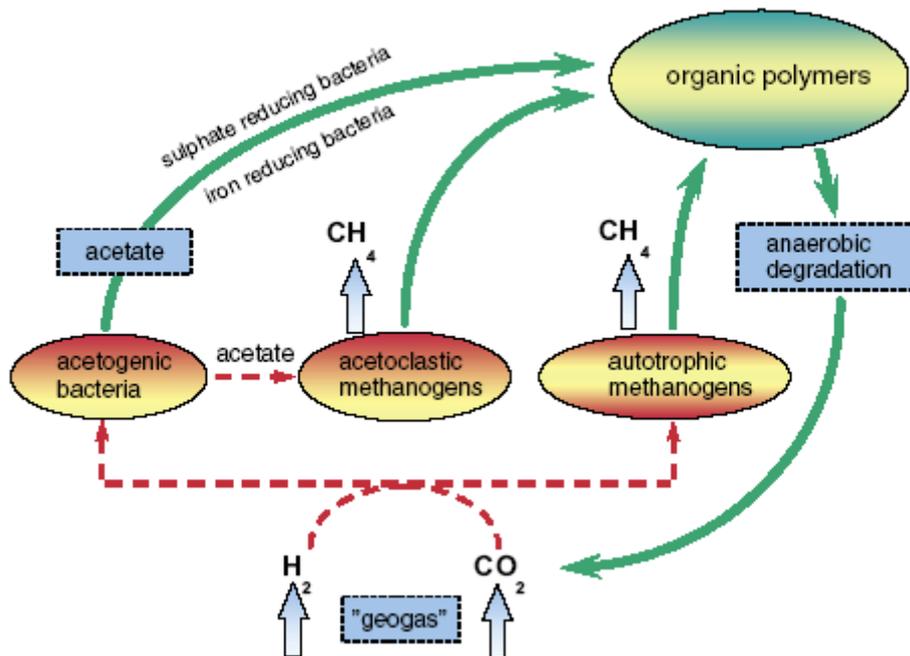


Figure 9. The deep hydrogen-driven biosphere model, illustrated by the carbon cycle. At repository depth, the geosphere temperature and water availability conditions are such that subterranean micro organisms are capable of performing a life cycle that is independent of sun-driven ecosystems. Hydrogen and carbon dioxide from the deep crust of Earth can be used as energy and carbon sources. Phosphorus is available in minerals such as apatite, and nitrogen for proteins, nucleic acids, and other compounds can be obtained by nitrogen fixation, as nitrogen gas is present at adequate concentrations in many groundwaters (SKB 2006).

The quite limited study of the microbiological content of Olkiluoto groundwaters has shown that sulphate reducing bacteria (SRB) are the most abundant species and tend to be particularly associated with groundwaters at an intermediate depth range (~ 250-330 m). The SRB levels and SO_4 concentrations appear to be unrelated, however. The deeper, saline groundwaters contain very low amounts of SRB and iron reducing bacteria (IRB). The population of SRB and IRB seems to be strong in the transition zone between SO_4 - rich and -poor groundwaters, where redox conditions change from sulphidic to methanic and both methane and dissolved sulphide contents increase. The transition zone may favour microbial activity. Several studies indicate that anaerobic bacterial consumption of CH_4 is active at a base of the SO_4 reduction zone (e.g. Niewöhner et al. 1998, Whiticar 1999). Above this zone in SO_4 -rich layer, reduction of SO_4 may be curtailed due to deficiency of organic nutrients developed in the system that is buffered by high concentrations of SO_4 .

Colloids do not sedimentate due to gravitation, but could be transported in the water and they may increase transport of radionuclides in the geosphere significantly only if sorption of radionuclides on colloids is irreversible and colloids themselves are stable and non-sorbing. In natural analogue studies, it has been observed that a significant fraction of uranium, thorium and rare Earth elements (REE) in groundwater may be

attached to colloids and, especially, to larger particles, which are not transported in the water like colloids (Chapman et al. 1991, Blomqvist et al. 2002). On the basis of isotope ratios in decay chains it has been concluded that sorption on colloids and particulate material is reversible. Colloids and particulate material seem to have a minor role in the transport of radionuclides from uranium and thorium ore bodies (Chapman et al. 1991).

Inorganic complex forming agents, e.g. carbonates, hydroxides and phosphates in the groundwater have been taken into account in estimating solubility and sorption coefficients of elements (Vuorinen & Leino-Forsman 1992, Olalla 1992a, Hexane & Hotter 1992). The most important organic complex forming agents are humic and fulvo acids, which are the end products from degradation of organic material. Only a small fraction of total organic carbon (TOC) content of the groundwater consists of humic and fulvo acids. Due to lack of thermodynamic data, organic complexes cannot usually be taken into account in estimating solubility's of radionuclides by means of geochemical models. However, natural analogue studies have shown that the deficiency is not very significant from the safety point of view.

Bacteria may also carry radionuclides in a similar way to colloids. However, the lifetime of bacteria is short, their concentration and sorption of radionuclides on them are typically lower than in the case of colloids. It can thus be concluded that bacteria do not have any significant effect on transport of radionuclides in the geosphere (Rasilainen 1991, 2004, 1992, Pedersen 2006).

Gases

In Finland, the highest gas concentrations have been encountered in saline groundwater in basic rock types. Results of the earlier hydrochemical research programmes at Olkiluoto have already indicated that saline groundwater contains massive amounts of dissolved gases (Pitkänen et al. 2004, Posiva 2003, Sherwood Lollar). The gas contains methane, hydrogen, nitrogen and helium and is considered to be of inorganic origin. The concentrations of gases are typically so low that they appear in dissolved form at the pressure prevailing at the disposal depth and are bubbled at more shallow depths (SKB 1991, 1992). CH₄ concentrations are huge, near saturation at 800 m depth (Gascoyne 2000, 2002). The latest comprehensive discussion about gases of SR-Can is discussed by SKB (2006).

Total dissolved gases show fairly a coherent increasing trend with depth indicating relatively good reliability of current gas sampling system (Pitkänen et al. 2004). Large variations are also observable in single samples reflecting, however, uncertainty in quantitative results. This is caused by variation in the contents of the main gas phases such as N₂, CH₄ and H₂ in parallel samples. Gascoyne (2002) has discussed the uncertainty question in detail and made suggestions of further development on gas sampling and measurement technologies. He considered that the main reason for uncertainty is due to the variable amount of water recovered during sampling.

The amount of dissolved gases deep in the bedrock of Olkiluoto are high compared with the results found at the other sites in Finland, for example, at Hästholmen, with similar elemental compositions, sampled with same equipment and corresponding depths (Pitkänen et al. 2001). Gas contents are about the same in SO₄-rich brackish groundwaters at Olkiluoto and Hästholmen but at greater depths, the contents at Olkiluoto are many times higher than at Hästholmen. The higher contents result primarily from large amounts of reactive gases, i.e. hydrocarbons and hydrogen.

Of the other atmospheric gases, O₂ shows a large scatter with depth (Figure 10a) indicating that its appearance is due to contamination from the atmosphere during sampling or sample treatment. Helium and N₂ have, instead, relatively coherent increasing trends with depth suggesting that they are relatively reliable data. Helium is considered to originate in the bedrock either by radioactive decay or crustal degassing and N₂ by crustal degassing (Pitkänen et al. 2004). Significant amounts of hydrocarbons (HC) and hydrogen are, in principle, unstable in the presence of O₂ (e.g. Whiticar 1990) particularly if suitable microbes exist (methanotrophes). This supports atmospheric contamination as an origin for O₂.

Significant amounts of hydrocarbons (HC) and hydrogen are, in principle, unstable in the presence of O₂ (e.g. Whiticar 1999) particularly if suitable microbes exist (ethanotrophes). This supports atmospheric contamination as an origin for O₂. Higher HC than CH₄ are summed together in Figure 10b and they mainly consist of ethane and propane (Pitkänen et al. 2004).

Hydrocarbons and hydrogen show generally increasing trends with depth, whereas CO₂ decreases. However, the trends of both methane and higher HC are bimodal in the upper 400 m. The decreasing trend belongs to brackish SO₄-rich groundwater samples in which the signature of Litorina seawater is strongest (Pitkänen et al. 2004). These trends correspond well with the concept that hydrocarbons and SO₄ are unstable in a common system due to bacterial reduction of SO₄ with anaerobic reduction of organics (e.g. Niewöhner et al. 1998, Whiticar 1990) and that the simultaneous presence of high contents of CH₄ and SO₄ indicates a mixing of different waters (Plummer et al. 1994). Carbon dioxide is a dissociation product of dissolved carbonate and H₂ is probably a crustal degassing product, but may also have been derived during methane polymerisation. The origin of hydrocarbons is much more complicated (Gascoyne 2000).

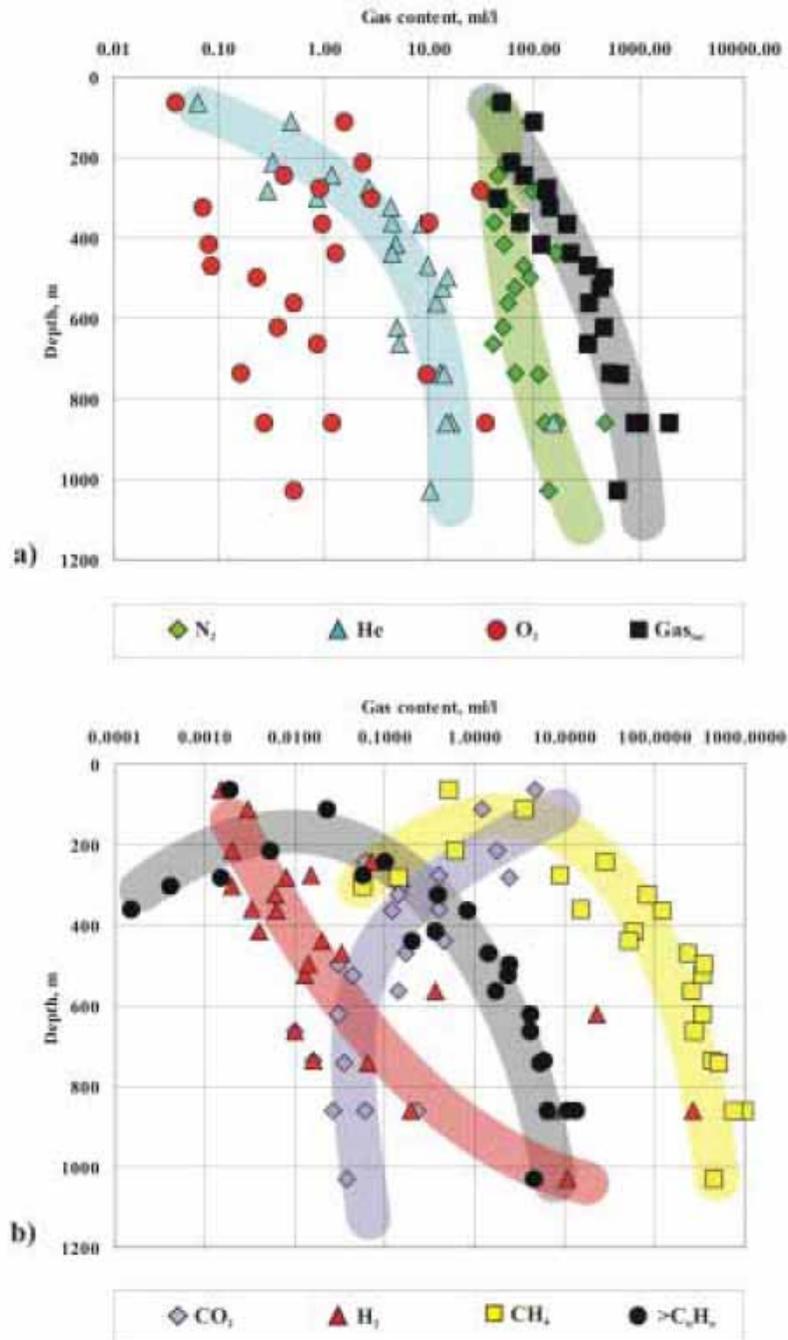


Figure 10. The content of dissolved gases (ml gas/l water at NTP) with depth in Olkiluoto groundwater samples (PAVE samples), a) total dissolved gases, N_2 , He and O_2 , and b) CO_2 , H_2 , CH_4 and higher hydrocarbons (C_nH_n). Indicative trend lines are represented by the coloured paths (Pitkänen et al. 2004)

Atmosphere

Relevant processes include physical transport of gases, aerosols and dust in the atmosphere and chemical and physical reactions. There are a variety of pathways through which contaminants released from a repository could become suspended as particulates or gases in the atmosphere:

- Processes affecting soils include degassing, wind erosion, ploughing, irrigation and saltation
- Processes affecting surface/sea waters include degassing, bubble bursting and wind suspension or aerosol formation
- Processes involving vegetation include forest fires and peat fires which can become potential agents for atmospheric contamination if the material is contaminated

Atmospheric deposition can lead to contamination of surfaces that are remote from the original source. The atmosphere also has a huge dilution potential. Wind is a major force in the transport of contaminants through the atmosphere, by processes of advection, dispersion and diffusion. Atmospheric processes include advection/dispersion, precipitation/rainfall, wet and dry deposition and contaminant transport as gases or as particulates (dust, aerosols). At Olkiluoto the metrological data is presented by Ikonen (2005, 2006) and Haapanen et al. (2006 in preparation).

Meteorology

Meteorology is characterized by precipitation, temperature, pressure and wind speed and direction. These factors can influence contaminant movement through biosphere and to some extent in soil overburden and upper bedrock. For instance, rain, snow, and other forms of precipitation may remove airborne contaminants and deposit them on various ground surfaces, including plants. They have a major influence on the behaviour and transport of contaminants in the environment through recharging of surface water bodies and leaching of soils. Daily and seasonal variations may have a wide influence. At Olkiluoto the metrological data is presented by Ikonen (2005, 2006) and Haapanen et al. (2006, in preparation).

4.1.3 Transport

Recycling processes mediated by living components of ecosystems include bulk movements of solids and liquids by flora and fauna, as well as metabolic processes of nutrients and other materials. Recycling processes mediated by non-living components of ecosystems include movements of solids, liquids and gases in the atmosphere, water bodies, soils and sediments.

Atmospheric transport

Various processes in the atmosphere contribute to transport within the biosphere system. These include:

- Evaporation
- Gas transport by convection and diffusion in the atmosphere
- Aerosol formation and transport
- Sea spray formation and transport
- Precipitation
- Washout and wet deposition
- Dry deposition
- Wind-driven erosion

Water-borne transport

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

- Infiltration of water into soil
- Surface run-off
- Percolation of water through soils and sediments under the influence of gravity
- Capillary rise
- Groundwater recharge and discharge
- Saturated zone groundwater transport
- Multiphase flow
- Advection and diffusion (water and suspended solids) in stream flow
- Advection and diffusion (water and suspended solids) by tidal and marine currents
- Erosion of solid materials by waters
- Aerosol generation by wave and wind action

Solid-phase transport

These are processes related to the exchange of solid materials within and between environmental media. Various processes may contribute to the movement of solid materials within terrestrial and aquatic environments. These include:

- Settling of suspended solids within water bodies
- Erosion and suspension of sea bed sediments by wave action and turbulence
- Coastal erosion
- Deposition of sediment during flooding
- Wind-driven aerosol material by rain splash
- Aerosol generation by fire
- Land slip

Transport via flora and fauna

These are transport pathways within the environment associated with biological processes and organisms. Potential relevant phenomena include:

- Root uptake of water and nutrients from soil solution
- Plant respiration
- Plant transpiration
- Translocation of materials within plants
- Consumption of soils, sediments and foods by animals
- Inhalation of aerosols by animals
- Metabolism of materials within animal body tissue
- Interception of rainfall, aerosol or suspended sediment by plants and animal surfaces
- Weathering and /or volatilization of materials from plant and animal surfaces
- Redistribution and mixing of soils or sediments by activities of plants or burrowing animals (bioturbation)
- Recycling associated with death and decay of organisms or parts of organisms

4.2 FEPs related to underground construction in GBIZ

Miller et al. (2002) have identified 54 processes, which could be induced in the sub-surface as a result of construction of an underground rock characterization facility. In this report the main geosphere-biosphere processes are classified into physical, hydrological, geochemical and biological processes according to their significance in GBIZ.

Physical processes

The excavation of the tunnel is to be accompanied by the drilling of a series of boreholes from the ground surface or lateral boreholes from the tunnel itself to provide sites for monitoring. These boreholes may provide potential radionuclide pathways to the surface, once the repository is operational, although they may be sealed or left open for monitoring purposes.

Uplift is caused by tectonic and glacial processes, the most significant of which is isostatic rebound in response to retreat of the last ice sheet. This slow, continuous process may lead, over time, to continuous changes in the stress field, groundwater chemistry, increased groundwater flow through the excavations, increased surface erosion rates and changes in geosphere and biosphere characteristics. The spatial scale is >100 m and countrywide, the temporal scale continuous. The rate of the process is slow and coupling with biological processes is potentially high.

Hydrogeological processes

As the tunnel is excavated, a number of hydrogeological processes will occur, largely caused by changes to the fracture network and the hydraulic head differentials. The distribution of hydraulic heads or groundwater pressure differences will evolve in response to the excavation of the tunnel and pumping of groundwater from the surrounding rock mass. These head changes will have an influence e.g. on the following issues:

- Water table drawdown, giving new water table positions or interfaces between different water bodies
- Groundwater mixing and composition
- Groundwater head gradients and flow directions
- Groundwater flow rates and fluxes
- Groundwater and solute residence times

The spatial scale is 10 to >100 m and the temporal scale for the processes is weeks to decades. The rate of the processes is fast and coupling with physical and geochemical processes is potentially strong.

The various groundwater bodies have different densities due to varying salinity and, less importantly temperature. Groundwater salinity generally increases with depth and may also vary laterally according to groundwater recharge and discharge zones, and past and present saline interfaces related to sea-level. The variation in groundwater density may cause different water bodies to flow, as denser waters move down the hydraulic gradient, displacing less dense waters. This could lead to groundwater mixing. These effects will be moderated by the time the repository is closed and a new equilibrium will be established, albeit in general, the site will experience transient evolution associated with post-glacial land uplift for a few thousands of years in the future. The spatial scale is 10 to >100 m and the temporal scale for the processes is years to decades. The rate of the processes is fast and coupling with physical and geochemical processes is potentially strong.

As Olkiluoto is a coastal site, it is probable that the saline water interfaces (or transition zone) exist at depth between water of marine origin and water of meteoric origin. It is possible that the saline water interface would migrate and become more diffuse in response to natural changes in the coastline due to isostatic uplift of the land surface. More significantly pumping of the tunnel is likely to induce flow of saline water towards the excavations, either as vertical upconing or lateral migration. This could induce mixing of saline and non-saline waters. The extent of upconing or migration will be dependent on the rate and duration of pumping, and the hydraulic characteristics of the rock. In extremes the saline water interface could migrate into the proposed repository near-field. The saline water interface may return to its original geometry after the repository is closed and pumping ceases.

The spatial scale is >100 m and the temporal scale for the process is continuous. The rate of the process is slow and coupling with physical and geochemical processes is high (e.g. Pitkänen et al. 2004, Löfman 2005).

At Olkiluoto the hydraulic conductivity of the rock mass decreases with depth from about 10^{-7} m/s in the upper 200 m to around 10^{-9} m/s below 650 m. The mean transmissivity of fractures is of the order of 10^{-7} m²/s. Below 500 m saline groundwater does not show any mixing with meteoric water. In the 400-700 m depth range the groundwater is saline and salinity increases with depth. It is dominated by Ca-Na-Cl and is chemically reducing. At depths shallower than 150 m, the chemistry is dominated by HCO₃ and the waters are largely anoxic. Between about 100-500 m, the waters are brackish, dominated by NaCl and SO₄. The age and salinity of the groundwaters increases with depth and the waters are greater than 10 000 years old where they become saline (Pitkänen et al. 1999a, b, Pitkänen et al. 2004).

Geochemical processes

Solids

The main focus is on possible changes to the characteristics of naturally occurring and introduced solid materials. Mineralogical and geochemical data on fracture-filling and fracture-coating phases can provide information on the radionuclide sorption properties of the rock, e.g. iron oxyhydroxides are particularly effective in sorbing actinides. Geochemical data on the fracture coatings will provide information on the redox buffering capacity of the rock in the near field. The spatial scale is <1 to 10 m and the temporal scale for is weeks to decades. The rate of the process is slow and coupling with physical, hydrogeological, geochemical (liquid) and biological processes is strong.

Liquids

The main focus is on possible changes to groundwater characteristics; pH, Eh, major elements, trace elements, including REE (Rare Earth Elements) and radionuclides, colloids, particulates and dissolved gases.

Groundwater mixing, e.g. due to upconing of the saline water interface, could cause significant changes in the composition of the groundwaters, e.g. mixing near-surface groundwater with deeper groundwaters could cause shift in carbonate equilibrium and affect calcite linings in fractures. Mixing could also change the major element composition of groundwaters, pH and Eh and it would potentially change the speciation of radionuclides. Humic and fulvic acids may be introduced by mixing of surface waters with deeper waters. These organic acids typically include a variety of different trace metals, and could complex with radionuclides to modify their migration properties.

Radionuclides, natural and man-made, will be redistributed in the groundwater system by mixing processes. The concentrations of H-3 and other fallout nuclides, C-14 and Cl-36 may be changed over years and decades. The redistribution of these nuclides will be important for resetting the baseline for any planned post-closure monitoring. These effects will be moderated by the time the repository is closed and a new equilibrium will be established. There would be no likely impact on radionuclide transport behaviour until before a canister has failed. The spatial scale is <1 to >100 m and the temporal scale is weeks to decades. The rate of the process is slow and coupling with hydrogeological, geochemical (liquid and gas) and biological processes is strong.

Gases

Both natural and introduced gases will exist around the tunnel. These gases may be dissolved in groundwater or be free as gas bubbles as a separate gas phase. Dissolved reactive gases such as oxygen, carbon dioxide, hydrogen, methane and other hydrocarbon gases can influence the redox state of groundwater. This could in turn affect sorption and redox buffering capacities of the geosphere.

Biological processes

Microbiology

A number of important microbiological population groups e.g. sulphate reducing bacteria will occur in the subsurface naturally or may be introduced during tunnel excavation. Generally, microbiological processes have spatial scales of meters but if fracture systems are connected to flowing fractures further away from the site, the distance scale may extend.

The tunnel construction operations would cause perturbations to the sub-surface microbiological populations. It is likely, however that different microbiological populations than those induced by tunnel construction would develop in the subsurface after the repository has been closed for some time. The spatial scale is <1 to 10 m and the temporal scale is days, weeks to decades. The rate of the process is fast and coupling with physical, hydrogeological and geochemical processes is strong. The changes in microbiological activities would be caused principally by:

- Temperature changes
- Hydrochemistry changes, especially Eh and pH
- Nutrients (mainly C, H, N, O, S, P) and energy supply changes
- Groundwater changes

Macrobiology

The macrobiology (flora and fauna) will be affected by the tunnelling operations, and populations can be expected to be perturbed. Coupling with physical, hydrogeological and geochemical processes is weak. The main processes are:

- Macrobiological colonization of the access tunnel
- Floral colonization of the access tunnel
- Faunal colonization of the access tunnel
- Modification of the surface ecosystem (e.g. root zones in the soil surrounding the tunnel)

4.2.1 Level of understanding of key processes

The TILA-99 assessment involved a defective canister scenario which pessimistically assumed that non-sorbing and weakly sorbing nuclides would remove from the repository almost immediately. However, the current far-field models take a more realistic approach, assuming that radionuclides will initially move through fractures into

the geosphere and subsequently to surface at distance from repository (Miller et al. 2002). Land rise is taken into account in assessments, which may result in both terrestrial and aquatic systems potentially receiving releases from the repository. Due to uncertainty in locations of major fracture zones could be incorrect and actual discharge areas could be quite different from those initially predicted. A number of discharge points could occur from the repository and therefore multiple discharge areas need to consider.

Most of the variability associated with future events in the GBIZ is driven by climate change. However, the transfer of radionuclides across the geosphere-biosphere interface is usually complex, involving numerous interlinked physical, chemical and biological processes that often occur in cyclical or episodic ways. Generally, such processes would lead to dilution of the radionuclide concentration in the groundwater, though the degree of dilution may vary from site to site and according to the upper extent of the region covered within geosphere model. On the other hand, in certain circumstances, some of these processes have potential to concentrate radionuclides at or near the surface. Changes in the system conditions may remobilize such accumulations and thus might cause larger exposures of people than would otherwise be projected.

The transport of radionuclides in the geosphere-biosphere interface can be considered in local (lake with its catchment area), regional (e.g. the Baltic Sea) and in global (ocean) scale. An estimation of the spatial scales over which significance processes may occur suggest, that in most cases, they would be limited to the < 1 (local) to tens or hundreds of meters (site) range. Many, particularly geochemical and biological processes, are likely to be restricted to zone adjacent to the tunnel walls only a few 10s of centimetres thick due to a very low hydraulic conductivity of the rock mass. Some physical and hydrogeological processes may, however impact on a larger volume, up to 100 m from the tunnel in response to changes in a stress field and pumping of groundwater (Miller et al. 2002).

An estimation of the temporal scales over which these high significant processes may occur suggest that, in many cases, they would remain limited to the weeks to decades range (i.e. effectively for as long as the tunnel remains open). This is, particularly for the hydrogeological, geochemical and biological processes, because these systems will be perturbed by the presence of the tunnel (Miller et al.2002).

The biosphere is more dynamic and changing than other components of the disposal system, such as geosphere, and thus the evolution of the biosphere with time could significantly affect dose predictions to humans and the natural environment. The principal variability in the biosphere is driven by climatic change. The biosphere is a diverse system under continuous development and impossible to model accurately. Thus some inherent uncertainty already in the conceptual level of modelling has to be accepted. In addition of needs to handle spatial and temporal variations, radionuclide transport models in biosphere are complex, non-linear, and include a number of input parameters that are usually time-dependent, associated with large uncertainties and often correlated to each other (BIOPROTA 2005).

In order to assess future human activities, such as probability of different land-use types and location of drilled wells, description of past evolution and history of the site are also needed (Ikonen et al. 2004). The focus of the geosphere-biosphere descriptions is on potential discharge locations. Spatial and temporal distribution of potential discharge locations as well as dilution during geosphere transport should be assessed on the basis

of groundwater flow analyses. There are a number of possible pathways and several transport mechanisms with importance to the transfer rate of solute elements at the GBIZ as well as the spatial distribution of exchange rates (e.g. Wörman 2003):

- ***Diagenetic processes*** in bottom sediments of oceans, lakes and streams govern the retention of soluble elements that pass through sediments in streams and lakes draining the catchment area in which the repository is placed. The water saturated parts of the quaternary deposits host many biotic processes with relevance for accumulation of solute elements as well as for the pathway selection in ecosystems. Diagenetic processes in lake or sea sediments are normally classified in terms of deposition of suspended solids, re-suspension, erosion, bioturbation and mineralisation (Berner 1980). There are also several chemical reactions that are depth dependent due to the fact that there are gradients in oxygen (redox-potential) and organic content. The increasing oxygen content towards the water–sediment interface leads to a higher mobility of radionuclides towards the interface, whereas this variation is counteracted by the higher organic content in surficial sediments. The corresponding processes also exist in other drainage systems, e.g. mires and lakes (Salomon & Fröstner 1984).
- ***Hydrological/hydraulic interactions*** between surface waters and groundwater in catchments arise due to the spatial variation in hydraulic potential on different scales. In lakes the recharge or discharge areas are governed by regional flow patterns and redistribution of contaminated sediments can occur due to erosion and deposition patterns.

In streams, the exchange of solute from the surface water to the sub-surface can occur in a meandering river that has different flow directions in relation to the direction of the groundwater flow (Wroblickly 1995) and in streams with spatially varying slopes (Harvey & Bencala 1993). Superimposed on these exchange patterns comes the exchange caused by the regional topography of the watershed with hills and valleys. All together, the exchange pattern can be complicated and it is furthermore complicated by heterogeneities of the hydraulic conductivity of the quaternary deposits and underlying bedrock.

- ***Regional hydrological systems*** with special retention characteristics like wetlands and lakes can significantly prolong the export of solute elements from land to the sea. Indirectly, this retention has implication to the solute exposure to terrestrial and limnological ecosystems. Retention characteristics and residence times of wetlands and lakes are important for overall residence times of radionuclides in the GBIZ.
- ***Root systems of trees and plants*** can mediate the transport of water and solute elements from the ground to the surface. Even if the dominating transport of water at the GBIZ is probably due to infiltration and discharge (hydraulic potential), pathways directly to the biota may have a special importance to dose assessments.

- **Human activities** like groundwater management and mining could potentially have a severe implication to the exchange processes at the GBIZ. Tunnel constructions affect the groundwater movements in large areas and could function as drains even for regional areas.
- **Global changes** cause time variable conditions that potentially could be very important for the risk perspective. For instance, with time it is very likely that former sea sediments form part of the continents or *vice versa* due to land rise or sea level changes.

4.2.2 FEPs of less significant to GBIZ within the biosphere timeframe

Deformation, elastic, plastic or brittle

A fault is a large discontinuity or fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other. Fractures may be caused by compressional or tensional forces in the Earth's crust (Garisto et al. 2004).

Over the next million years, the most significant force is that due to glaciation and deglaciation. The basement rocks of Olkiluoto have gone through five phases of plastic deformation. Those to the SE are more deformed than those to the NW of the area. Later deformation was more brittle, producing a number of minor faults. Large brittle deformation zones trend mostly NW-SE and NE-SW throughout the area. Generally, fractures are about 2 m in size, 90 % of them are less than 5 m long with apertures of less than 1 mm. Common fracture filling minerals include calcite, pyrite, pyrrhotite, kaolinite, illite, vermiculite and montmorillonite and none is in strict equilibrium with the groundwater. Based on observations of existing fractures, it is expected that glacial-related deformations will cause movements along existing fractures, rather than creation of new fractures (e.g. Kotilainen & Hutri 2003). These effects are considered unlikely for the repository.

Earthquakes

The Finnish bedrock belongs to one of the least seismic areas on the globe today. The main cause of small earthquakes is believed to be the push from North Atlantic Ridge resulting in NW-SE horizontal stress (Kaakkuri 1991). In the Fennoscandian shield, the most important deformation mechanism of the Earth's crust is continuous slow aseismic sliding (Slunga 1990, Saari 1992). Vertical deformations are caused mainly by postglacial land uplift and horizontal deformations by the plate-tectonic push. Movements take place in the fault zones (Chen 1991, Vuori 1991).

Studies of the previous glaciation of Fennoscandia suggest that the majority of seismic activity related to ice unloading occurred immediately after the deglaciation, approximately 10 000 to 8 000 years BP (Saari 2000). The seismic activity related to post-glacial faulting appears to have occurred preferentially along old faults or fault zones, rather than as new crustal ruptures. Field studies of some of these faults suggest that earthquakes as large as 5.3 to 7.5 may have occurred (Kuivamäki et al. 1998).

In the melting phase of the glaciers, land uplift was quite rapid and involved vertical displacements of bedrock blocks. In Finnish and Swedish Lapland, there are several

displacement zones, which has been dated to the last deglaciation phase. Postglacial displacements seem to have taken place in the old fracture zones of the bedrock (Lagerbäck & Witschard 1983, Vuorela 1990).

After glaciation/deglaciation the land uplift would be 10 to 100 times faster than at present and stronger earthquakes than nowadays could exist (Vieno et al. 1985). In Finland occurs 10 to 20 earthquakes/year with the magnitude from 1 to 3.5 in the Richter scale (Institute of Seismology 2005). Small earthquakes or seismic deformations of the bedrock do not affect the long-term safety of the GBIZ. Large displacements caused by postglacial land uplift or plate-tectonic forces are most likely to take place in old regional fracture zones, which are taken into consideration in locating of the repository.

The geosphere might be affected by the growth of existing faults or the creation of the new ones, with consequent changes in groundwater flows and possibly groundwater composition. Potential effects on the biosphere include liquefaction of soil, formation of new discharge areas, and alteration of river courses and destruction of dams. Observations have shown that the effect and magnitude of seismic events are greater at the surface than underground.

Saari (2000) outlines uncertainties concerning estimation of future seismicity:

- The estimates of the maximum magnitude could be lower if it is assumed that about 80% of the seismic block movements will occur in the short period of time immediately following the ice retreat; and
- The estimates of the maximum magnitude could be higher if the crustal rebound is much higher than currently envisioned.

The other two concerns have opposite impacts, but it is unknown if they compensate or if one dominates. The crustal rebound uncertainty is more critical as it is not conservative. A final issue relating to post-glacial earthquakes is that they should not occur homogeneously in time over the entire 100 000 year period (La Pointe & Hermansson 2002).

4.2.3 FEPs irrelevant to GBIZ within the biosphere timeframe

Orogeny

Tectonic structure and orogeny give rise to large scale processes such as continental drift, orogeny, crustal deformation, faulting, folding and subduction. They typically occur over periods of hundreds of millions of years (Paulamäki & Kuivamäki 2006, Garisto et al. 2004).

The Finnish bedrock is part of the Baltic Shield, which was formed, folded and metamorphosed mainly during two Eons; the Archean (> 2 500 million years ago) and Proterozoic (1 800-2 300 million years ago) during the Svecokarelian orogeny. During the last 300 million years, there have been no intense geological processes accompanied by magmatic activities or large-scale movements in the bedrock. Neither any orogenic process is currently proceeding in the immediate vicinity of the Baltic Shield. Hence, the probability of strong infracrustal geological processes occurring within the next

hundreds or thousands of years is minimal or unlikely in Finland (Nurmi et al. 1985, Salmi 1981).

Volcanism

Concerning the volcanism, the Finnish bedrock is one of the most stable regions on the Earth (Niini et al. 1982, Kuivamäki & Vuorela 1985). The last magmatic processes have occurred more than 350 million years ago in the North-eastern Lapland (Kuivamäki & Vuorela 1985). Volcanism and other magnetic processes are considered improbable.

Meteorite

Wuschke et al. (1995) found the radiological risk from meteor impact scenario to be small, largely because the probability of a meteor impact of sufficient magnitude to affect the repository is low; at longer times, the cumulative probability of an impact increases.

Conversely, it can be considered the consequences of a “likely” meteor. Specifically, meteors with a one-in-a-million per year chance of directly hitting the repository would be about 0.1-1 m diameter. Such meteors hit the Earth as a whole about 100 times per year. Although most such meteors would break up on their way the atmosphere, if a 1 m diameter meteor would hit ground intact it could create a crater up to 20 m diameter and 4 m deep. This would have no effect on the repository, but would of course alter the biosphere drastically, but due to low probability, conservative risk indicator is assumed. According to calculations of Geological Survey of Finland, the probability that the meteorite could crash to the repository is $4.6 \times 10^{-11} \text{ a}^{-1}$ (Kukkonen 1982).

Warm climate effects (tropical and desert)

If the regional climate becomes tropical, then the region may experience extreme weather patterns (e.g. monsoons, hurricanes) that could result in flooding, storm surges and high winds with implications on erosion. The high temperatures and humidity associated with tropical climates result in rapid biological degradation and soils will become generally thick.

In more arid regions total rainfall, erosion and recharge may be dominated by infrequent storm events. Desertification as a result of extended drought could lead to deforestation and loss of grassland. Dust storms might become a common feature causing soil erosion and alkali flats might form causing the accumulation of flats and contamination of soil surface. A lowered water table would affect natural biota, and might also lead to the use of deep water-supply wells to support local agriculture. These changes may also be associated with rapid alteration of topography associated with enhanced effect on erosion (Garisto et al. 2004). The development of tropical/warm-desert conditions in Finland is unlikely over millions year time frame of interest.

Mining

Mining and other underground activities might have occurred before construction and operation of the repository and their existence has been forgotten or their location unknown. These activities might also have taken place after construction and operation of the repository after the presence of the repository or the existence of its potential hazard has been forgotten. It is also possible, but very unlikely that mining activities

could take place during construction and operation of the repository for reasons unrelated to repository activities (Garisto et al. 2004). The Olkiluoto site is located in an area of common rock types and has low ore and mineral potentials according to present knowledge.

Drilling activities (human intrusion)

Boreholes may have been drilled before construction of the repository and their existence forgotten or their location unknown. Other boreholes might also be drilled after the presence of the repository or the existence of its potential hazards has been forgotten.

Potential impacts include direct exposure to excavated waste or contaminated water and rock, and creation of altered groundwater and contaminant transport pathways between the repository and surface environment. In addition, these activities could affect the characteristics of the critical groups; for instance, the most exposed individuals might be a drilling crew (Garisto et al. 2004). The human intrusion issues, as sabotage and archaeological investigations are treated as “what if cases” in the radionuclide transport report of the Posiva’s Safety Case (Vieno & Ikonen 2005).

Species evolution

Species evolution means the possibility of biological evolution or genetic manipulation of humans, microbial, animal and plant species, and related consequences. Over the time scales considered in some repository safety assessments, natural evolution of plants and animal species is possible. Forced evolution of plant and animal species by selective breeding and genetic manipulation, especially species used for human foods, has occurred over very recent time scales and presumably will continue. Evolution may affect anatomical features and physiological processes. The rate of evolution varies for a given organism, depending on the rate of changes in the environment. It also varies between organisms and it can be very rapid in bacteria and microbes which have short generation times. The potential negative implications of such evolution on the repository are threefold:

- New species causing unexpected degradation of engineering barrier materials
- New species resulting from repository causing human harm
- New surface species having unexpected sensitivity or interaction with released contaminants resulting in greater human exposure

Biological evolution, whether driven by natural random genetic variation and selection or by deliberate future human actions, is not predictable in any quantitative manner. It is also likely that microbiological evolution (which is much faster and therefore more important to consider than animal evolution) will not lead to significant new exposure or risk pathways (Garisto et al. 2004).

Miscellaneous FEPs

The unusual events or processes that have been identified as miscellaneous and do not clearly belong to any above mentioned categories are (Garisto et al. 2004):

- Earth tides, or the movement of surface and groundwater caused by attraction to the moon – no significant effect
- Telluric currents, or the movement of electrical charges deep below the earth's surface - no significant effect
- Intrusion of animals to the repository on the basis of current understanding - low probability
- Reversal of the Earth's magnetic poles (every 500 000 years) with effects on the ionosphere – no significant effect
- Changes in solar flux (possibly dropping by 10 % over the next billion years) – low probability – no significant effect

4.3 Level of available site data on key processes

Site investigations and monitoring for the disposal of spent fuel at Olkiluoto started in 1987 and over the years extensive geological, geophysical, rock mechanics, hydrogeological, hydrogeochemical, geochemical, radiological, meteorological and biological investigations and different monitoring programmes have been carried out (Ikonen 2006, Haapanen et al.2006, in preparation, Posiva 2006, Posiva 2005, Posiva 2003a). The source data, assumptions and the models which are used to describe processes and interactions in safety analyses are mainly based on extensive theoretical, experimental and empirical information. However, it can not be assumed that the knowledge of nature and functioning overall system is fully complete (e.g. Posiva 2003a, Posiva 2005).

The features, events and processes of GBIZ have been identified and audited and the outcome of the exercise was that most of them need to be taken into consideration when the expected evolution of the disposal system is evaluated. The selected FEPs in the GBIZ have been divided into groups and furthermore in the sub-divided different categories. The most important external driving forces are climate evolution, land uplift, sea level changes, circulation of groundwater, and effects of permafrost and glaciation/interglacial stages. The most important internal/domain driving forces are topography, surface soil, overburden, aquatic ecosystems, ecological communities. The transportation processes include natural cycling and distribution, atmospheric, water and solid-phase transport, transport mediated through fauna and flora. Some human actions are also taken into consideration.

FEP database and formal scenario development methodologies often tend to deal with matters on fairly theoretical level without giving much practical guidance for the modelling of release and transport of radionuclides. The completeness and robustness of performance assessments can be assessed only by considering the analysed scenarios, assumptions, models and data together (Vieno & Nordman 1999, Posiva 2005). The international, SKB's and Posiva's exercises have provided a broad and deep background of features, events and processes. However, at the current stage, there are uncertainties related to and inconsistencies between the different models. Reasons for the inconsistencies include e.g. varying modelling approaches and different assumptions made during modelling.

Treating all types of data and the interpretations of the different observations in a similar and unbiased manner enhances confidence. A protocol has been developed for checking the use of data sources (Posiva 2005, 2006):

- The data that have been used
- The available data that has not been used and the reason for their omission (e.g. not relevant, poor quality, lack of time, etc.)
- If applicable – what would have been the impact of considering the unused data?
- How is the accuracy of data established for the different data types?
- Listing data (types) where accuracy is judged to be low – and determine whether their accuracy is quantifiable
- If biased data are being produced, can these be correct for bias?

5 REVIEW OF POSIVA SAFETY CASE FOR TREATMENT OF GBIZ

5.1 Interfaces of far-field and biosphere modelling domains

Biosphere assessment models are routinely decoupled, to a greater or lesser extent, from the models that are used to evaluate the release of radionuclides from the waste repository and transport through the geosphere (Egan et al. 2001). The link to the biosphere in such a system is described as the “source term”. In order to describe the source term relevant to biosphere modelling, it is necessary to describe the boundary interface across which link between models is established, and which in turn is partly dependent on the assumed release mechanism. In addition, the source term should describe the characteristics of the release itself, expressed in terms of its timing, content and other properties. Source term characteristics are the basic attributes of the source term from the geosphere to the biosphere, including:

- Radionuclide and other hazardous materials content
- Physical and chemical properties of the release

The groundwater composition of the bedrock has important effect on release of the radionuclides (Egan et al.2001). In Finland the groundwater surface is mainly at the same level as the surface of the bedrock, which will be taken in account in all stages.

In “traditional” performance assessments the transport of radionuclides in groundwater in the geosphere is often undertaken using a chosen continuum model that accounts for advective and dispersive/diffusive transport as well as interaction with the host material. The radionuclide flux from the geosphere is often assumed to enter the first compartment of a compartmentalized biosphere model. In this case the modelling approach for the biosphere is different from that in the geosphere and it is assumed that the biosphere and geosphere models can be “decoupled” and considered independently.

In setting up the conceptual model for the whole system under consideration it is important that FEPs are included with concern of geosphere-biosphere interactions, at least initially. This will enable biosphere processes to be identified, which affect the geosphere, and *vice versa*. This identification will be particularly useful in subsequent consistency checks. Models that encompass both the biosphere and geosphere need to be able to deal with the different timescales and zone. The vertical movement of radionuclides in unsaturated soils will depend upon short term variations in rainfall and evaporation rates.

Biosphere models generally represent the effects of such short term processes as effective vertical transfer rates, but even these effective rates may be much more rapid than the transfer rates in groundwater in the bedrock. In practice, the definition of the location of the geosphere-biosphere interface will depend upon:

- The working definitions being employed for the “geosphere” and the “biosphere”
- The system FEPs where biosphere processes affect the geosphere and *vice versa*
- The modelling tools available for calculating radionuclide transport

The various definitions of the GBIZ interface would be possible. The erosion can be a significant source of radionuclides entering the biosphere, and it might not therefore be a valid assumption to neglect this process. This being a case, should the interface be at the rock/soil interface? In this case it is not obvious how a receiving biosphere compartment would be defined; if it is to be a soil compartment above a rock then the flux of radionuclides to the river is not represented. Alternatively, should more than one interface be considered? If the interface is to be defined for the radionuclides to the river, should the interface be at the rock/sediment interface or the sediment/river interface? (Egan et al. 2001).

The source term to the biosphere is also defined as constant activity concentration in the irrigation water (Bq/m^3) for each radionuclide. Those radionuclides with a short half-life in decay series are only considered in the radioactive decay in biosphere. The parent radionuclides are assumed to be in secular equilibrium in the geosphere model. This, in some cases, may not be very appropriate, due to the different mobility of parents and daughters (BIOPROTA 2005).

One way to look geosphere-biosphere interface is that biosphere processes are directly affected by activities (natural and human) occurring at the surface, whilst geosphere processes are not. In reality there is no simple cut-off on this basis in the interface; changes in the geomorphology and hydrology (including the formation of the ice sheets) will affect groundwater flows at depth. The deeper one goes, the less important are surface processes (Egan et al. 2001).

5.2 Consideration of cross-domain effects in modelling domains

The GBIZ needs understanding of the prognostic nature of estimated shoreline positions as well as the topographic evolution including changes in time (Figure 11). Ekström & Broed (2006), Broed (2006, in preparation) and Mäkiahö (2005) have presented scenarios on development of shoreline and topography at Olkiluoto.

The shoreline displacement history of the Baltic Sea has a very dynamic postglacial history which has been studied by generations in the countries bordering the sea (e.g. Voipio 1981, Björck 1995, Rantataro 2001, 2002, Posiva 2003, Eronen 2005, Gustafsson 2004, Lahdenperä 2006). These studies have produced a good knowledge about the main stages of the Baltic Sea. Rantataro (2001, 2002) has presented the conceptualised sea bottom sediment stratigraphy at the offshore of Olkiluoto (Figure 12 and 13).

Shoreline displacement in general is caused by several factors and it has had strong regressive trend at the Olkiluoto area throughout the Holocene (Tikkanen 1981, Eronen et al. 1995, 2001). The relative sea-level (RSL) has fallen quite quickly causing the shoreline to move rapidly towards the open sea (Jones 1977, Ristaniemi et al. 1997). This is due to facts that the ground at Olkiluoto is relatively flat (Posiva 2003a, Lahdenperä et al. 2005) and on the other hand the Glacial Isostatic Adjustment (GIA) is a quite forceful process (Kaufmann et al. 2000, Milne et al. 2001). It is very likely that the regressive trend is going to continue at Olkiluoto for several thousands of years mainly because of the remaining GIA (Figure 14) (Eronen et al. 2001).

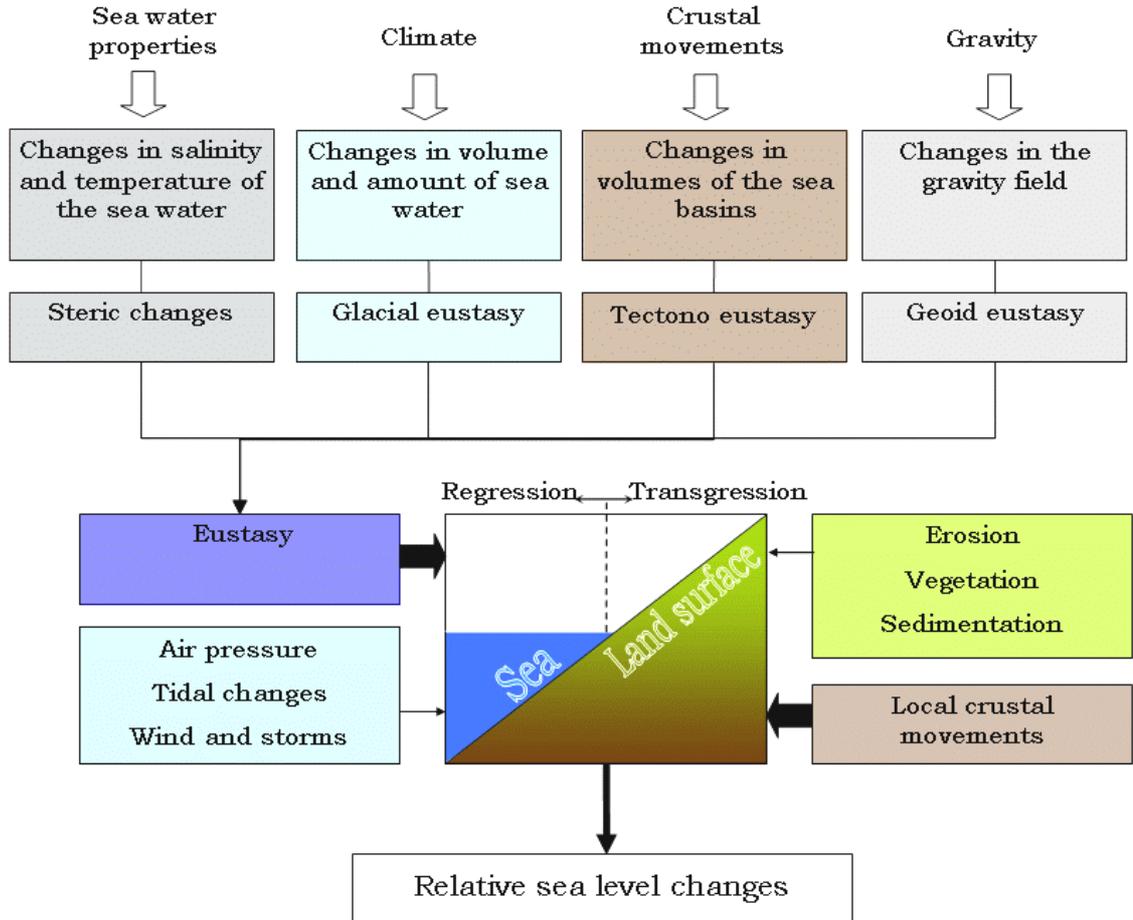


Figure 11. Factors inducing relative sea level changes and shore displacement. Eustasy is caused primarily by global components whereas the rise or fall of the Earth's surface is more of regional and local origin. Modified after Mörner (1980) and Mäkiäho (2003) in Mäkiäho (2005).

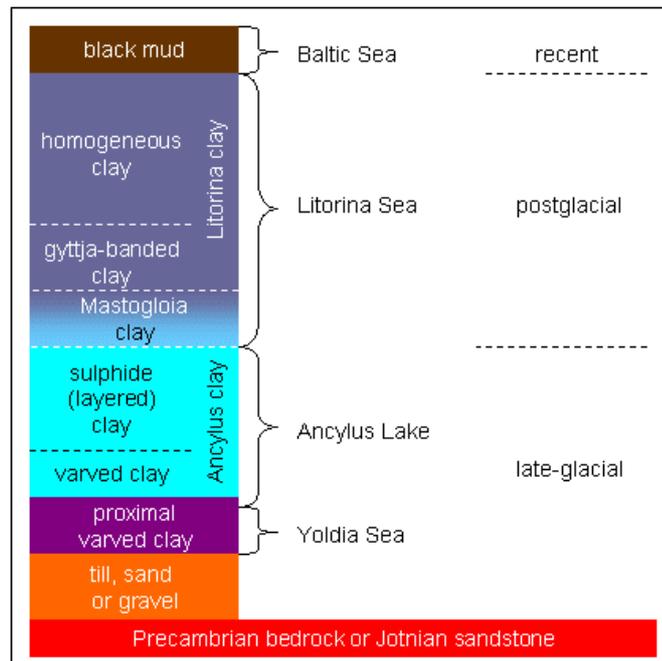


Figure 12. Conceptualised sea bottom sediment stratigraphy (Posiva 2003).

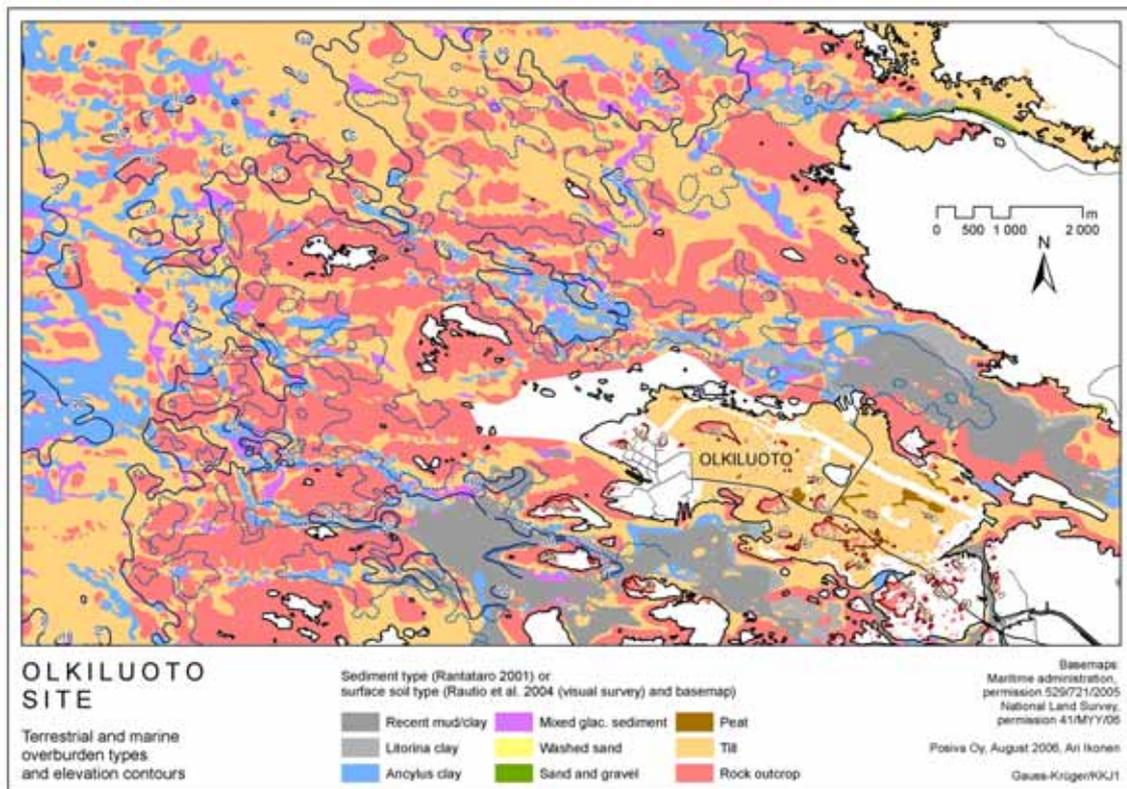


Figure 13. Topography and terrestrial and marine overburden types at the Olkiluoto Island and surrounding sea areas (after Rantataro 2001 and Rautio et al. 2004 in Posiva 2006).

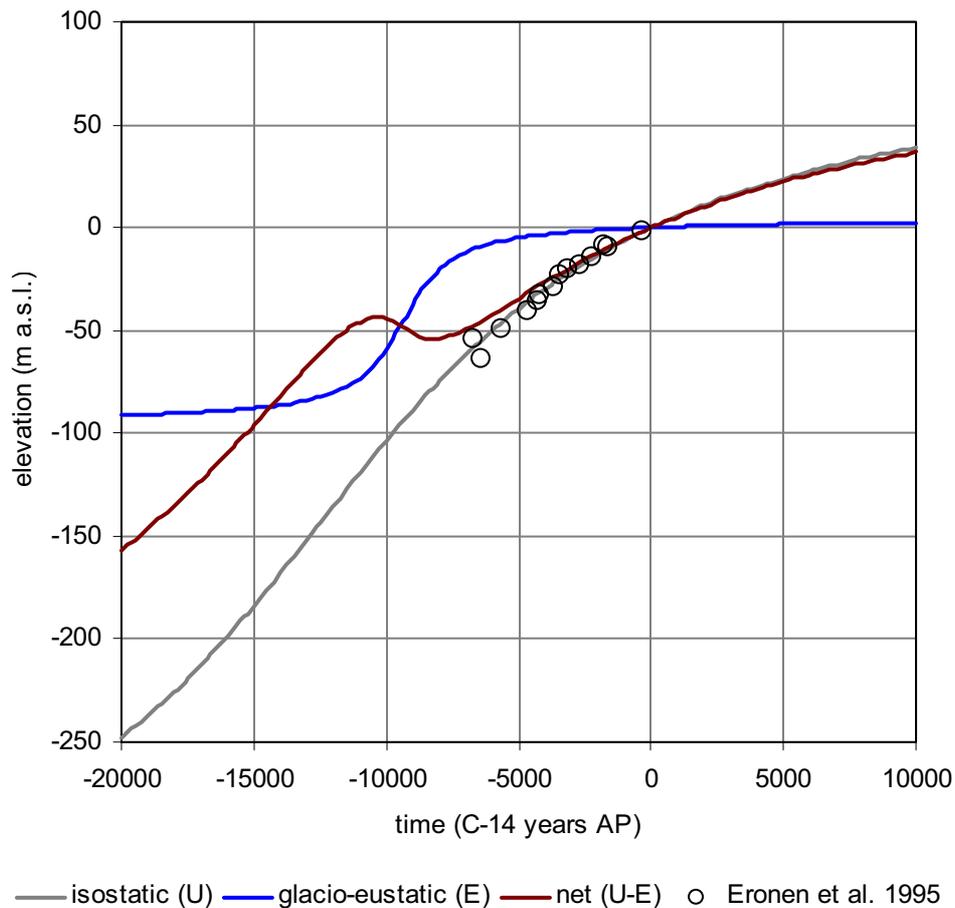


Figure 14. The postglacial land uplift and the global sea level rise at the Olkiluoto area (Löfman 1999). Curves are based on data by Pässe (1996). Circles denote the empirical data by Eronen et al. (1995). The time range is from 20 000 ago to 10 000 years AP.

Taking into account of land uplift rate and its estimated changes and variability (inland vs. shoreline), and the scenarios of sea level changes, the relative rise of altitude can be calculated for a given date and a given point of the area. In coastal areas such as Olkiluoto, this will not give fully correct result, however. In addition, development of main drainage areas needs to be assessed. Especially important for this is the Eurajoki river basin, since the flow path might change to another direction if a threshold arises at the river mouth (as might be at the mouth of the Eurajoensalmi strait/bay). This kind of forecasts needs more information on the geological conditions, e.g. sedimentation. Also for the purposes of the radionuclide transfer modelling of the Olkiluoto site, basic properties of the main drainage areas are needed, too. These properties are such as the locations of main water-bearing features (rivers, lakes, and mires), areas of the catchments, lake volumes and depths, main water flow rates, and amounts of accumulating sediments etc. (Ikonen 2005).

The first step of assessing the development of soils and sediments is to merge the existing maps (e.g. Figures 15, 16 and 17) on the temporal snapshots (Mäkiäho 2005). After this, the observed and interpreted stratigraphy needs to be generalised to enable reasonable description of the future stages. For example, Lahdenperä et al. (2005)

identified surface till, C-horizon till, peat and mud as main terrestrial overburden types, illustrating the adequate level for the Safety Case modelling. After the simplified overburden types and layers are fixed for the present situation, evolution of former sea-bottom sediments into soils needs to be described for the snapshots of future time. This can most likely be done on the basis of generic literature with the accuracy level of the selected main overburden types. The typical properties of the main types need to be derived to estimate the mass balances and flows.

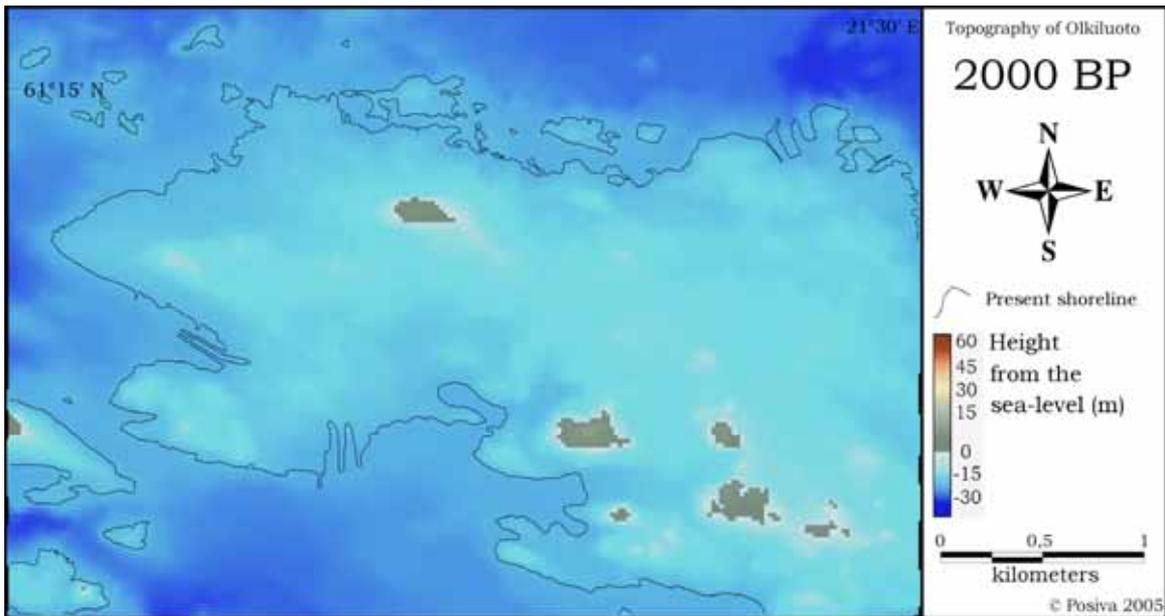


Figure 15. Topography of the Olkiluoto area at 2000 BP (Mäkiäho 2005).



Figure 16. Topography of the Olkiluoto area at 500 AP (Mäkiäho 2005).

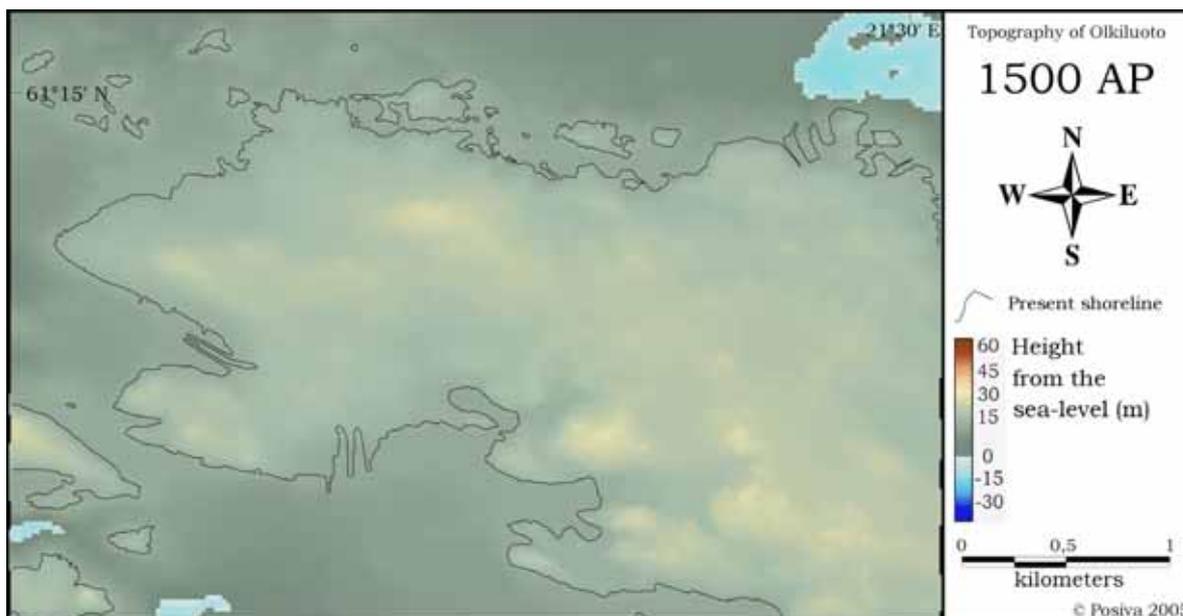


Figure 17. Topography of the Olkiluoto area at 1500 AP (Mäkiäho 2005).

5.2.1 Effects of biosphere/surface systems in far-field modelling

In the future the characteristics of the biosphere will vary over time and the most important long-term external factors are shore-line displacement and the glacial cycle highly related to global climate change. Long term internal development will also affect the persistence of the ecosystems. This is obvious e.g. for lakes, which transform to mires, but this can also be applied to wells, agricultural land and mires which also have constraints in life length and thus also a maximum time for radionuclide accumulation.

The positions of discharge locations of radionuclides into biosphere are essential input to the modelling of radionuclide transport in the biosphere and they will vary with time. The positions for such discharges are determined by the transport in the geosphere-biosphere interface zone, the transport in quaternary deposits and the surface hydrology.

The main types of aquatic ecosystems at the Olkiluoto area are lakes, springs, running waters and the Baltic Sea. The major abiotic features describing these systems are geometry (depth, volume, elevation and area), water turnover and chemistry which in turn affect the mix of species present and their relative abundance.

For the safety assessment, the water flow is a fundamental parameter, which usually is driven by the effective runoff, infiltration and precipitation in the drainage area and water level fluctuations. Both these variables are sensitive to the climate. The runoff, together with the water volumes in lakes and other reservoirs, determines the water turnover times.

Especially in a future perspective when the discharge and recharge sites are estimated to be far from the shore-line, running water will be an important component in the transfer and potential accumulation of radionuclides. Up to now there is a quite limited amount of information available on water turnover times. These factors affect the selection of

models, e.g. terrestrial and aquatic. For most contexts this is handled by selecting an appropriate configuration of ecosystem objects to provide a snapshot representation of the overall environment for each time period (e.g. Broed 2006, in preparation, Mäkiäho 2005). A critical parameter is how long the ecosystem persists which affects the total amount of radionuclides accumulated in the system. For the marine ecosystem, which persists throughout the major part of the interglacial period, shore-line displacement has significant effects on model parameters which affect calculated radionuclide concentrations.

There are three extreme cases for the fate of radionuclide entering a water body (SKB 2004):

- Direct inflow through the bottom or shore with no significant accumulation, with subsequent dilution and transport to other water bodies. This type of discharge would result in a rapid dilution but also an immediate dose (Bergström et al. 1999, Karlsson et al. 2001).
- Accumulation in bottom sediments through diffusion, with subsequent sorption, precipitation and/or biological uptake. This may cause accumulation of radionuclides that can give high doses at the later transition of the ecosystem, but the interim no/slow release to the water body with no/low dose.
- Accumulation due to precipitation in an oxidising near-surface environment, sorption and biological uptake at the shore. This case can give high immediate doses due to concentration in vegetation and low dilution by surface water. However, the long-term accumulation is expected to be less than when accumulation in sediments occurs.

In the terrestrial models, the key factors determining the transfer of radionuclides are the groundwater flux and processes in the overburden; i.e. hydrology and sorption processes, stratigraphy of the soil, root uptake and a further uptake and transfer in the food chain. The hydrological processes in the overburden are important in order to estimate the mixing of groundwater with deep groundwater. The groundwater fluxes in the quaternary deposits are also of importance for sub-horizontal radionuclide transport at depths where the radionuclides are inaccessible to biota. Since the discharge points to surface ecosystems seems to be sea- and lake floors, the upward transport in the quaternary deposits towards terrestrial ecosystems as well as to areas with high abundance of roots, is important to estimate.

The mire development and succession of forest are the major internal factors which affect the distribution of the different types of terrestrial ecosystems. Human land-use is another important factor affecting the properties of the terrestrial ecosystems, although the land-use to a large extent is constrained by the available soil types.

Due to rapid change of the biosphere and quaternary deposits on a geological time frame, there is an additional need to reconsider how the available and additional data can be utilised for long-term analyses. It is important to show clear relationships between the site investigation programmes and the modelling contexts in which the data is eventually utilised.

5.2.2 Effects of far field/geosphere in biosphere modelling

Transport by groundwater is recognised as the most important potential route by which radionuclides from waste in a deep repository might be carried back to the near-surface. So, it is appropriate that intensive effort has been/will be put into development of hydrogeological models to help an understanding of the Olkiluoto repository site (Posiva 2005), to test the feasibility of concepts and whether they match to observational data, and to develop predictive tools that can reliably assess the future behaviour of the disposal system (Vieno & Ikonen 2005). Models are also used to test the significance of parameters and sensitivity to change, and to identify data requirements. Groundwater flow models are inevitably based on simplifying assumptions; the natural world is so varied and complex so, it can never be fully characterised and represented, and the aquifer structure and boundaries cannot be fully known.

In the groundwater flow analyses attempts have been made to track the pathlines and to identify the discharge areas for groundwater departing from the repository. At Olkiluoto, the discharge areas in today's conditions are near the shoreline (Löfman 1999 a,b). As land rise proceeds the discharge areas might probably move further away from the repository and, when the sea retreats, it comes more likely that discharge will take place in water basins separated from the sea or at dried-out areas. At the same time previous discharge areas will be revealed from under sea. It thus seems that in the long term, after some thousands of years, various freshwater, forest, peat land, agricultural and even urban environments are represented among the possible discharge areas. The following general observations have been drawn from the regional-to-site-scale analyses of the groundwater (Vieno & Nordman 1999):

- In the deep bedrock, a major part of the groundwater flow takes place in the hydraulically significant fracture zones.
- The repository affects the flow only locally.
- The overall flow pattern in the vicinity of the repository is governed by the local relatively flat topography. At Olkiluoto the flow direction in the vicinity of the repository locating below the island is downwards whereas it is upwards or horizontal at the shoreline and below the sea.
- Brackish and saline groundwaters at Olkiluoto are not stagnant; flow is brought by the land uplift.

If radionuclides are released from the geosphere directly into the sea, individual dose rates will, at least in the short term, be significantly lower compared via the well pathway (Bergström & Nordlinder 1991, Barrdahl 1996). This would be only for very unlikely earlier releases. The reasons for this are the effective dilution in the sea and the absence of drinking and other freshwater exposure pathways.

In the inland environments, the fate of radionuclides released from the geosphere depends on the discharge spot and the mobility of the nuclides in the biosphere. If the discharge goes into a brook or lake, some long-lived and weakly-sorbing nuclides, like I-129, may migrate along water courses into the bigger lakes, but then the concentrations will be diluted significantly. On the other hand, if the discharge spot is a peat bog, a major part of the well-sorbing nuclides will initially remain there. Later the radionuclides sorbed in peat can be redistributed as a consequence of the gradual evolution of the bog, and at the latest during the next glaciation. Similarly lake

sediments, and at the coastal site sea sediments, may act as sinks of radionuclides, having then also a potential to release them in a later phase of the evolution of the lake or sea bay (Vieno & Nordman 1999).

5.3 Radionuclides of most interest based on recent modelling

Radionuclides are formed during reactor operation by fission of nuclei of U-235 and Pu-239, in particular, and by the capture of neutrons by nuclei in metal parts of fuel. The formers are called fission products and latter the activation products. Moreover, uranium can form plutonium and other heavier elements by absorbing one or more neutrons. These and other elements (including uranium) are called actinides and they decay to radioactive daughters in several steps, finally forming stable isotopes of metals lead or bismuth (Rasilainen 2004).

The radionuclides I-129, Ra-226, Tc-99, Cl-36, Cs-135, Se-79, Ni-59, Pu-239, Am-241, Np-94, Np-237 and uranium are believed to represent the variety of transport properties of the nuclides of interest, and this set could be used in preliminary modelling exercises. The problems which have been raised concerning the main radionuclides are that existing models are made for only single radionuclides (Cs-137 and Sr-90). Appendix 2 presents the key issues in geosphere-biosphere aspects of assessment of the long-term impact of contaminant releases associated with radioactive waste management (Leclerc-Cessac & Smith 2003). Appendix 3 presents the various radionuclides of concern from the point of view of long-term management and their status with respect to various transmutation schemes (ANDRA 2002).

Assessing the impacts of releases of radioactivity into the environment rely on a great variety of factors. Important among these is an effectively justified level of understanding of radionuclide behaviour in the environment, the associated migration pathways and the processes that contribute to radionuclide accumulation and dispersion among and within specific environmental media (Vieno & Nordman 1999, Posiva 2003, Posiva 2005, Bergström et al 2006). In addition, evaluating the consequences of any radionuclide releases on human health relies on the use of appropriate physiological and dosimetric models for calculating doses and risks (BIOPROTA 2005).

Chemical properties of the associated transport medium, such as Eh and pH of groundwater, and any changes in such properties at the geosphere-biosphere interface are important in determining the transport and accumulation of particular contaminants in environment. In addition, the spatial and temporal characteristics of release to the biosphere (e.g. whether smooth or discontinuous) may be significant consideration in biosphere assessment.

Radionuclides can be transported with the flowing groundwater i.e. advection. The other processes that can be important under stagnant conditions is diffusion, especially matrix diffusion, i.e. radionuclides diffuse into the stagnant water in the micropores of the rock and thereby retain and transport more slowly than in the flowing water. The timescale for advection relative to the timescale for matrix diffusion determines the relative importance of latter process. Sorption, where the radionuclides sorb to the surfaces of the fracture system and the rock matrix, is also crucial for radionuclide transport. Thus, matrix diffusion and sorption are the two most important retention processes for radionuclides in the geosphere.

The factor which can be of importance for retention is sorption on colloidal particles and transport with them. The chemical environment in the water determines what speciation (chemical form) the radionuclides will have, which is crucial particularly for the sorption phenomena. Some nuclides can be transported in the gas phase.

Radioactive decay influences the groundwater's content of radionuclides and must therefore be included in the description of transport phenomena (SKB 2003, 2004). A significant process affecting concentrations of radionuclides in the groundwater when they arrive from the geosphere into the biosphere, which was not explicitly discussed in localisation of the SR-97 Process Report (Rasilainen 2004), is mixing and dilution taking place, for example, in major fracture zones and in the upper part of the geosphere (Rasilainen 2004).

The high flow rates and short transit times used in the geosphere-transport analyses of radionuclides in performance assessments seem to be in some contradiction with the interpreted geochemical ages of deep groundwaters, which are typically some thousands of years or even much higher in the case of saline waters. However, it should be noted that in modelling of geosphere transport of radionuclides the focus of interest is on the small fraction of the groundwater, which may move rapidly in the fastest flow channels in the fractured bedrock. Furthermore, geochemical studies have indicated that deep groundwaters are usually mixtures containing several components with different origins and ages, but all of them seem to have considerable age (Pitkänen et al. 1996, 1998, 1999, 2004, Posiva 2005, Luukkonen et al. 1999).

An issue raised in the reviews of the TILA-99 safety assessment and Posiva's research, technical design and development programmes for the preconstruction phase of the repository (Ruokola 2000, Andersson & McEwen 2000) were, whether a more "geochemical" approach (e.g. Read et al. 2002) could be developed for modelling of radionuclide transport in safety assessments. It was pointed out that the "physical" approach based on an advection–dispersion–matrix diffusion model results in a continuous dispersion and dilution of the concentrations along the migration path. Where as a mass transport in the nature involves more complex geochemical processes including, for example, enrichment and potential remobilisation in the spatially and temporally varying geochemical conditions. However, there are some fundamental differences between releases from the repository and mass transport, for example, around a uranium ore body (ANDRA 2002):

- In the nature, the enrichment of uranium typically takes place in a case where is mass transport from oxidising conditions into the reducing conditions. In the repository safety assessment has been dealt with the opposite case, transport from the deep reducing conditions towards the oxidising conditions near the ground surface.
- In safety assessment calculations the time frame of interest is at most one million years, whereas mass transport in the nature has taken place over billions of years.
- Releases from a few defective canisters only add minor amounts of waste elements into natural mass flows.

Nevertheless, it has been recognized that a more integrated approach needs to be developed on geochemistry, flow and transport of groundwater and solutes, and

transport of radionuclides in the scale of the repository and site, and in the spatially and temporally varying conditions (Rasilainen 2004).

For the biosphere, radionuclide fate and transport models are generally built by following the processes and pathways that radionuclides take as they migrate in the biosphere and become incorporated into the bodies of biota that inhabit it. It has been called ecosystem and food chain modelling. Many biosphere and food chain models presently exist for tracing the movement of contaminants and radionuclides (Bergström et al. 1999, Davis et al. 1993, Klos et al. 1996, SKB 1999, Vieno & Nordman 1999). The underlying principles are based on compartmentalizing the biosphere into the aquatic and terrestrial components, into their physical entities such as water, air and soil and then the food chain or animal compartment for humans and animals (BIOPROTA 2005).

Interaction matrix for terrestrial environments

The International Union of Radioecology Report (2006) has presented the general matrices representation of the migration of radionuclides in terrestrial and aquatic ecosystems for individual radionuclides, C-14, Cl-36, Tc-99, Np-237 and U-238. Table 2 presents physical transport, chemical interaction, biological processes and an intake route of the terrestrial matrix and Table 3 of the aquatic matrix. The transfer processes in the definitions are the same as for the terrestrial matrix. However, it should be noted that the list processes are not exhaustive in the aquatic matrix. The transfer processes are listed in Appendix 4 (IUR Report 2006).

Each type of aquatic environment is characterised by specific properties: lakes and lagoons by a low flow regime and variable salinity; rivers by unidirectional and variable freshwater flow regime; estuaries and fjords by bidirectional and variable tidal and freshwater flow regime, and variable and transitional salinity; coastal sea by a tidally dominated transport and salinity.

Aquatic ecosystems are also heterogeneous media, composed of: (1) a water column including anything that is dissolved within it (i.e. $< 0.45 \mu\text{m}$) and suspended particles (i.e. $> 0.45 \mu\text{m}$); (2) bed sediment; and (3) benthic and pelagic biota, including primary producers, primary and secondary consumers.

Generic processes to any aquatic environment are of physical, chemical and biological nature (see Appendix 4). Physical processes (Table 4) include: advection (transport of a solute or suspended particle with the water), dispersion (diffusion), erosion and deposition of particle bound contaminants (burial/release). Chemical transformations (Table 5) are decay and speciation, complexation and degradation (DOC, POC, Fe-Mn oxides), adsorption and desorption. Sorption is influenced by many physical and chemical factors such as salinity, pH, dissolved oxygen, particle characteristics and concentration. Biological processes (Table 6) are governed by ingestion (water, sediment, and biota) and adsorption across body surfaces.

Table 2. Transfer processes of the terrestrial interaction matrix (IUR Report 2006).

| Physical transport | | Chemical interactions | Biological processes | Intake routes |
|--------------------------|---------------------------|--|-------------------------|---------------|
| Advection | Irrigation | Adsorption | Biofilms | Inhalation |
| Capillary rise | Leaching | Carbonate production | Biological weathering | Ingestion |
| Colloid transport | Leaf fall | Chemical weathering | Bioturbation | Uptake |
| Death | Mechanical weathering | Complex formation | Excretion of microbiota | |
| Degassing | Particle transport | Desorption | Fertilisation | |
| Deposition (dry and wet) | Pollen and seed release | Fermentation | Microbial metabolism | |
| Diffusion | Pressure pumping | Fixation | Photosynthesis | |
| Diffusive exchange | Recharge by surface water | Ion exchange | Root exudation | |
| Droplet production | Release due degradation | Isotopic exchange | Root respiration | |
| Eructation | Release from solution | Mineral dissolution | Root uptake | |
| Evaporation | Release of OM | Mineral precipitation (mineralisation) | Symbiotic association | |
| Excretion | Respiration | Precipitation | Transport by arenchyma | |
| Exhalation | Resuspension | Solution | Transport by microbiota | |
| External contamination | Seepage | Sorption | Utilisation | |
| Gas evolution | Solution at boundaries | | | |
| Gas sorption | Through-flow | | | |
| Groundwater recharge | Transpiration | | | |

Table 3. Transfer processes of the aquatic interaction matrix (IUR Report 2006).

| Physical transport | | Chemical interactions | Biological processes | Intake routes |
|--------------------------|-------------------------|-----------------------|-----------------------|---------------|
| Advection | Droplet production | Adsorption | Biological weathering | Inhalation |
| Dispersion | Evaporation | Carbonate production | Bioturbation | Ingestion |
| Capillary rise | Excretion | Chemical weathering | Excretion | Uptake |
| Colloid transport | Erosion of bed sediment | Complex formation | Photosynthesis | |
| Death | Gas evolution | Desorption | Root uptake | |
| Degassing | Particle transport | Dissolution | Degradation | |
| Deposition (dry and wet) | Release due degradation | Fermentation | | |
| Diffusion | Release from solution | Fixation | | |
| Exhalation | Respiration | Isotopic exchange | | |
| | Resuspension | Mineralisation | | |
| | | Precipitation | | |
| | | Sorption | | |

Table 4. Physical Transport Processes in aquatic environments (IUR Report 2006).

| Advection and dispersion of solutes | Advection and dispersion of particulates | Erosion and deposition |
|--|--|--|
| High in fluvial, estuarine and fjordic systems (10s km in few hours) Moderate in open coastal locations Low in lakes and lagoons | Fine-grained permanently suspended fraction (AD as solute) Temporarily suspended fraction (AD less than solute) | Only relates to temporarily suspended load Current thresholds for deposition/erosion Can be periodic or intermittent |

Table 5. Chemical Transformations in aquatic environments (IUR Report 2006).

| Decay and speciation | Complexation and degradation | Adsorption and desorption |
|---|---|--|
| Influences sorption (kinetics V's Kds) Influences bioavailability and toxicity | Influences sorption (kinetics vs. Kds) Influences bioavailability and toxicity | Influences bioavailability and toxicity Influence advection and dispersion Influence (e.g., through burial) speciation/complexation status |

Table 6. Uptake and exposure pathways in aquatic environments (IUR Report 2006).

| Ingestion (particle/solid bound) | Adsorption (dissolved phase) | External exposure from (no assimilation into biota) |
|---|--|--|
| Detritus/organic material Primary consumers (filter feeders/ grazers) Secondary consumers Tertiary consumers | Uptake across external body services (gills, mantle cavity, body wall) Uptake across gut wall | Sediment & water external to biota Internal sediment and water (ingested and within the gut, but not assimilated) |

5.3.1 Neptunium-237

There are few environmental data for neptunium; due to difficulties of measurement in the past. Considerable gaps also exist in the understanding of the environmental behaviour of neptunium. This is reflected in the interaction terrestrial and aquatic matrices for this radionuclide, Appendices 5 and 11 (IUR Report 2006), where there is no clear differentiation in the importance of the transfer processes (IUR 2006).

It is possible, that enrichment takes place in specific environments, as is the case for other actinides, especially the redox-sensitive ones such as Pu. Environments like that are anoxic water bodies or waters with high content of humus. From a point of view of waste management such environments are of vital interest. All the studies has far pointed to the fact that neptunium may be more soluble than either Am or Pu in oxidizing systems, but that when reduction occurs, Np solubility may decrease. This is particularly important to consider in the context of waste management scenarios. Deposition to soil organic and inorganic matter is considered of potential significance for Np-237, but not the newly added deposition to outcrop of parent material (IUR Report 2006).

In the context disposal of solid radioactive waste, Np-237 is envisaged as entering the biosphere by abstraction of contaminated groundwater or by natural groundwater flux to soils or surface water bodies. Thus, transfer from parent material to soil solution and to water bodies is regarded as being of potential importance. Either groundwaters or surface waters contaminated by Np-237 may be used for irrigation, resulting in the direct contamination of vegetation or in soil solution.

Np-237 is moderately reactive with inorganic matter, but quite highly particle reactive with organic matter. Therefore, exchange between soil solution and both soil organic matter and soil inorganic matter are likely to be of importance. Incidentally transfers to soil from surface waters and groundwaters to soils may occur with the Np-237 attached to suspended particulates, so these transfers may be direct and not via soil solution. This is of limited importance, as once Np-237 is present in soil substantial binding to soil solids will occur. The high affinity for organic matter means that particle and, more particularly, colloid transport may be of significance as well as transport in soil solution.

Volatilization of Np-237 has not been identified as being of any significance, so processes relating to the soil atmosphere are not considered important. As Np-237 is only taken up to a limited degree by roots of vegetation, external contamination from atmospheric deposition or by soil solids is likely to be of greater importance. Some external contamination from parent materials could also occur, but this is thought likely to be of limited importance compared with soil contamination.

Limited bioavailability of Np-237, symbiotic associations between vegetation and soil microbiota are likely to be of limited importance, as is uptake by microbiota from soil solution. Similarly, microbiologically mediated transfer between soil inorganic matter, soil microbiota and soil organic matter are thought to be of limited significance. However, Np-237 may have a long residence time in parent material, so ongoing processes of pedogenesis may result in it becoming incorporated in developing soil.

Animals may ingest Np-237 in drinking water and vegetation. However, because of the low bioavailability of Np-237 to plants, adventitious ingestion of Np-237 bound to soil solids may be of comparable importance. Excretion of systemic Np-237 by animals will mainly contaminate vegetation, soil solution and soil organic matter (IUR Report 2006).

Np-237 is highly particle reactive in the aquatic environment and therefore tends to migrate to bottom sediments. In aquatic systems, bottom sediments are the most likely environmental sink and Np-237 migration will be closely associated with sediment transport. It is possible that enrichment takes place in specific environments, as is the case for other actinides, especially the redox-sensitive ones such as Pu. Such environments are anoxic water bodies or waters with high humus content. From a waste management point of view such environments are of vital interest (IUR Report 2006).

5.3.2 Carbon-14

The dynamics of carbon transport in both terrestrial and aquatic ecosystems is quite well understood. The general terrestrial and aquatic ecosystems interaction matrices for C-14 are presented in Appendices 6 and 7 (IUR Report 2006). The main processes are considered to have the highest importance for describing the cycling of C-14 in terrestrial ecosystems: photosynthesis, respiration by the above ground vegetation and

animals and the soil biota, fermentation by animals and soil biota, exhalation and diffusion of gases from soil atmosphere, ingestion and utilization of soil organic matter by soil biota. In a case of aquatic ecosystems, the processes classified as most important are: photosynthesis, consumption, respiration, decomposition and excretion by primary products, herbivorous fish, carnivorous fish and detritivores.

The primary interactions of C-14 take place as a consequence of processes occurring in the soil zone. There is thought to be a limited role for the participation of parent material, whether it is outcrop or is present underlying soil and sub-soil. For this reason, interactions with parent material have not been identified as being importance.

Post-closure radiological assessments of solid radioactive waste disposal have shown that the generation of C-14 methane and C-14 carbon dioxide can be of radiological significant (Vieno & Nordman 1999, Vieno & Ikonen 2005). These gases are produced by microbial degradation of wastes and can be transported to the surface together with hydrogen produced from metal corrosion in reducing conditions. If continuous gas-filled pathways are produced, such transport can be rapid. C-14 carbon dioxide may be a limited problem, as it would be expected to react with a cement/concrete in the near field. However, C-14 methane is likely to be non-reactive in both the near field and geosphere, but will be subject to microbial metabolism to C-14 carbon dioxide in the soil zone. In addition, C-14 may be released from a repository in solution in groundwater. Such groundwater may be extracted from wells and used for irrigation and other purposes. It is not clear how much of the C-14 would be lost from extracted groundwater before that groundwater is utilised. In particular, losses from solution during spray irrigation might be substantial (IUR Report 2006).

It seems unlikely that C-14 containing aerosols will be of importance. Therefore C-14 in the atmosphere is likely to be present as carbon dioxide, though perhaps also to limited degree in methane. In a view of this, deposition to water bodies or vegetation is considered to be of limited importance compared with uptake to vegetation by photosynthesis. Direct entry of either carbon dioxide or methane into soil solution from the atmosphere is thought to be of less importance compared with exchange between the above-ground atmosphere and soil atmosphere by both diffusive exchange and pressure pumping. This is a bi-directional process and C-14 present in the soil atmosphere is mainly lost to the above-ground atmosphere by this route. Once C-14 labelled gases are present in the soil atmosphere, bi-directional exchange processes with soil solution are considered to be of importance.

It is recognized that C-14 may be present in dissolved form in surface water bodies and groundwater and these waters may be abstracted and used for irrigation. If spray irrigation is used, much of the activity in the water may be lost to the atmosphere during dispersal of spray. Direct transfer from water bodies into the soil atmosphere are considered to be of little importance compared with percolation of the water to become soil solution and subsequent release (IUR Report 2006).

The release rate of constraint of C-14 is rather low and is based on the assumed enrichment of inorganic C-14 in the biosphere. However, during corrosion of metals in anaerobic conditions carbon may release mainly as methane, which does not retard in anything – but on the other hand, not cause significant dose exposures. However, the release rate of C-14 as methane is limited by the corrosion rate of metals (NEA 2002).

C-14 in vegetation may be released to the soil zone by root respiration where it will enter the C-14 pool in soil solution and soil atmosphere. Leaf fall could represent a major flux that results in dispersal of some distance from the original site of contamination.

Soil microbiota is of great importance in the carbon cycle. Their more substantial role is considered to be uptake of C-14 from soil solution, soil atmosphere and soil organic matter, with the resultant production of microbiological biomass. Uptake from soil solution is thought to be the most important of these three pathways. It has been suggested the following issues for consideration as priorities for research concerning terrestrial ecosystems (First Workshop of the IUR task Force “Radiology and Waste”, 2003):

- Metabolism of methane in soil and the interaction between the soil solution and the soil atmosphere
- Root uptake by plants
- Uptake from the sub-canopy and above-canopy atmosphere
- Losses from irrigation waters during extraction and application
- Partitioning of uptake from the gastrointestinal tract
- Characterization of body pools

5.3.3 Chlorine-36

Chlorine-36 is radioactive isotope (half-life 300,000 years) produced by cosmic radiation in the upper atmosphere and in subsurface by in situ neutron flux. In the context disposal of solid radioactive waste, Cl-36 is envisaged as entering the terrestrial environment either in irrigation waters or in natural groundwater discharges to soils and surface water bodies (IUR Report 2006). Transfer to the above-ground atmosphere is likely to be limited, hence return pathways from the atmosphere are also likely to be limited. Thus, return pathways from the atmosphere to the terrestrial environment are not considered to be of importance. However, Cl-36 can enter groundwaters and surface waters in solution, typically as chloride. This may become associated with organic matter, upward migration from parent material is thought likely to be dominated by chlorine in solution (IUR Report 2006). The general terrestrial and aquatic ecosystems interaction matrixes for Cl-36 are presented in Appendices 8 and 9 (IUR Report 2006).

Some losses from surface water bodies to atmosphere could occur by the generation of gases. Although the production of chlorine-containing gases from environmental media has been identified, the degree of such evolution is thought to be very limited. Cl-36 in surface waters is highly available to plants by root uptake and can also be absorbed and translocated following irrigation.

If ingested in drinking water by animals, it is almost completely absorbed from the gastrointestinal tract and retained in the body on a timescale of days to weeks. When Cl-36 is added to soil in irrigation waters or by flooding, it will initially enter soil solution and will, in general, remain in solution, and therefore, be highly mobile in soil system. In addition, Cl-36 in surface waters can percolate through soils to contaminate parent materials or can enter parent materials directly at outcrop. Ingestion of vegetation of Cl-36 can be an important route of contamination of animals. However, uptake by vegetation from soil is likely to be the result of rapid kinetics in both directions; root

exudation and root uptake are both likely to be important and symbiotic associations with soil microbiota may be an important factor influencing uptake. Vegetation interactions at the outcrop of parent materials are thought to be of little importance compared with vegetation/soil interactions.

Although root exudation into soils is identified as a potentially important process, root exudation directly to surface water bodies and groundwaters is considered much less important. Losses of parts of vegetation to atmosphere are also thought to be most conveniently represented as direct transfer from vegetation to soil organic matter, though some consideration may need to be given to the dispersal of Cl-36 as a result of leaf fall.

Animals excrete Cl-36 mainly in urine, though minor losses may also occur in faeces. Excretion is largely as the chlorid and can contaminate vegetation directly as well as soil solution. Some Cl-36 may be released in organic form either in faeces or on the death of animal, contaminating vegetation and soil organic matter. Although direct contamination of water bodies can occur, this is thought to be of less significance than contamination of terrestrial system.

Cl-36 tends to be conservative in soil solution, sub-horizontal transport and release to surface water bodies has to be taken into account, as do downward percolation to groundwater. Although evaporation of soil solution can result in increased concentrations of Cl-36 in surface horizons, it does not result in a significant flux of Cl-36 to atmosphere.

Experimental studies have shown that Cl-36 can interact strongly with organic materials in soils (notably humic acids). Therefore, interactions between soil solution and soil organic matter should be addressed. These interactions could be direct, but they could also be mediated or modified by soil microbiota. For this reason, it seems most appropriate to consider interactions between soil solution, soil organic matter and soil microbiota. It may be worth considering adventitious intake of organic material from the litter layer, as this could contain similar concentrations of Cl-36 to living plants. Nevertheless, the intake of this material is likely to be limited in comparison with living plant material in most circumstances.

As Cl-36 is highly bioavailable to vegetation, external contamination by soil organic matter is considered to be of little significance. Also, the limited degree of association of Cl-36 with soil solids makes resuspension of little importance. Resuspension of microbiota is also not envisaged as an important pathway. The First Workshop of the IUR Task Force "Radiology and Waste" (2003) presentation was focused on Cl-36 behaviour in the soil-plant system, with especial emphasis on the following issues:

- The absence of absorption by soil, a prevailing role of fixation by biota and the migration with the soil moisture flux
- The root uptake by plants, which is characterized by quite high concentration factors
- The dependence of Cl-36 behavior in the environment on stable chlorine content

The balance of the input and output of stable chlorine into the system is an important factor that needs to be taken into account when modelling Cl-36 migration in the

environment. It is also important to improve the description of the dynamics of chlorine remobilisation (leaching) from soil organic matter due to disintegration of the organics (IUR Report 2006).

5.3.4 Uranium

The three natural uranium isotopes found in the environment, U-234, U-235, and U-238, undergo radioactive decay by emission of an alpha particle, however, lower levels of both beta and gamma radiation are also emitted. The dominant isotope, U-238, forms a long series of decay products that includes the key radionuclides Ra-226, and Rn-222 (Figure 18). The decay process continues until a stable, non-radioactive decay product is formed (e.g. Suksi 2001). The general terrestrial and aquatic ecosystems interaction matrixes for U-238 are presented in Appendices 10 and 11 (IUR Report 2006).

The principal interest in U deposits lies in the mechanisms that have been responsible for their low-temperature weathering and the subsequent remobilisation of U-series elements. This is because these mechanisms operate in conditions that are essentially similar to those under which the evolution of a nuclear waste repository will take place. Naturally occurring U and Th are of particular interest because they show different solubility characteristics (Langmuir 1978, Langmuir & Herman 1980) and their isotopes occur in the same radioactive decay series (Suksi 2001).

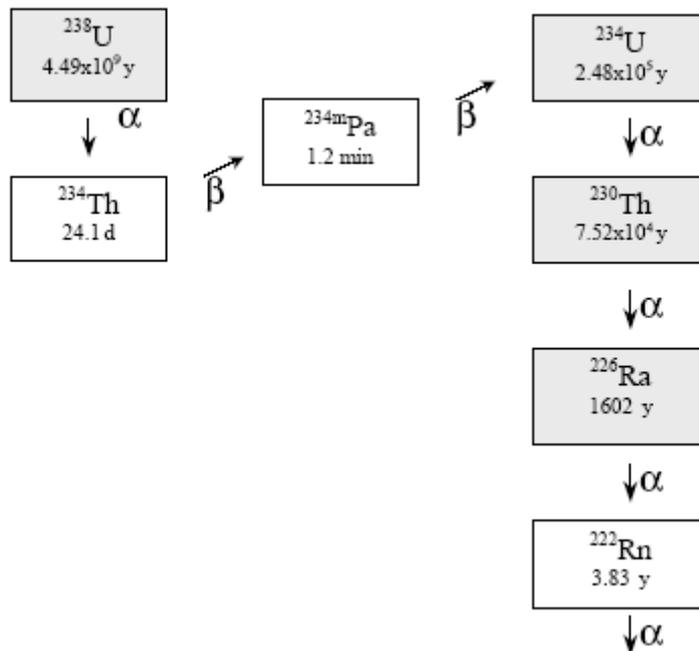


Figure 18. Beginning of the uranium decay series with respective half-lives. Important nuclides in terms of long-term radionuclide transport studies are indicated (Suksi 2001).

Critical flow path is characterised as a smooth and straight fracture and complex chemical interactions are modelled with the help of a laboratory-based distribution coefficient K_d , which is normally determined in one set of chemical conditions. K_d is defined as the ratio of the quantity of the adsorbate (i.e. metal or radionuclide) adsorbed per unit mass of solid to the quantity of the adsorbate remaining in solution at equilibrium (ml/g or m³/kg). Such overly simplified modelling is justified by the assumption of conservatism, i.e. the model assumes a pessimistic situation (Vieno & Nordman 1999).

Chemically, uranium is a hard-donor cation with a strong tendency to complex with oxygen-containing ligands. Oxidation state U^{6+} is much more soluble (even mg/l level) than U^{4+} , which is considered to be insoluble (ppb level). Therefore, U released in the near-surface oxidising groundwater zone shows mainly increased concentrations in shallow groundwater samples. Deep groundwaters are generally from a reducing environment where U is poorly soluble and typically precipitates. Uranium release is very complicated in such conditions. It depends on such factors as the distribution of U within the rock matrix and on fracture surfaces, the type of U-phases, the chemical state of U in the solid phase and the geochemical properties of the groundwater, such as the availability of reducing and complexation agents

The greater solubility of U^{6+} as the uranyl ion (UO_2^{2+}) is due to its ability to form stable soluble complexes with various organic and inorganic ligands. The occurrence and distribution of uranyl species in surface and subsurface environments is controlled by the redox conditions, pH and the CO_2 partial pressure (e.g. Giblin et al. 1981, Dongarra 1984, Gascoyne 1992). The behaviour of the U-234 isotope is further controlled by α -decay and related recoil "hot atom" chemistry. Uranium concentration in aqueous solutions is affected by dissolution, precipitation, co-precipitation and sorption, U^{4+} being affected more strongly than U^{6+} . In low ionic strength solutions with low U^{6+} concentrations dissolved uranyl concentrations will likely be controlled by cation exchange and adsorption processes (e.g. Ames et al. 1983, Hsi & Langmuir 1985, Payne et al. 1994). In oxidising conditions with high U concentrations uranyl concentrations are additionally controlled by the formation of U^{6+} minerals (e.g. Langmuir 1978).

Radioactive disequilibrium develops because the decay series elements have diverse chemical properties and half-lives. A pronounced disequilibrium is easily produced between the U and Th isotopes because pH and Eh control U behaviour (Langmuir 1978) and Th is practically insoluble in a wide range of natural conditions (Langmuir & Herman 1980). Accordingly, any disequilibrium occurring between U-234 and Th-230, for example, indicates past changes in the chemical environment, i.e. in pH and Eh. In groundwater-rock systems such changes are generally brought about through groundwater recharge and when oxic groundwaters are introduced in anoxic conditions. Taken together, as a result of disequilibrium processes the liquid phase has an excess of soluble radionuclides, and surfaces of the solid phase have a deficiency of them. The linkage between geochemical processes and U-series disequilibria offers information about temporal and spatial U transport. The interpretation starts from the fact that Th and U^{4+} are essentially insoluble in groundwater while U^{6+} and Ra are soluble (Suksi 2001).

Soil variables and the plant age and species seem to be important determinants of uranium uptake and further distribution within the plant (Shahandeh et al. 2001). The level of carbonate, phosphate, organic matter and oxy-hydroxide of Fe and Al in soils

greatly influence the uranium solubility and mobility. U forms highly soluble complexes with carbonate in calcareous soils, inducing a higher U availability for plants compared to more acidic soils devoid of carbonates. Inversely, P fertilisation of U-contaminated soils is shown to induce a significant decrease of the water-soluble and extractable U with as a result a reduction of the net uptake by plants while the biomass production is improved (Rufyikiri et al. 2006). Uranium uptake and possible consequent toxic effects are probably better related to soluble and easily exchangeable level in soils rather than total uranium.

There is a large amount of useful data for uranium, covering a wide range of environmental conditions. The variability in the data is, however, very large, reflecting the large variability observed in the speciation of uranium. There are knowledge and data gaps in several aspects of the uranium cycling in aquatic systems, such as the role of sediments as reservoir, the role of colloids, the exchange processes between solution and suspended particles, the role of microbiology and organic matter. It might also have a better understanding on relationships between speciation, bioavailability and bioaccumulation. In particular, the role of soil-plant interactions and uranium translocation in plants is poorly understood. For long-term assessments it would also be necessary to take into account the issue of uranium equilibrium with its daughters. The pathways associated with the daughters will have to be considered and the model appropriately (Second Workshop of the IUR Task Force "Radioecology and Waste" 2003).

Hedin (1997) illustrates radiological properties (radioactivity, external gamma and neutron radiation, radiotoxicity) of spent fuel as a function of time. Heat generation, risk and consequences of criticality, as well as release potential of radionuclides from a deep repository are discussed, too. A comparison of the radiological properties shows that after a few hundred thousand years the radioactivity and radiotoxicity of spent fuel will be lower to the levels of the uranium mineral from which the nuclear fuel has been produced (Figure 19). This decrease in the radiotoxicity of spent fuel is a main reason why rigorous quantitative analyses are not required in the very long term.

For long-term assessments it is also necessary to take into account the issue of uranium equilibrium with its daughters. The pathways associated with the daughters will have to be considered and the models appropriately parameterised (IUR Report 2006).

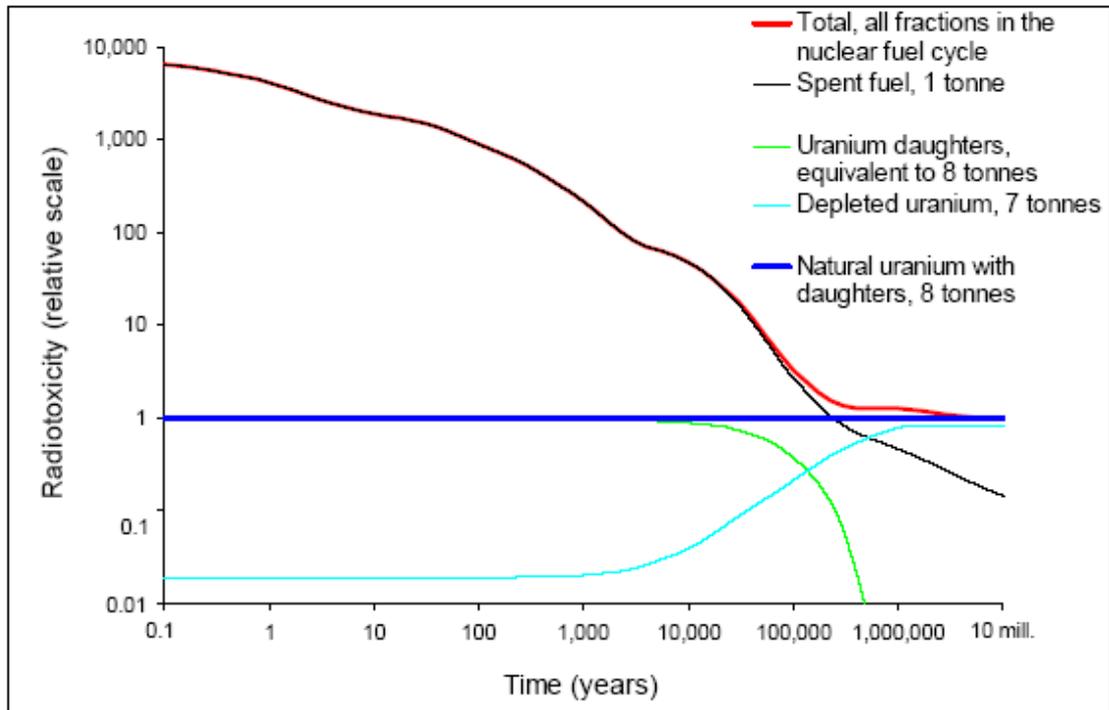


Figure 19. Radiotoxicity on ingestion of uranium mineral (thick blue line), and of all fractions that arise when the same quantity of uranium mineral is used in the nuclear fuel cycle (thick red line) of light water reactors. The different fractions comprise the spent fuel, and the depleted uranium and the daughter nuclides of uranium that are separated when the uranium mineral is processed to nuclear fuel (Hedin 1997).

5.3.5 Radon and other daughters of Ra-226

Release rates of Ra-226 and moderate short-lived nuclides may be significantly higher than that of the long-lived parent and depend crucially on conditions close to the geosphere-biosphere interface. There is only a small amount of Ra-226 in the spent fuel initially and for several thousands of years (Vieno & Nordman 1999, NEA 2002). Radon soil-concentration has been used in an experimental way to map close-subsurface geological faults, because concentrations are generally higher over the faults. Similarly it has found some limited use in geothermal prospecting. Radon emanation from the soil varies with soil type and with surface uranium content, so outdoor radon concentrations can be used to track air masses to a limited degree.

5.3.6 Iodine

There are both radioactive and non-radioactive isotopes of iodine. I-129 and I-131 are the most important radioactive isotopes in the environment. Both I-129 and I-131 are produced by the fission of uranium atoms during operation of nuclear reactors and by plutonium (or uranium) in the detonation of nuclear weapons. I-129 has a half-life of

15.7 million years; I-131 has a half-life of about 8 days. Both emit beta particles upon radioactive decay.

Iodine reacts easily with other chemicals, and isotopes of iodine are found as compounds rather than as a pure elemental nuclide. Thus, I-129 and I-131 found in nuclear facilities and waste treatment plants quickly form compounds with the mixture of chemicals present. However, iodine released to the environment from nuclear power plants is usually a gas.

Radioactive iodine can be inhaled as a gas or ingested in food or water. It dissolves in water thus, it moves easily from the atmosphere into humans and other living organisms. Radioactive iodine is usually emitted as a gas, but may contaminate liquids or solid materials as well.

Iodine is generally present in environments as an anion (either iodide or iodate) and is therefore soluble in groundwater and migrates with the speed of groundwater through rock and overburden to low-lying landscape positions such as wetlands where it can be retained by the organic matter of soils (iodine can only be retained in its oxidised form). Organic matter and bacterial activity seem to play an important role. Peat bogs are rich in organic matter and therefore iodine is likely to accumulate in peat bogs. In the Second Workshop of the IUR Task Force "Radioecology and Waste" (2003) the biogeochemical cycle of iodine in the peat bog emphasized on following issues:

- The transfer of iodine along the carbon cycle in the peat bog (plant uptake, speciation of iodine in the plant, consequences of the biodegradation of the plant material on the availability of iodine in the peat)
- The role of the redox potential on the migration and the speciation of iodine in the peat bog
- An understanding of the mechanisms that govern the fate of iodine in peat bogs will form the basis for a better model of the transfers of this element in these types of ecosystems.

5.3.7 Technetium

It has been shown that chemical of Tc (VI) leads to the formation of nearly insoluble Tc (IV) species and therefore there is limited migration from groundwater and through an anoxic/oxic front. The main source of Tc in the marine environment is the nuclear fuel reprocessing. The concentrations of Tc coming from reprocessing plants reach several mBq/l, while the contamination with fallout from nuclear tests has resulted in concentrations of 10-20 μ Bq/l. Technetium exhibits complex chemical, biochemical and biogeochemical interactions. In general Tc tends to remain dissolved in waters, which makes it an excellent tracer of the movement of water masses (IUR Report 2006). The general aquatic ecosystem interaction matrix for Tc is presented in Appendix 12 (IUR Report 2006). Tc behaves generally conservatively in water in the form of TcO_4^- . In general, Tc tends to remain dissolved in waters, which makes it a significant tracer of the movement of water masses. In anoxic environments Tc is reduced and can be fixed by sediments together with Fe and Mn. The enrichment factors of Tc tend to increase with the salinity, which is in contrast with the enrichment factors for caesium, that tend

to decrease when salinity increases. These observations could be useful for testing models (First Workshop of the IUR Task Force “Radioecology and Waste” 2003).

The behaviour of Tc in the environment is dictated by its chemical speciation. There is limited data available of K_d in different redox conditions. The data of soil-to-plant concentration factors is also limited, especially for non-agronomic, natural, plants. The behaviour of Tc in humic systems has been poorly studied (IUR Report 2006).

5.3.8 Dose rate estimates

Vieno & Nordman (1999) has presented potential releases and transport of radionuclides from the repository into the geosphere and biosphere in the TILA-99 report where they presented a number of different scenarios. The main conclusions were:

- In the sensitivity analyses based on the small hole case and median flow and transport data (SH-ns50 and SH-sal50); the maximum release rate ratio belongs to Cs.
- In the sensitivity analyses based on small hole case and very high flow and transport data (SH-vhflows and SH-vhflowsal); the maximum release rate ratio belongs to Cs-135 and in some cases to Sr-90.
- In the sensitivity analyses based on the disappearing canister case and medium flow and transport data (DC-ns50 and DC-sal50), the maximum release rate ratio belongs usually to Sn-126, in some scenarios to Cl-36, I-129 or Cs-135.
- In the sensitivity analyses based on disappearing canister case and very high flow and transport in non-saline conditions (DC-vhflows), the maximum release rate ratio belongs in different scenarios to Sn-126, Np-237, Ra-226, Pu-239 and Cl-36.
- Among the “what if”-scenarios, the most conspicuous release rate ratio, $1.7 \cdot 10^{-1}$ Bq/y, belongs to Pu-239 in the postglacial faulting scenario.
- Among the sensitivity analyses the highest release rate ratio appears among the scenarios based on the disappearing canister case and very high flow and transport in saline conditions. The maximum release rate ratio belongs usually to Ra-226.

Karlsson & Bergström (2000) have calculated *ecosystem specific dose conversion factors* (EDFs) for six hypothetical recipients for an annual release 1 Bq of each radionuclide considered during 10 000 years. The recipients were well, lake, running waters, coastal area, agricultural land and peat bog. The EDFs were compared with the “*dose conversion factors*” (DCFs) used in TILA-99 (Vieno & Nordman 1999) (Table 7). For most recipients and radionuclides the EDFs were higher than DCFs, which was due to fact that the DCF concept did not include any accumulation of radionuclides in the biosphere as the EDFs did (Karlsson & Bergström 2000). Together with a large

number of exposure pathways related to the areas of accumulation this leads to higher exposures. In TILA-99 only the well case was included. The dilution volume is an important parameter in all water modules as an effective water turnover will lead to lower exposures (Vieno & Nordman 1999).

Table 7. The major radionuclides present in the spent fuel in Finnish deep repository, their half-lives and dose coefficients for external exposure (Svensson 1979), ingestion (ICRP 1991) and inhalation (ICRP 1996) used in calculations in Karlsson & Bergström (2000). The dose conversion factors used in TILA-99 are also presented (Vieno & Nordström 1999).

| Nuclide | Type of dominating decay | Half-life year | External exposure Sv/h)/Bq/m ³ | Ingestion Sv/Bq | Inhalation Sv/Bq | Dose conversion factors (Sv/Bq) used in TILA-99 |
|---------|--------------------------|----------------|---|-----------------------|-----------------------|---|
| C-14 | β | 5 730 | 0 | 5.8·10 ⁻¹⁰ | 2.0·10 ⁻⁹ | 2.9·10 ⁻¹⁵ |
| Cl-36 | β | 301 000 | 0 | 9.3·10 ⁻¹⁰ | 7.3·10 ⁻⁹ | 4.7·10 ⁻¹⁵ |
| Ni-59 | β | 75 000 | 0 | 6.3·10 ⁻¹¹ | 1.3·10 ⁻¹⁰ | 3.2·10 ⁻¹⁶ |
| Ni-63 | β | 96 | 0 | 1.5·10 ⁻¹⁰ | 4.8·10 ⁻¹⁰ | 7.5·10 ⁻¹⁶ |
| Se-79 | β | 1 130 000** | 0 | 2.9·10 ⁻⁹ | 2.6·10 ⁻⁹ | 1.5·10 ⁻¹⁴ |
| Sr-90* | β | 29 | 0 | 2.8·10 ⁻⁸ | 3.6·10 ⁻⁸ | 1.5·10 ⁻¹³ |
| Zr-93* | β | 1 530 000 | 0 | 1.1·10 ⁻⁹ | 1.0·10 ⁻⁸ | 6.1·10 ⁻¹⁵ |
| Nb-94 | β, γ | 20 300 | 1,6·10 ⁻¹³ | 1.7·10 ⁻⁹ | 1.5·10 ⁻⁹ | 8.5·10 ⁻¹⁵ |
| Tc-99 | β | 213 000 | 0 | 6.4·10 ⁻¹⁰ | 4.0·10 ⁻⁹ | 3.2·10 ⁻¹⁵ |
| Pd-107 | β | 6 500 000 | 0 | 3.7·10 ⁻¹¹ | 8.5·10 ⁻¹¹ | 1.9·10 ⁻¹⁶ |
| Sn-126* | β, γ | 100 000 | 3·10 ⁻¹⁵ | 4.7·10 ⁻⁹ | 2.8·10 ⁻⁸ | 2.5·10 ⁻¹⁴ |
| I-129 | β | 15 700 000 | 3.4·10 ⁻¹⁶ | 1.1·10 ⁻⁷ | 1.5·10 ⁻⁸ | 5.5·10 ⁻¹³ |
| Cs.135 | β | 2 300 000 | 0 | 2.0·10 ⁻⁹ | 3.1·10 ⁻⁹ | 1.0·10 ⁻¹⁴ |
| Cs-137 | β, γ | 30 | 5.6·10 ⁻¹⁴ | 1.3·10 ⁻⁸ | 9.7·10 ⁻⁹ | 6.5·10 ⁻¹⁴ |
| Sm-151 | β | 90 | 4.6·10 ⁻¹⁸ | 9.8·10 ⁻¹¹ | 4.0·10 ⁻⁹ | 4.9·10 ⁻¹⁶ |
| Ra-226* | α | 1 600 | 6.0·10 ⁻¹⁶ | 2.8·10 ⁻⁷ | 3.5·10 ⁻⁶ | 1.1·10 ⁻¹¹ |
| Th-229* | α | 7 340 | 2.0·10 ⁻¹⁵ | 4.9·10 ⁻⁷ | 1.1·10 ⁻⁴ | 3.1·10 ⁻¹² |
| Th-230 | α | 77 000 | 3.5·10 ⁻¹⁷ | 2.1·10 ⁻⁷ | 4.3·10 ⁻⁵ | 1.1·10 ⁻¹² |

| Nuclide | Type of dominating decay | Half-life year | External exposure Sv/h)/Bq/m ³ | Ingestion Sv/Bq | Inhalation Sv/Bq | Dose conversion factors (Sv/Bq) used in TILA-99 |
|---------|--------------------------|----------------|---|---------------------|---------------------|---|
| Pa-231 | α | 32 760 | $1.8 \cdot 10^{-15}$ | $7.1 \cdot 10^{-7}$ | $1.4 \cdot 10^{-4}$ | $9.6 \cdot 10^{-12}$ |
| U-233 | α | 158 500 | $5.9 \cdot 10^{-17}$ | $5.1 \cdot 10^{-8}$ | $3.6 \cdot 10^{-6}$ | $2.6 \cdot 10^{-13}$ |
| U-234 | α | 244 500 | $3.1 \cdot 10^{-17}$ | $4.9 \cdot 10^{-8}$ | $3.5 \cdot 10^{-6}$ | $2.5 \cdot 10^{-13}$ |
| U-235* | α | 703 800 000 | $1.1 \cdot 10^{-14}$ | $4.7 \cdot 10^{-8}$ | $3.1 \cdot 10^{-6}$ | $2.4 \cdot 10^{-13}$ |
| U-236 | α | 23 415 000 | 0 | $4.7 \cdot 10^{-8}$ | $3.2 \cdot 10^{-6}$ | $2.4 \cdot 10^{-13}$ |
| U-238* | α | 4 468 000 000 | 0 | $4.5 \cdot 10^{-8}$ | $2.9 \cdot 10^{-6}$ | $2.4 \cdot 10^{-13}$ |
| Np-237* | α | 2 140 000 | $1.8 \cdot 10^{-15}$ | $1.1 \cdot 10^{-7}$ | $2.3 \cdot 10^{-5}$ | $5.5 \cdot 10^{-13}$ |
| Pu-238 | α | 88 | $1.3 \cdot 10^{-17}$ | $2.3 \cdot 10^{-7}$ | $4.6 \cdot 10^{-5}$ | $1.2 \cdot 10^{-12}$ |
| Pu-239 | α | 24 065 | $6.6 \cdot 10^{-18}$ | $2.5 \cdot 10^{-7}$ | $5.0 \cdot 10^{-5}$ | $1.3 \cdot 10^{-12}$ |
| Pu-240 | α | 6 537 | 0 | $2.5 \cdot 10^{-7}$ | $5.0 \cdot 10^{-5}$ | $1.3 \cdot 10^{-12}$ |
| Pu-241 | β | 14 | 0 | $4.8 \cdot 10^{-9}$ | $9.0 \cdot 10^{-7}$ | $2.4 \cdot 10^{-14}$ |
| Pu-242 | α | 376 300 | 0 | $2.4 \cdot 10^{-7}$ | $4.8 \cdot 10^{-5}$ | $1.2 \cdot 10^{-12}$ |
| Am-241 | α | 432 | $1.1 \cdot 10^{-15}$ | $2.0 \cdot 10^{-7}$ | $4.2 \cdot 10^{-5}$ | $1.0 \cdot 10^{-12}$ |
| Am-243 | α | 7 380 | $2.9 \cdot 10^{-15}$ | $2.0 \cdot 10^{-7}$ | $4.1 \cdot 10^{-5}$ | $1.0 \cdot 10^{-12}$ |
| Cm-245* | α | 8 500 | $3.2 \cdot 10^{-15}$ | $2.1 \cdot 10^{-7}$ | $4.2 \cdot 10^{-5}$ | $1.1 \cdot 10^{-12}$ |
| Cm-246 | α | 4 730 | 0 | $2.1 \cdot 10^{-7}$ | $4.2 \cdot 10^{-5}$ | $1.1 \cdot 10^{-12}$ |

*Radionuclides which decay chains are considered in TILA-99

** In TILA-99 a half-life of $6.5 \cdot 10^4$ was used for Se-79

In the Table 8 are presented the ratios of EDFs and DCFs for unit releases for well, lake, running water, coastal areas, agricultural land and peat bog. A comparison for unit release to well between the EDFs and the DCFs revealed that all EDFs were higher than the DCFs. The ratios varied from 9 up to 240, the highest ratio was for Nb-94 and lowest for Ra-226. The EDFs were higher mainly due to the much smaller mixing volume considered in the approach compared to WELL-scenario in TILA-99 ($2\,630\text{ m}^3/\text{year}$ versus $100\,000\text{ m}^3/\text{year}$) (Vieno & Nordman 1999). The ratios or unit releases to a lake differed widely (0.027 -160). For many radionuclides the ratio was lower than

1. The highest ratio was for C-14 and lowest for Pa-231. The dilution volume in the lake was larger than in the TILA-99 (800 000 m³/year compared to 100 000 m³/year).

The ratios for unit releases to running waters varied also widely; from 0.41 to 410. The ratios were below 1 for two radionuclides, Ra-226 and Pa-231. The ratios for most radionuclides were lower than 6 and only a few radionuclides showed extreme ratios, C-14 (410), Cs-135 (210), Cs 137 (200) and Sn-126 (96) because of their high uptake and accumulation in fish. The ratios for unit releases to a coastal area were all below 1. The lowest ratio for Pu-231 was 0.00003 and highest for C-14 was 0,012. This is due the larger dilution volume used in EDFs compared to the TILA-99 and also that the large part of the radionuclides were supposed to leave the system through outflow reducing the amount available for exposure to the local population. Some radionuclides were also brought out from the water phase through binding to settling sediment particles.

The ratio to agricultural land varied considerably. The lowest value (0.00029) was for Pu-238 and the highest for Se-79 (130). The other radionuclides which had low ratios were C-14, Ni-63, Sr-90, Zr-93, Cs-137, Sm-151, Ra-226, Pa-231, Pu-239, Pu-240, Am-241, Cm-245 and Cm-246. The half-lives of the radionuclides are of important since nuclides are assumed to reach the biosphere within the groundwater and thereafter migrate towards the top soil from below.

For most radionuclides the ratios to a peat bog varied with range 2.5-5 100. The lowest value was for C-14 and the highest for Cl-36. The only exception was Se-79 with ratio 130 000. The extreme value for Se-79 is due to combination of strong sorption to peat and high root uptake factors. For most radionuclides the difference was very large this is not surprising since the retention of radionuclide instead of dilution was the primary concept in model. The variation in results of peat was large compared to the results for agricultural land. This reflected the lack of knowledge of all these elements' behaviour in peat. The other reason for differences in all cases was that in EDF values were mean values whereas in DCF values were deterministic values (Karlsson & Bergström 2000).

Table 8. The ratio between the EDF and DCF from TILA-99 (Vieno & Nordman 1999) for each from continuous releases of 1Bq/year to well, lake, running water, agricultural land and peat bog (Karlsson & Bergström 2000).

| Nuclide | Well EDF/DCF | Lake EDF/DCF | Running water EDF/DCF | Coastal area EDF/DCF | Agricultural land EDF/DCF | Peat bog EDF/DCF |
|---------|-----------------|-----------------|-----------------------------|----------------------------|---------------------------------|---------------------|
| C-14 | 83 | 160 | 410 | 0.012 | 0.009 | 2.5 |
| Cl-36 | 130 | 4.5 | 15 | 0.0021 | 100 | 5 100 |
| Ni-59 | 130 | 1.7 | 13 | 0.0024 | 34 | 940 |
| Ni-63 | 79 | 1.6 | 12 | 0.0024 | 0.10 | 210 |
| Se-79 | 140 | 9.3 | 44 | 0.017 | 130 | 130 000 |
| Sr-90 | 80 | 1.2 | 4.1 | 0.00035 | 0.21 | 120 |
| Zr-93 | 57 | 0.61 | 2.1 | 0.00028 | 0.48 | 77 |
| Nb-94 | 240 | 4.5 | 46 | 0.00046 | 28 | 260 |
| Tc-99 | 140 | 0.84 | 2.3 | 0.00011 | 23 | 140 |
| Pd-107 | 95 | 1.3 | 5.3 | 0.00024 | 15 | 370 |
| Sn-126 | 120 | 5.6 | 92 | 0.0010 | 52 | 3 800 |
| I-129 | 130 | 4.5 | 13 | 0.0017 | 93 | 60 |
| Cs-135 | 140 | 28 | 210 | 0.0025 | 30 | 290 |
| Cs-137 | 85 | 28 | 200 | 0.0025 | 0.003 | 55 |
| Sm-151 | 63 | 0.76 | 4.5 | 0.00041 | 0.001 | 12 |
| Ra-226 | 9 | 0.054 | 0.41 | 0.00004 | 0.69 | 120 |
| Th-229 | 87 | 0.20 | 4.8 | 0.00008 | 1.3 | 2 300 |
| Th-230 | 120 | 0.25 | 6.0 | 0.00009 | 2.4 | 3 700 |
| Pa-231 | 44 | 0.027 | 0.66 | 0.00003 | 0.56 | 360 |
| U-233 | 69 | 0.18 | 1.3 | 0.00020 | 1.5 | 26 |
| U-234 | 68 | 0.18 | 1.3 | 0.00020 | 1.6 | 26 |
| U-235 | 67 | 0.18 | 1.3 | 0.00020 | 1.5 | 25 |

| Nuclide | Well EDF/DCF | Lake EDF/DCF | Running water EDF/DCF | Coastal area EDF/DCF | Agricultural land EDF/DCF | Peat bog EDF/DCF |
|---------|-----------------|-----------------|-----------------------------|----------------------------|---------------------------------|---------------------|
| U-236 | 67 | 0.18 | 1.3 | 0.00020 | 1.5 | 25 |
| U-238 | 65 | 0.17 | 1.3 | 0.00020 | 1.4 | 23 |
| Np-237 | 75 | 0.67 | 6.4 | 0.00007 | 4.0 | 220 |
| Pu-238 | 53 | 0.068 | 1.6 | 0.00009 | 0.00029 | 31 |
| Pu-239 | 100 | 0.085 | 2.1 | 0.00009 | 0.77 | 340 |
| Pu-240 | 92 | 0.085 | 1.9 | 0.00009 | 0.52 | 290 |
| Pu-242 | 120 | 0.092 | 2.3 | 0.00009 | 1.0 | 380 |
| Am-241 | 62 | 0.61 | 3.7 | 0.00030 | 0.067 | 200 |
| Am-243 | 90 | 0.65 | 4.0 | 0.00030 | 2.4 | 1 800 |
| Cm-245 | 91 | 0.71 | 3.9 | 0.00028 | 0.81 | 910 |
| Cm-246 | 86 | | 3.8 | 0.00028 | 0.57 | 760 |

Pu-241 was not considered in SR and no ratio can therefore given

5.3.9 Uncertainties

Karsson & Bergström (2000) have presented preliminary uncertainty analyses for the five radionuclides: Cl-36, Se-79, Sn-126, I-129 and Cs-135. When looking on biological, chemical, physical and human related parameters to the well case, the biological parameters dominated the uncertainty for I-129, Cs-135 and Sn-126, whereas biological, chemical and physical parameters contributed about the same amount for Se-79. For Cl-36 chemical parameters dominated the uncertainty. Releases to lake for Se-79, Sn-126 and Cs-135 the bioaccumulation factor for fish, suspended matter and sedimentation rate contributed most to the uncertainty. The transpiration of water plants was the most important for Cl-36, whereas the distribution rate for milk contributed most to the uncertainty for I-129.

Releases to running water for all radionuclides except Cl-36 the bioaccumulation for fish dominated the uncertainty (Sn-126: 98 %, Se-79: 90 %), Cs-135: 68 % and I-129:41 %). Important factors for the uptake and accumulation of radionuclides in running water seem to be i.e. water chemistry and ecological parameters such as length of the biological food chain (Karlsson et al. 2000b). For Cl-36 transport of water plants (27 %), soil K_d (22 %) and runoff (22 %) contributed about the same amounts. Chlorine is very mobile element and is not accumulated in fish. In total in the running waters biological parameters dominated the uncertainty for Se-79, I-129, Cs-135 and Sn-126 whereas chemical-physical parameters were most important for Cl-36.

Releases to coastal areas for Se-79, Sn-126 and Cs-135 the bioaccumulation factor for fish and the residence time of the water in the inner coast contributed most to uncertainty. The latter parameter was important for the outflow of radionuclides from the coastal areas which decreases the concentrations and thus it can be estimated relatively well from site-specific studies. The transpiration of water plants was the most important parameter for I-129, Cs-135, and Cl-36.

For all five radionuclides the field area contributed significantly to uncertainty in releases to an agricultural land. It describes the size of an area which may have been influenced by contaminated groundwater from the repository. The size of the area depends e.g. on the groundwater flow patterns and varies seasonally. Soil K_d dominated the uncertainty for Cs-135 and was also important for Cl-36 and Se-79. The uncertainty of root uptake factor was important for I-129 and also for Cl-36, Se-79 and Sn-126.

In peat bogs the size of peat bog area was totally dominant explaining 81 % of the uncertainty for Cs-135, 70 % for I-129, 66 % for Sn-126, 65 % for Se-79 and 52 % for Cl-36. The other sources of uncertainty were peat K_d and root uptake factor. The peat bog size was important for dilution of radionuclides since the radionuclides sorbed in the peat bog are assumed to be homogeneously distributed within the area. In total, chemical-physical parameters dominated the uncertainty for all radionuclides whereas human related parameters had no importance (Karlsson & Bergström 2000).

There are high uncertainties coupled to any forecasts of future states of the geosphere-biosphere and also of future human behavior. The problem with lacking knowledge about what happens at the geosphere-biosphere interface needs to be further addressed. One way of modelling the geosphere-biosphere is to model releases different kind of recipients under the different time periods with consideration of accumulated radioactivity within certain the biospheric parts, e.g. that the radionuclides deposited in sediments during a “lake phase” are present within the soil in the following “land phase”.

The development module systems calculate dose conversion factors for different ecosystems but there is no coupling between the systems. In reality, radionuclides are transferred e.g. from lake to a stream and can be further transferred to e.g. a peat bog depending on the structure of the biosphere. In coming revisions of the safety assessment for the repository different modules should be connected to each other in order to follow the radionuclides through different ecosystems. The models should also be developed further so that time dependent releases can be calculated.

5.4 Level of consistency between modelling domains and conceptual models

It is important to understand the key processes which control radionuclide transfer in the GBIZ in order to convincingly convey results of the PAs to stakeholders. The potential GBIZ issues in Finland include (BIOPROTA 2005):

- Primary exposure (direct discharge to a water body or wetland area)
 - Discharge at rocky outcrops
 - Discharge through sediments
- Secondary exposure (sediment, contaminated by discharges, subsequently emerging as dry land)

According to BIOPROTA (2005) problems which arise in PAs through the range of FEPs that require consideration such as type of rock present, the positioning of the repository relative to the coast, dispersion and mixing in near-surface aquifers, and the potential for periglaciation and glaciation. Numerous FEPs may be of important to the GBIZ, but many are poorly understood. Not all can be considered and it is therefore important to identify those that are of greatest importance to the GBIZ. Potentially important issues in FEP analyses include (BIOPROTA 2005):

- Emission routes. Radionuclide emissions from the geosphere to the biosphere could result from a number of processes including gaseous and erosive releases and transport via groundwater. Radionuclide transport within the GBIZ is unlikely to be unidirectional. The influence of the geosphere and biosphere on the transfer mechanisms requires greater understanding.
- Biotic influence. Biota can influence radionuclide cycling and migration from the geosphere to the biosphere. However, the mechanisms are poorly understood. Potentially important mechanisms include transportation of groundwater and radionuclides from depth by forest systems and the influence of micro-organisms on radionuclide-relevant chemical and transport processes.
- Human influence on the GBIZ may be of importance. For example, greenhouse gases, acid rain, impermeable made ground can all influence the transport of radionuclides across the GBIZ.
- Chemical process. Rates of chemical processes within the GBIZ are greater than at depth and can be further influenced by electron imbalances that are greater towards the surface. The other elements may influence transport processes directly, for example through co-precipitation. A greater understanding of radionuclide cycling processes within the GBIZ and how other chemicals will affect reaction dynamics and radionuclide transport is therefore required.
- Climate change. There is an inherent uncertainty in the prediction of how climate change will affect the biosphere and thus range of receptors for radionuclides. This therefore impacts ability to predict the important features of the GBIZ for particular PAs. Climate change is also likely to impact on transport processes, including exerting and influence upon biologically influenced transport processes, and hydrochemical and geochemical processes.
- Hydrology and hydrogeocmistry. The hydrogeological model includes the concept of present-day groundwater composition and flow paths as well as palaeohydrological evolution. The time intervals of interest in palaeohydrology can include the short timescales of anthropogenic influence and the very long timescales of geological processes, with the focus of present day study being on a timescale of up to about 10 000 years. This timescale is of interest, as it makes use of information which it is possible to apply with a fairly high level of confidence (Posiva 2005).
- The rate of infiltration is affected by soil characteristics including ease of entry, storage capacity, and transmission rate through the soil. The soil texture and

structure, vegetation types and cover, water content of the soil, soil temperature, and rainfall intensity all play a role in infiltration rate and capacity.

- The crystalline bedrock consists of solid rock cut by a network of fractures. Water flows primarily along network of paths formed by a small portion of interconnected fractures (water-bearing fractures). The hydraulic characteristics of the rock are mainly defined by the properties of the fracture network, i.e. permeability, density, size and orientation distribution of fractures.

5.5 Handling of GBIZ in SR-Can

The main purpose of the SR-Can in the safety assessment of the final repository is to investigate whether the repository can be considered radiologically safe over time. In principle, this is established by comparing estimated releases of repository derived radionuclides and associated radiation doses with regulatory criteria. An important purpose of this safety assessment is, therefore, also to demonstrate near-complete isolation of the wastes under a wide range of circumstances and for a very long time.

Appropriate scientific and technical support for all statements made and data selected is essential to give confidence in the calculated results. Demonstrating understanding of the disposal system and its evolution is thus a crucial component in any safety assessment. The methodology used in the repository system the host rock and the geosphere-biosphere interface will evolve over time. Future states of the system will depend on (SKB 2006):

- Its initial state,
- A number of radiation related, thermal, hydraulic, mechanical, chemical and biological processes acting internally in the repository system over time,
- External influences acting on the system

Following the Swedish regulations, SR-Can (SKB 2004) will include three types of scenarios:

- Main scenario, which includes the expected evolution of the repository
- Less probable scenarios, which include alternative sequences of events to the main scenario
- Residual scenario, which evaluates specific events and conditions to illustrate the function of individual barriers

In the base variant of the main scenario, the repository is assumed to have been built according to the specifications with allowed tolerances. The main scenario includes that a small fraction of the canister of the order off one canister in a thousand, is expected to have an initial welding defect, such that the minimum copper thickness is less than the target value of 15 mm. The external conditions for the disposal system are defined in terms of a reference climate evolution (SKB 2004, Vieno & Ikonen 2005).

A variant of the main scenario will consider human-induced greenhouse effects. Other future human actions are not considered in the main scenario. Other variants of the main

scenario will consider alternative backfill materials, alternative interpretation of site data into bedrock models, as well as possible variants generated as the analyses of the base variant of the main scenario proceeds. Less probable scenarios will consider future human actions, and possibly also alternative processes and external conditions to the main scenario. Residual scenarios will consider out-of-tolerances deviations from the reference design of the repository. Uncertainties are covered and the significance of barrier functions are illustrated by means of bounding and “What if” analysis (SKB 2004, Vieno & Ikonen 2005).

The SKB FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or determined to be irrelevant for the KBS-3 concept. Based on the results of the FEP processing, an SR-Can FEP catalogue, containing FEPs to be handled in SR-Can, has been established (SKB 2006).

There is no unique way in which to classify uncertainties in a safety assessment. The classification adopted by SKB (2006) is, however, compatible with international practice (NEA 1991, 1997a) in SR-Can analysis. SKB has previously discussed the classification and nature of uncertainties in detail. (SKB 1996, Andersson 1999).

- *System uncertainty* concerns comprehensiveness issues, i.e. the question of whether all aspects important for the safety evaluation have been identified and whether the analysis is capturing the identified aspects in a qualitatively correct way, e.g. through the selection of an appropriate set of scenarios. In short, have all factors, FEPs, been identified and included in a satisfactory manner?
- *Conceptual uncertainty* essentially relates to the understanding of the nature of processes involved in repository evolution. This concerns not only the mechanistic understanding of a process or set of coupled processes, but also how well they are represented, and what is not represented, in a possibly considerably simplified mathematical model of repository evolution.
- *Data uncertainty* concerns all quantitative input data used in the assessment. There are a number of aspects to take into account in the management of data uncertainty. These include correlations between data, the distinction between uncertainty due to lack of knowledge (epistemic uncertainty) and due to natural variability (aleatoric uncertainty) and situations where conceptual uncertainty is treated through a widened range of input data. The input data required by a particular model is in part a consequence of the conceptualisation of the modelled process, meaning that conceptual uncertainty and data uncertainty are to some extent intertwined. Also, there are several conceivable strategies for deriving input data. One possibility is to strive for pessimistic data in order to obtain an upper bound on consequences in compliance calculations; another option is the full implementation of a probabilistic assessment requiring input data in the form of probability distributions.

The broad nature of the main scenario in SR-Can and other modern Safety Case (ONDRAF/NIRAS 2001, NAGRA 2002, McMurry et al. 2003), takes into account all the FEPs that are certain or almost certain to occur and thus describes the overall evolution of the disposal system, has in some respects diminished the role of a priori scenario development or analysis. Furthermore, the total number of the scenarios is typically not high. For example, SR 97 (SKB 1999) included only five scenarios: base

scenario, canister defect scenario, climate scenario, tectonics – earthquake scenario, and scenarios based on human actions. On the other hand, the practice adds pressure on the selection of the calculation cases and variants by means of which the actual performance of the disposal system under the influence of the expected evolution is assessed, as well as on posterior evaluation of the comprehensiveness of scenario (main scenario together with the less probable or residual scenarios) and the calculation cases and variants.

5.6 Safety Case Plan of Posiva

Safety Case includes a number of common elements with varying roles at the different phases of the repository development programme. These key elements and their relationships are outlined in Figure 20 developed within the Integration Group for the Safety Case (IGSC) of the OECD/NEA.

The concept of the Safety Case emerged in nuclear waste disposal in the late 1990's, and the term was not used in the TILA-99 safety assessment. The TILA-99 report (Vieno & Nordman 1999) focused on release and transport analyses of radionuclides. Together with the parallel and supporting reports – for example, on the investigation sites (e.g. Anttila et al. 1999), canister design (Raiko & Salo 1999), FEPs and scenarios (Vieno & Nordman 1997), geochemistry (Pitkänen et al. 1999), flow and transport (Löfman 1999, Poteri & Laitinen 1999), evolution of the disposal system (Crawford & Wilmot 1998), and databases (Ollila & Ahonen 1998, Vuorinen et al. 1999) – TILA-99 provided several of the key elements of a Safety Case. A profound synthesis of the multiple lines of evidence was, however, missing. The Posiva Safety Case portfolio is presented latest in the Safety Case Plan of Vieno & Ikonen (2005) and Ikonen (2006).

Principles of Safety Case

The purpose and context of the Safety Case includes strategies for siting, design and implementation of the repository as well as the strategy for performing of safety assessments (Vieno & Ikonen 2005). The information and analysis tools for safety assessment, which are collectively termed the assessment basis, include:

- The system concept – that is a description of the repository design including the engineered barriers, the geologic setting and its stability, how both engineered and natural barriers are expected to evolve over time, and how they are expected to provide safety
- The scientific and technical information and understanding, including the detailed support for the expected evolution and safety of the disposal system and assessments of the uncertainties in scientific understanding
- The analysis methods, computer codes and databases that are used in the modelling of the disposal system.

The adequacy and reliability of the assessment basis for carrying out safety assessments must also be addressed as a part of the Safety Case (Vieno & Ikonen 2005, Ikonen 2006). Finally, a synthesis will be made that draws together key findings from the Safety Case, namely the principal evidence, analyses and arguments that quantify and substantiate a claim that the repository is safe, including an evaluation of uncertainty.

This judgement is a statement of expert confidence in the safety of the disposal system in the context of the assessment basis available at the current stage of the repository programme (Vieno & Ikonen 2005). Outline of the safety concept for KBS-3 type repository for spent fuel in crystalline bedrock is presented in Figure 21 (Posiva 2003, Vieno & Ikonen 2005).

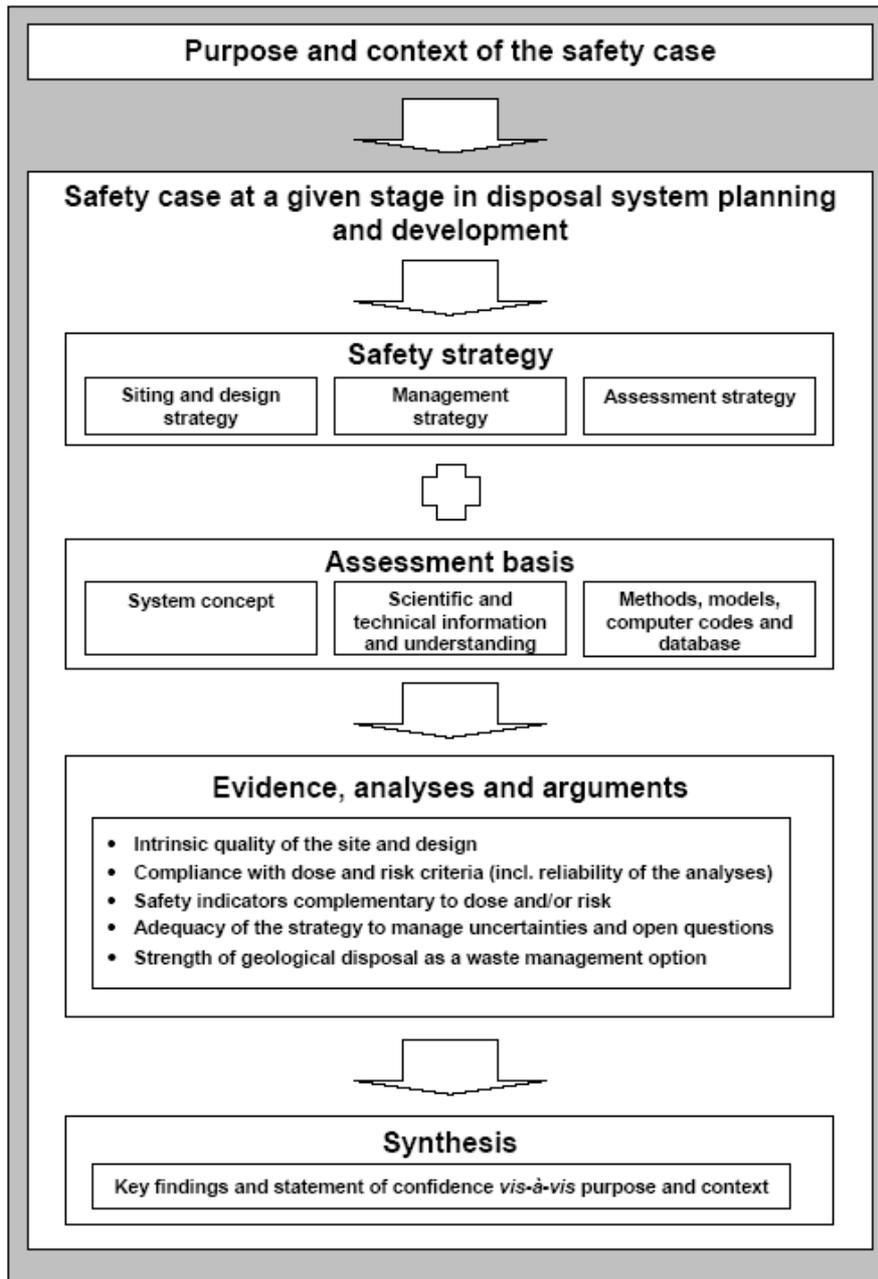


Figure 20. Overview of the relationship between the different elements of a Safety Case (NEA 2004b).

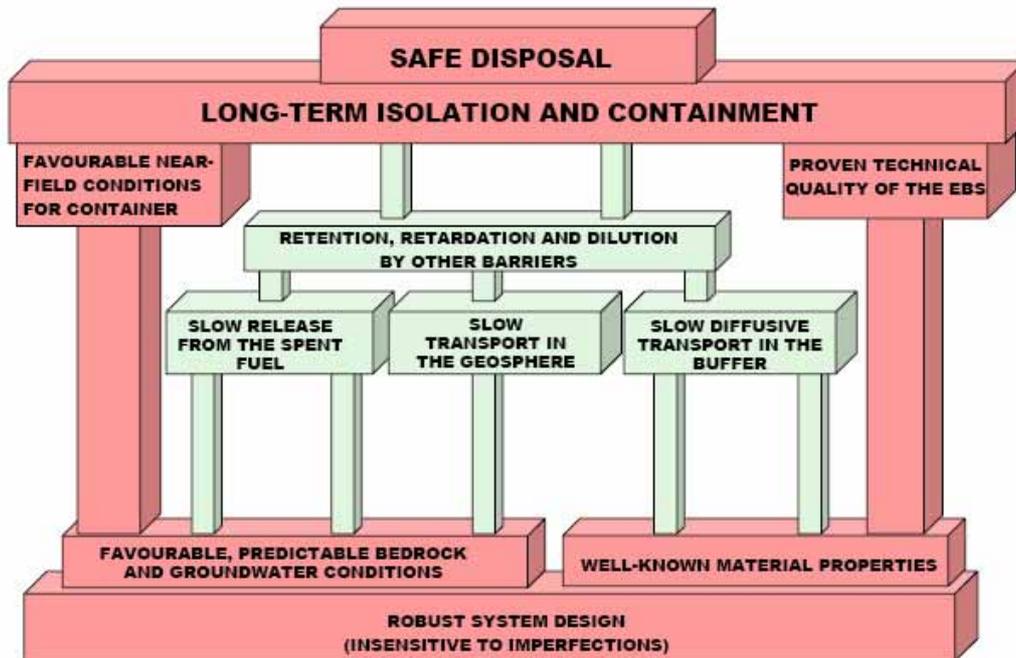


Figure 21. Outline of the safety concept for KBS-3 type repository for spent fuel in crystalline bedrock. Red pillars link characteristics of the disposal system to other characteristics on which they primarily depend. Green pillars indicate secondary characteristics and dependences (Posiva 2003, Vieno & Ikonen 2005).

Safety Case portfolio

In Posiva's case, a specific feature is the long time span of the investigations. By 2012, the investigations at the Olkiluoto site and on the KBS-3 disposal concept will have been continued over thirty years. The investigations will be continued over the construction and operation period of the repository which will extend over several decades. Several comprehensive safety assessments have already been carried out and more will be performed when the construction and operation of the repository progresses in stages. An additional advantage for Posiva's programme is the close cooperation with the parallel programme of SKB studying and assessing a similar disposal concept at the investigation sites at the other side of the Baltic Sea (Vieno & Ikonen 2005).

To benefit from the advantages of long site investigation programme and close cooperation with the parallel programme of SKB, and to facilitate flexible and progressive development of the Safety Case, a portfolio approach will be employed in the reporting of the Safety Case. In practice, this implies that the main components of the Safety Case will be living, fairly independent reports based on supporting technical reports. At the various milestones of the programme (e.g. interim reporting in 2006 and 2009, and the PSAR in 2012), the reports will be linked and complemented to a Safety Case by means of additional analyses and a summary report (Vieno & Ikonen 2005).

The Safety Case portfolio will be compiled of a number of main reports as illustrated in Figure 22 (Vieno & Ikonen 2005). Especially important is to notice that the

geoscientific and scientific reports aim to be as realistic as possible, whereas the radiation safety related reports need to be conservative by the regulations. The Safety Case portfolio will be compiled of the following main reports:

- Olkiluoto site report
- Reports on the characteristics of the spent fuel, canister and repository designs
- Process report describing processes affecting the evolution of the disposal system
- Evolution of the site and repository
- Biosphere assessment
- Radionuclide transport
- Complementary evaluations of safety
- Summary report.

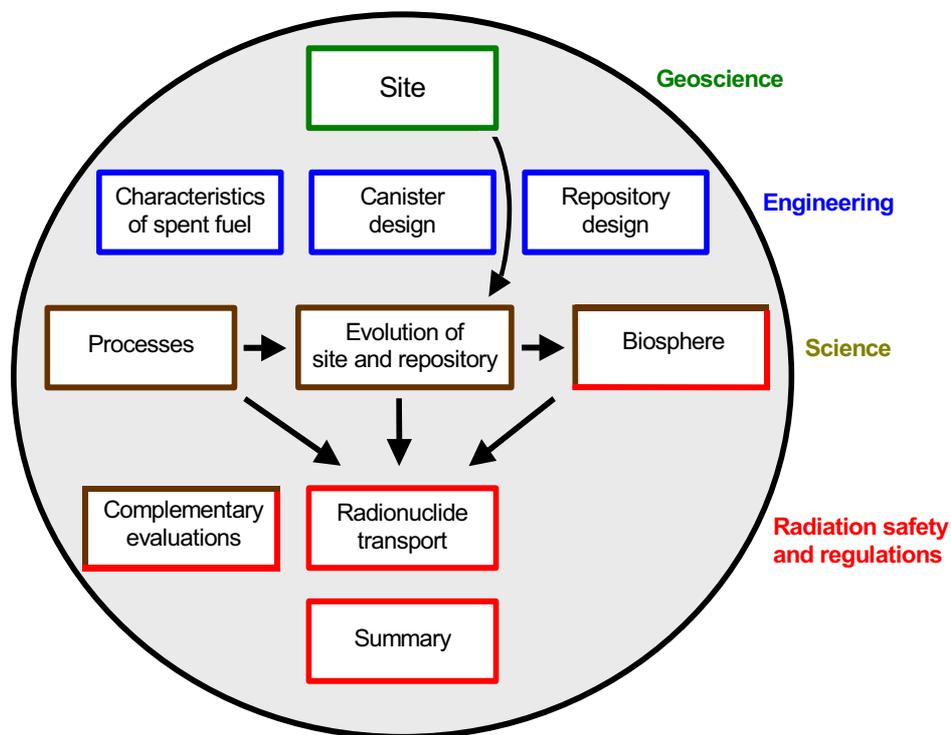


Figure 22. Main reports of the Safety Case. The nature of the reports is indicated by the colours of the boxes and the arrows show the most important transfers of knowledge and data (Vieno & Ikonen 2005).

For practical reasons and in order to provide consistent and transparent discussions and assessments, all biosphere matters will be dealt with in a Biosphere assessment report at the main level of Safety Case reporting, instead of distributing them among the Site, Process, Evolution and Radionuclide transport reports (Vieno & Ikonen 2005). The Biosphere Assessment Portfolio was introduced in the Safety Case planning report (Vieno & Ikonen 2005). Similarly as the overall Safety Case consists of main component reports, of which Biosphere Assessment is one, the biosphere assessment is divided into a number of more easily manageable components each producing one or more background reports to be summarised and integrated at the Safety Case main level, i.e. in the Biosphere Assessment report, into a portfolio (Figure 23). Dialogue scheme

between the Safety Case components and the Biosphere Assessment main phases is presented in Figure 24 (Ikonen 2006).

In addition to structuring the biosphere assessment portfolio into thematic folders, the folders are categorised in three levels: Science reports aim to form the realistic discussion basis for the assessment and to give recommendations that are easier to accept in the scientific community to the further assessment modelling, where numerous simplifications and assumptions are required. The technical documentation is the bridge between the recommendations and the actual assessment; it describes the assessment models and the selected data. The assessment reports then include the actual radionuclide transport calculations of the concentrations in environmental media, and the assessment of exposures to both humans and the other biota. Finally, the summary and full conclusions of the biosphere assessment will be presented in the Biosphere Report (Ikonen 2006).

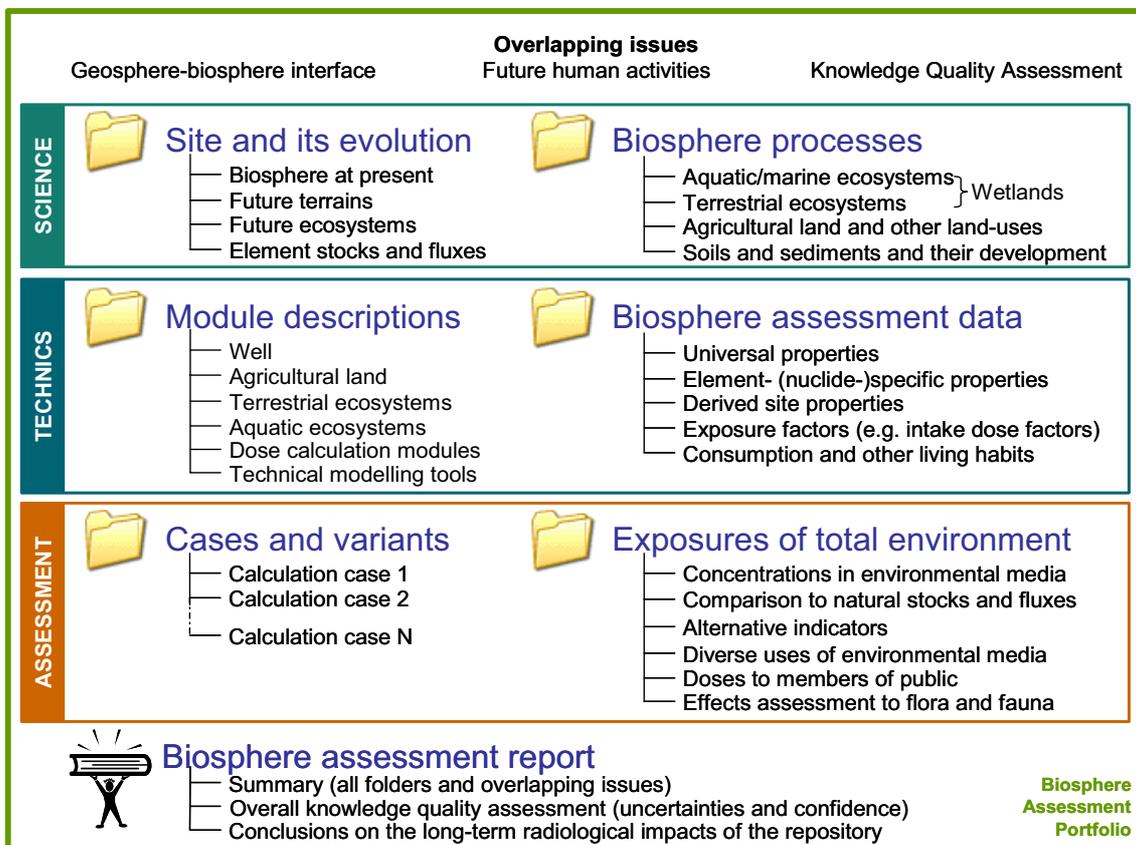


Figure 23. Folder structure and main components of the Biosphere Assessment portfolio (Ikonen 2006).

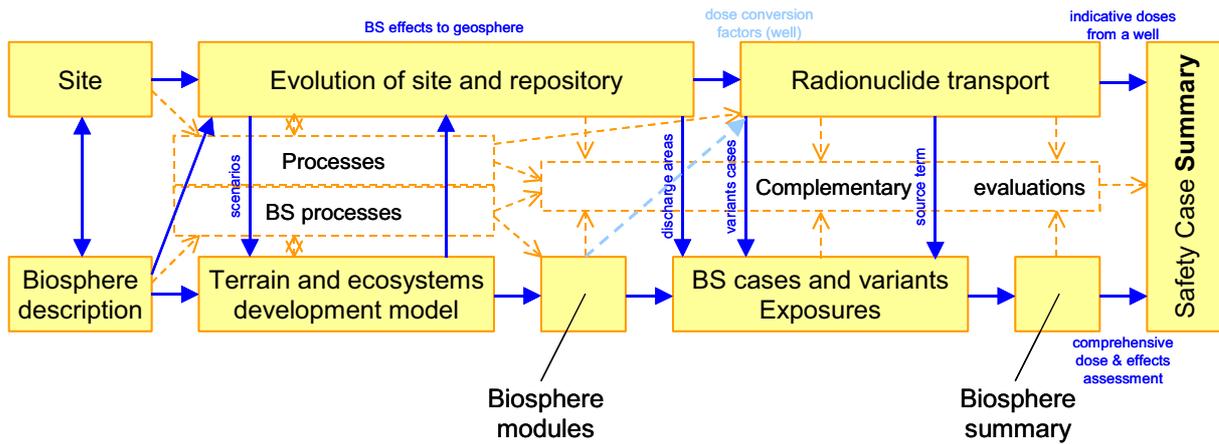


Figure 24. Idealistic dialogue scheme between the Safety Case components and the Biosphere Assessment main phases. Due to the tight time schedule this is not entirely conceivable in practice, but with the planned iteration the approach should produce an adequately mature overall understanding for the PSAR to be then further developed (Ikonen 2006).

For constructing site-specific biosphere models, descriptions of present-day conditions and future evolution of the Olkiluoto site focusing on the next several thousand years are needed. The level of details depends on the models, and the models should be based on the knowledge and data on the site; an iterative process is required. A stepwise methodology for this has been outlined in Posiva (2003), Ikonen et al. (2004), Ikonen (2006), Haapanen et al. (2006, in preparation) and in Figure 25.

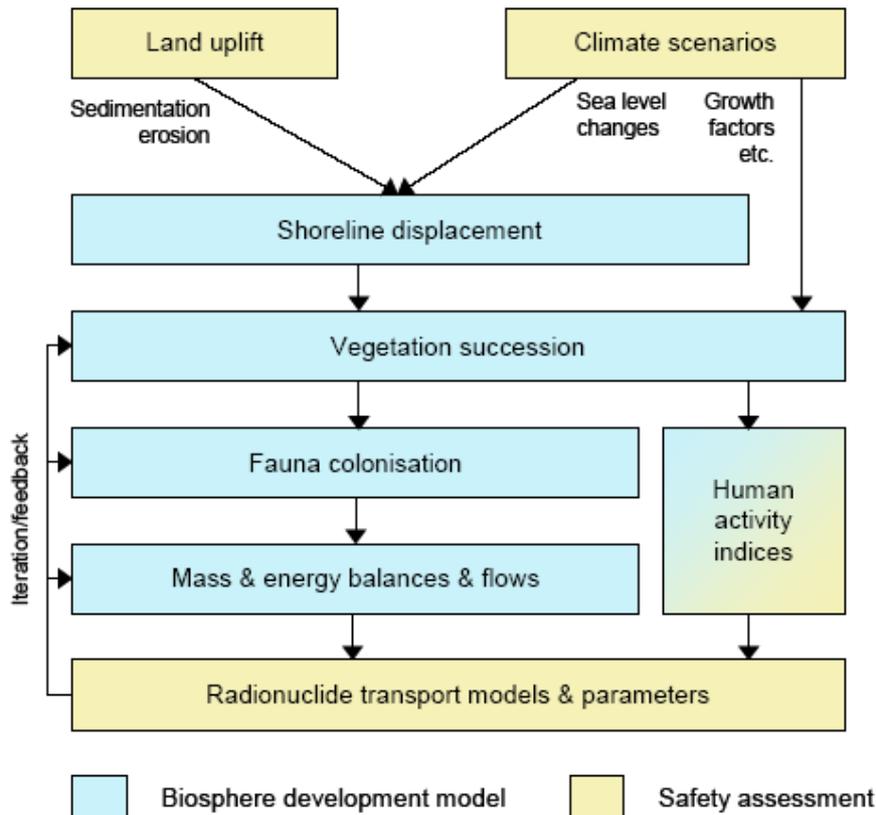


Figure 25. Stages of the biosphere development modelling approach (Ikonen et al. 2003).

5.7 Recommended treatment of GBIZ

The change from bedrock groundwater to bioavailable region takes place without gaps in the top bedrock, the overburden and aquatic environments. However, the transfer of radionuclides across the geosphere-biosphere interface is usually complex, involving numerous interlinked physical, chemical and biological processes that often occur in cyclical or episodic ways.

It is acknowledged that a genuine site-specific treatment and incorporation of overburden and aquifers into the GBIZ models are needed to cover all relevant FEPs and to treat properly the zone in the modelling chain of groundwater flow, geosphere and biosphere transport of radionuclides (Vieno & Ikonen 2005). Numerous FEPs are important to the GBIZ and many overlap in the modelled interface zone. However, many are still poorly understood. In the GBIZ safety modelling, all can not be considered and it is therefore important to identify those that are of greatest importance. The international, TVO's, Posiva's and SKB's (e.g. SKB 2006) exercises have provided a significant background databases of features, events and processes which may affect disposal of spent fuel in copper-iron canisters in a KBS-3 type repository. In spite of that the FEP analyses need more detailed and consistent understanding and discussion. This report will give direct input to the Posiva's Process Report (2007, in preparation).

Uncertainties cannot be avoided in modelling and it is thus necessary to assess and demonstrate the level of confidence in the modelling and its results. However, there is no unique way in which to classify uncertainties in a safety assessment. Tools for confidence assessment have been developed in SKB (SKB 2006), and Posiva (Posiva 2005). The protocol includes:

- Data that have been used
- Available data that have not been used and the reason for their omission (e.g. not relevant, poor quality, lack of time)
- What would have been the impact of considering the unused data
- How is the accuracy of data established (e.g. using QA procedures)
- Data types where accuracy is judged to be low and quantification of the accuracy if possible
- Biased data produced and used in the modelling and how these can be corrected for the bias
- How well is the initial state known, qualitatively and quantitatively, i.e. are all important aspects of the initial state identified and how well can they be quantitatively described?
- Have all relevant internal processes been identified in the relevant time frames? How well are they understood mechanistically?
- Have all relevant external events and phenomena been identified? How well can they be quantified?
- How can a representative account of the system evolution be given, taking into account all the types of uncertain factors mentioned above? How well can the internal processes be represented mathematically to give a realistic account of the system evolution? How well are all the input data necessary for the quantification of the system evolution known?

A large number of factors affecting long-term safety need to be handled in the assessment in a quality assured (QA) manner. These factors, or features, events and processes, FEPs, are collected in a database that is also used as a QA instrument. In broad terms, a QA plan for a long-term safety assessment of a spent nuclear fuel repository aids in assuring that all relevant factors for long-term safety have been appropriately included and handled in the safety assessment. Although no QA system will rigorously prove that this is the case, a purpose designed QA plan and QA system will assist the in carrying out the safety assessment in a structured and comprehensive manner and aid in judging the quality and comprehensiveness of the assessment.

6 CONCLUSIONS

The systematic analyses of FEPs are recognised in all national high-level nuclear waste management programmes as an essential step to assure safety analyses of system evolution. The KBS-3 concept at Olkiluoto aims at long-term isolation and containment of spent fuel assemblies within copper-iron canister to prevent any releases of radionuclides from the repository into geosphere as well as into biosphere for 100 000 years, at least.

The principal variability in the GBIZ, especially in biosphere is driven by climatic change. The change from bedrock groundwater to bioavailable region takes place without gaps in the top bedrock, the overburden (both mineral and organic soil) and aquatic sediments. However, it is more appropriate to recognise that there are regions of space that should overlap the geosphere and biosphere model domains (see Figure 1). Thus, it is acknowledged that a site-specific treatment and incorporation of safety assessments are needed to cover all relevant FEPs and to treat properly the zone in the modelling chain of groundwater flow, geosphere and biosphere transport of radionuclides.

Problems envisaged with the treatment of the GBIZ are associated with defining the boundary conditions for both far-field and biosphere/near-field models and the derivation of the source term for biosphere modelling from the far field modelling. The GBIZ is not a separate modelling domain and the processes and events affecting the transport of radionuclides within the GBIZ should not be considered to be unidirectional; for example climate change or changes in land-use, originally appearing in the biosphere domain, will also have an effect on the (upper) geosphere.

The biosphere is more diverse system under continuous development and impossible to model accurately. Thus some inherent uncertainty already in the conceptual level of modelling has to be accepted. In addition of needs to handle spatial and temporal variations, radionuclide transport models in GBIZ are complex, non-linear, and include a number of input parameters that are usually time-dependent, associated with large uncertainties and often correlated to each other (BIOPROTA 2005).

In the future the characteristics of the GBIZ, especially in biosphere will vary over time and the most important long-term external factors are shore-line displacement and the glacial cycle highly related to global climate change. Long term internal development will also affect the persistence of the ecosystems. For instance, lakes will transform to mires, but this can also be applied to wells and agricultural land. All have constraints in life length and thus also a maximum time for radionuclide accumulation. The positions of discharge locations of radionuclides into GBIZ are essential input to the modelling of radionuclide transport and they will vary with time.

Assessing the impacts of releases of radioactivity into the environment rely on a great variety of factors. Important among these is an effectively justified level of understanding of radionuclide behaviour in the environment, the associated migration pathways and the processes that contribute to radionuclide accumulation and dispersion among and within specific environmental media.

In the radionuclide transport modelling the uncertainties is more related to limited knowledge than to spatial and temporal. Therefore modelling may also in the future be based on deterministic parameter values. Employing of relatively simple deterministic

models should facilitate comprehensive uncertainty analyses based on systematic combinations of the best-estimate and conservative parameter values (Vieno & Ikonen 2005).

A central theme in any safety assessment methodology must be the management of all relevant types of uncertainty. This management amounts to classifying and describing uncertainties, as well as handling them in a consistent manner in the quantification of the repository evolution and of the radiological consequences to which it leads. It also implies comparing the results of the assessment with regulatory criteria in such a way that appropriate allowance is made for the uncertainties associated with the assessment. Interaction matrices can be used to present effects and couplings, but elaborate enough discussion is needed for each process identified with consideration of nuclide-dependent behaviour. Besides existing FEP databases and cooperation with SKB, information may be obtained from the ongoing works within the international collaboration forum.

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APPENDICES

Appendix 1. List of FEP by FEP according to their importance in biosphere, geosphere and geosphere-biosphere interface zone. However, the most of the FEPs overlap and could be categorized in the other way (e.g. far-field), in this report the emphasis is on GBIZ.

Appendix 2. The various radionuclides of concern the key issues in geosphere-biosphere aspects of assessment of the long-term impact of contaminant releases associated with radioactive waste management (Leclerc-Cessac & Smith 2003).

Appendix 3. The main long-lived radionuclides of concern (ANDRA 2002).

Appendix 4. The main transport processes (IUR-Report 2006).

Appendix 5. The general interaction matrix of Np-237 in a terrestrial ecosystem (IUR-Report 2006).

Appendix 6. The general interaction matrix of C-14 in a terrestrial ecosystem (IUR-Report 2006).

Appendix 7. The general interaction matrix of C-14 in an aquatic ecosystem (IUR-Report 2006).

Appendix 8. The general interaction matrix of Cl-36 in a terrestrial ecosystem (IUR-Report 2006).

Appendix 9. The general interaction matrix of Cl-36 in an aquatic ecosystem (IUR-Report 2006).

Appendix 10. The general interaction matrix of U-238 in a terrestrial ecosystem (IUR-Report 2006).

Appendix 11. The general interaction matrix of U-238 and Np-237 in an aquatic ecosystem (IUR-Report 2006).

Appendix 12. The general interaction matrix of Tc-99 in an aquatic ecosystem (IUR-Report 2006).

APPENDIX 1

List of FEP by FEP according to their importance in biosphere, geosphere and geosphere-biosphere interface zone. However, the most of the FEPs overlap and could be categorized in the other way, in this report the emphasis is on GBIZ.

| PARAMETER | FEP | REFERENCE |
|--|-------------|-----------------------------------|
| Accumulation in peat | GBIZ | SKI/SKB |
| Accumulation in sediments | GBIZ | SKI/SKB |
| Accumulation in soils | GBIZ | WIPP |
| Accumulation in soils and organic debris | GBIZ | NEA |
| Accumulation of gases under permafrost | GBIZ | SKI/SKB, TVO-85 |
| Acid rain | Biosphere | AECL, WIPP, TVO-85 |
| Adsorption | GBIZ | BIOPROA |
| Advection | GBIZ | BIOPROTA |
| Aeolian deposition/erosion | Biosphere | WIPP |
| Agricultural and fisheries practice changes | Biosphere | NEA, NAGRA |
| Alkali flats (Extreme and continuous dry weather can cause the accumulation of salts and contaminants at the soil surface, where water continuously evaporates) | Biosphere | AECL |
| Alteration/weathering of flow paths | GBIZ | SITE-94, TVO-85 |
| Altered soil or surface water chemistry (e.g. by human activities) | GBIZ | NEA, WIPP, SKI/SKB, TVO-92 |
| Animal diets | Biosphere | AECL |
| Animal grooming and fighting | Biosphere | AECL |
| Animal soil ingestion | Biosphere | AECL |
| Animal uptake | Biosphere | NEA, WIPP |
| Animals | Biosphere | WIPP |
| Anthropogenic climate change | Biosphere | NEA, TVO-85 |
| Arable farming | Biosphere | WIPP |
| Ashes and sewage sludge, fertilizers | Biosphere | AECL |
| Atmosphere | Biosphere | NAGRA |
| Bacteria and microbes in soil | GBIZ | AECL |
| Basement alteration (Erosion of the crystalline bedrock) | Geosphere | NAGRA, TVO-85 |
| Bioaccumulation | Biosphere | AECL |
| Bioaccumulation and translocation | Biosphere | HMIP |
| Biocatalysis | Biosphere | BIOPROTA |
| Biochemistry | Biosphere | BIOPROTA |
| Biocolloids | Biosphere | BIOPROTA |
| Biocommunities | Biosphere | BIOPROTA |
| Biofilms | Biosphere | BIOPROTA |
| Bioconcentration | Biosphere | BIOPROTA |
| Biogas production | Biosphere | AECL |

APPENDIX 1 (2)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|---------------------------------|
| Biogeochemical processes | GBIZ | HMIP |
| Biological activity (sulphate-reducing bacteria) | GBIZ | TVO-92, TILA-96 |
| Biological evolution | Biosphere | AECL |
| Biological weathering | Biosphere | BIOPROTA |
| Biomagnification | Biosphere | BIOPROTA |
| Bioturbation | Biosphere | NAGRA, AECL, BIOPROTA |
| Capillary rise | GBIZ | NAGRA, BIOPROTA, AECL |
| Carcasses | Biosphere | AECL |
| Carcinogenic contaminants | GBIZ | AECL |
| Carbonate production | GBIZ | BIOPROTA |
| Cavings (Human intrusion by drilling) | GBIZ | WIPP, TVO-85 |
| Cavitation (Formed in the bedrock or soils due to intensive flow of groundwater, may be formed in the melting phase of glaciation) | Geosphere/repository | AECL, TVO-85 |
| Change in sea level | GBIZ | SKI/SKB, TVO-85, TILA-96 |
| Change of groundwater chemistry in nearby rock (TVO-92 includes a scenario where conditions in the repository and geosphere are assumed to be oxidising) | GBIZ | SKI/SKB, TVO-92 |
| Changes in fracture properties | Geosphere/repository | WIPP, TVO-85 |
| Changes in groundwater Eh | GBIZ | WIPP |
| Changes in groundwater flow | GBIZ | WIPP |
| Changes in groundwater pH | GBIZ | WIPP |
| Changes in groundwater recharge and discharge areas | GBIZ | WIPP |
| Changes in situ stress field (Effects of a particular type of drastic change are considered in the postglacial faulting scenario of TVO-92) | Geosphere/repository | NEA, TVO-92 |
| Changes in radionuclide inventory (Deals with the effects of radioactive decay) | GBIZ | SITE-94 |
| Changes in regional stress (Effects of a particular type of drastic change are considered in the postglacial faulting scenario of TVO-92) | Geosphere | WIPP, TVO-92 |
| Changes in sorptive surfaces | GBIZ | WIPP |
| Chemical ageing and recrystallation | GBIZ | BIOPROTA |
| Chemical denutiation and weathering | GBIZ | NEA, TVO-85, BIOPROTA |
| Chemical interactions | GBIZ | AECL |

APPENDIX 1 (3)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|--|
| Chemical precipitation | GBIZ | AECL |
| Chemical sabotage (Human intrusion is not mentioned in TILA-96, TVO-92 or TVO-85) | Biosphere | SKI/SKB |
| Chemical toxicity of wastes | GBIZ | SKI/SKB |
| Chemical transformations | GBIZ | NEA |
| Chemical weathering | GBIZ | WIPP, TVO-85 |
| Climate change (Glaciation related climate changes and the greenhouse effects) | GBIZ | AECL, WIPP, NEA; HMIP, TVO-92 |
| Coastal erosion and estuarine development | GBIZ | WIPP; NEA, TVO-92 |
| Coastal surge, storms and hurricanes (Very low consequences) | Biosphere | NEA |
| Coastal water use | Biosphere | WIPP |
| Colloids (Filtration, formation and ability, dissolution, transport, generation- source, complexing agents, particles in canister) | GBIZ | SKI/SKB, NEA, WIPP, AECL, NAGRA, TVO-92, SITE-94, TILA-96, BIOPROTA |
| Complex formation | GBIZ | BIOPROTA |
| Complexation of organics and agents | GBIZ | AECL, SKI/SKB, NEA, TVO-92 |
| Concrete (The TILA-96 and TVO-92 data related to retardation and transport of radionuclides is in general rather conservative when compared with other safety assessments) | Geosphere/repository | AECL, TVO-92, TILA-96 |
| Consolidation of seal (Related to disposal in salt formation) | Geosphere/repository | WIPP |
| Consolidation of waste | Geosphere/repository | WIPP |
| Consumption of uncontaminated products | Biosphere | NAGRA |
| Container failure | Geosphere/repository | TVO-92 |
| Contaminated products (non-food) | GBIZ | NAGRA |
| Convection, turbulence and diffusion (atmospheric) | Biosphere | AECL |
| Corrosive agents, sulphides, oxygen etc. | Geosphere | SKI/SKB |
| Critical groups (Agricultural labour, evolution, house location, individuality, leisure pursuits, pets) | Biosphere | AECL |
| Crop fertilizers and soil conditioners, crop storage | Biosphere | AECL |

APPENDIX 1 (4)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|---|
| Criticality (nuclear criticality) | GBIZ (Fuel) | AECL, SKI/SKB, TVO-85, SITE-94 |
| Crop fertilizers and soil conditioner, storage, cure for cancer | Biosphere | AECL |
| Cuttings (Materials intersected by the drill bit and brought to the surface in a human intrusion scenario) | Geosphere/repository | WIPP, TVO-85, TILA-96 |
| Damage to ozone layer (Very low consequences) | Biosphere | WIPP |
| Damming of streams or rivers, reservoirs, built/draind (Potential adverse effects on geohydrology are covered by the conservative flow model and data) | GBIZ | AECL, WIPP, NEA |
| Decontamination materials left (Effects of stray materials left in the repository) | Geosphere/repository | SKI/SKB, TVO-92 |
| Deep groundwater abstraction (Use of water from a bored well is the main exposure pathway in TILA-96 and TVO-92) | Geosphere/repository | NAGRA, TVO-92, TILA-96 |
| Deep saline water intrusion | Geosphere/repository | TVO-92, SITE-96, TILA-96 |
| Degradation of organic material (Deals with a case where the waste itself contains organic material) | GBIZ | WIPP |
| Degassing | GBIZ | BIOPROTA |
| Degradation of rock reinforcement and grout (The TILA-96 and TVO-92 data related to retardation and transport of radionuclides is in general rather conservative when compared to other safety assessments) | Geosphere/repository | TVO-92, SITE-94, TILA-96 |
| Deliberate drilling intrusion, mining intrusion (Olkiluoto is located in area of common rock types and have low ore or mineral potential) | Geosphere/repository | WIPP, HMIP, TVO-85 |
| Democratic change and urban development (Not considered) | Biosphere | NEA |
| Denudation | GBIZ | NEA, TVO-85 |
| Deposition (Wet and dry) | Biosphere | AECL, BIOPROTA |
| Dermal sorption (sorption in skin) | Biosphere | AECL |

APPENDIX 1 (5)

| PARAMETER | FEP | REFERENCE |
|--|----------------------|---|
| Desert and unsaturation (Very low probability) | Biosphere | SKI/SKB |
| Desorption | GBIZ | BIOPROTA |
| Diffusion | GBIZ | NEA, AECL, WIPP, SITE-94, BIOPROTA |
| Dilution | GBIZ | SKI/SKB, TVO-92, SITE-94 |
| Dilution of radionuclides in groundwater | GBIZ | SKI/SKB, TVO-92, SITE-94, BIOPROTA |
| Discharge zones | GBIZ | AECL, TILA-96 |
| Dissolution | GBIZ | BIOPROTA |
| Ditching | Biosphere | BIOPROTA |
| Drought (Very low probability) | Biosphere | AECL |
| Dust storms and desertification | Biosphere | AECL |
| Dry lake bed remobilization | Biosphere | AECL |
| Down cutting and gorge formation | Biosphere | AECL |
| Dual porosity | Biosphere | BIOPROTA |
| Earth tides (The pressure variations may cause a pulsating exchange of water between fractures and rock matrix. This can enhance retention of sorbing radionuclides in the rock matrix) | Geosphere/repository | SITE-94 |
| Earthmoving | Geosphere/repository | AECL, TVO-85 |
| Earthquakes | Geosphere | SKI/SKB, AECL, TVO-92 |
| Earthworks | Biosphere | NAGRA, TVO-85 |
| Ecosystem | GBIZ | BIOPROTA |
| Ecological change, response to climate | GBIZ | NEA |
| Effect of biofilms on microbial gas generation (Deals with the disposal of wastes containing organic matter) | GBIZ | WIPP |
| Effect of plate movement | Geosphere/repository | SKI/SKB, TVO-85 |
| Effect of pressure on microbial gas generation | GBIZ | WIPP |
| Effective moisture (Recharge) | GBIZ | NAGRA |
| Effects of saline-freshwater interface | GBIZ | NEA |
| Effects of dissolution | Geosphere/repository | TVO-92 |
| Effects of natural gases | Geosphere/repository | HIMP, TVO-92 |
| Element solubility | GBIZ | NAGRA |
| Enhanced diffusion | GBIZ | TVO-92, TILA-96 |
| Enhanced groundwater flow | GBIZ | SKI/SKB |

APPENDIX 1 (6)

| PARAMETER | FEP | REFERENCE |
|--|--------------------------------|------------------------------------|
| Erosion | GBIZ | TVO-85 |
| Erosion – lateral transport | GBIZ | AECL, NAGRA |
| Erosion on surface/sediments | GBIZ | SKI/SKB, TVO-85 |
| Erosion (Wind) | Biosphere | TVO-85 |
| Erosion/denudation | GBIZ | TVO-85 |
| Erosion/deposition | GBIZ | TVO-85 |
| Estuaries | Biosphere | WIPP |
| Evapotranspiration | Biosphere | NAGRA, BIOPROTA |
| Excavation effects | Geosphere/repository | NAGRA, WIPP, TVO-85, SITE-94 |
| Excretion (Microbiota) | Biosphere | BIOPROTA |
| Exfiltration to local aquifer, to surface waters | GBIZ | NAGRA |
| Exhalation | Biosphere | BIOPROTA |
| Exit from glacial/interglacial cycling (Most scenarios of TILA-96 and TVO-92 assume non-glacial conditions) | GBIZ | HMIP, TVO-92, TILA-96 |
| Exploitation and exploratory drilling | Geosphere/repository | NEA, NAGRA, TVO-85 |
| Explosion | Biosphere/Geosphere/repository | SKI/SKB, AECL, WIPP, TVO-85 |
| Exposure pathways | GBIZ | NAGRA |
| Exposure external Exposure ingestion Exposure inhalation (Drinking water is the only exposure pathway in TILA-96 and TVO-92 considers also other exposure pathways) | GBIZ | AECL, HMIP, TVO-92, TILA-96 |
| External contamination | Biosphere | BIOPROTA |
| Extraterrestrial events (Probability and consequences of meteorite impact) | Biosphere | SKI/SKB, TVO-85 |
| Extreme channel flow of oxidants and nuclides | GBIZ | SKI/SKB |
| Extremes of precipitation, snow melt and associated flooding | Biosphere | NEA |
| Far field hydrochemistry – acids, oxidants, nitrate | Geosphere/repository | SKI/SKB |
| Far field transport | Geosphere/repository | HMIP, TVO-92, TILA-96 |
| Fault movement | Geosphere/repository | BIOPROTA |
| Fermentation | Biosphere | BIOPROTA |
| Fracture flow (Advection) | Geosphere/repository | BIOPROTA |
| Faulting (TVO-92 includes a scenario where a major post-glacial fault is assumed to intersect the repository) | Geosphere/repository | NEA, AECL, WIPP, SKI/SKB, TVO-92 |

APPENDIX 1 (7)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|-----------------------------------|
| Filtration | GBIZ | AECL, TVO-85 |
| Fires | Biosphere | NAGRA, AECL, WIPP |
| Fish farming | Biosphere | NAGRA, AECL, WIPP |
| Fixation | GBIZ | BIOPROTA |
| Flooding (Potential adverse effects on groundwater flow are covered by the conservative flow model and data) | Biosphere | AECL |
| Flushing of water bodies | Biosphere | AECL |
| Fluvial deposition, erosion, sedimentation | GBIZ | WIPP, NAGRA, TVO-85 |
| Food preparation, food chain equilibrium | Biosphere | AECL, NAGRA |
| Formation of cracks, fractures, faults | Geosphere/repository | AECL, WIPP, TVO-85, TVO-92 |
| Formation of gases | Geosphere/repository | AECL, TVO-92 |
| Fracture infills (Positive FEP, precipitation of minerals as fracture infills can reduce hydraulic conductivities and enhance sorption of radionuclides) | Geosphere/repository | TVO-92, TILA-96 |
| Fracture mineralization and weathering | Geosphere/repository | NEA, TVO-85 |
| Fracturing (Large-scale fracturing in the geosphere, like post-glacial faulting scenario) | Geosphere/repository | TVO-92 |
| Freshwater sediment transport and deposition | Biosphere | NEA |
| Frost weathering | Biosphere | NEA, TVO-85 |
| Fulvic acids | GBIZ | AECL, TVO-92 |
| Future biosphere conditions | GBIZ | NAGRA |
| Future boreholes and undetected past boreholes | GBIZ | SKI/SKN, TVO-85 |
| Future climatic conditions | GBIZ | NAGRA |
| Game ranching | Biosphere | AECL |
| Gas discharge, effects, escape | GBIZ | NEA, HMIP, TVO-92, TILA-96 |
| Gas flow and transport, generation | GBIZ | SKI/SKB, TVO-92, SITE-94 |
| Gas leakage into buildings | Biosphere | AECL |
| Gas transport (Include bubble-mediated radionuclide transport) | GBIZ | BIOPROTA |
| Gas-water interactions | GBIZ | AECL |
| Geogas | GBIZ | TVO-92 |
| Geothermal | GBIZ | TVO-85 |
| Glacial climate | GBIZ | NAGRA |

APPENDIX 1 (8)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|---|
| Glacial/glacio-fluvial erosion, sedimentation | GBIZ | NAGRA |
| Glaciation | GBIZ | AECL, NEA, SKI/SKB, WIPP |
| Global effects | GBIZ | AECL, TVO-85, TVO-92, TILA-96 |
| Greenhouse effects, gas effects | GBIZ | AECL, NAGRA, TVO-85, TVO-92 |
| Ground and porewater chemistry and evolution | GBIZ | AECL |
| Groundshine | Biosphere | AECL |
| Groundwater abstraction | Geosphere/repository | TVO-92, TILA-96 |
| Groundwater chemistry Evolution Exploitation Flow Flow path Geochemistry Pollution | GBIZ | NAGRA, NEA, AECL, TVO-92, SITE-94, TILA-96 |
| Groundwater discharge and recharge | GBIZ | SKI/SKB, BIOPROTA |
| Groundwater mixing and dilution | GBIZ | SKI/SKB, BIOPROTA |
| Herbicides, pesticides and fungicides | Biosphere | WIPP |
| Household dust and fumes | Biosphere | AECL |
| Human diet | Biosphere | TVO-92, TILA-96 |
| Human induced actions on groundwater recharge | GBIZ | SKI/SKB, TVO-92 |
| Human induced changes in surface hydrology | Biosphere | SKI/SKB, TVO-92 |
| Human induced climate change | Biosphere | SKI/SKB, TVO-92 |
| Human lifestyle Human soil ingestion | Biosphere | NAGRA, AECL |
| Human-induced climate change | Biosphere | NAGRA, TVO-85 |
| Humic and fulvic acids | GBIZ | AECL, WIPP, TVO-92 |
| Hunter/gathering lifestyle | Biosphere | NAGRA |
| Hydrodynamic dispersion | Geosphere/repository | NAGRA, AECL, |
| Hydraulic properties | GBIZ | NAGRA, AECL, TVO-85 |
| Hydroponics (Related to rising certain greenhouse crops without soils) | Biosphere | AECL |
| Hydrothermal systems | Geosphere/repository | NAGRA, AECL, |
| Ice sheet effects (Loading, melt water recharge) | GBIZ | NAGRA, TVO-92 |
| Impact of a large meteorite (Very low probability) | Biosphere | WIPP, TVO-85 |

APPENDIX 1 (9)

| PARAMETER | FEP | REFERENCE |
|--|----------------------|--|
| Inorganic colloid formation | GBIZ | TILA-96, AECL |
| Incomplete near-field chemical composition | GBIZ | HMIP, TVO-85 |
| Industrial water use | Biosphere | AECL |
| Infiltration | GBIZ | WIPP |
| Ingestion Inhalation | Biosphere | WIPP, TVO-92, TILA-96, BIOPROTA |
| Inhomogenities (All the variants dealing with release and transport of radionuclides assume, steady time-invariant circumstances and boundary conditions in the near-field) | GBIZ | NAGRA, TVO-92, TILA-96 |
| Injektion | Geosphere/repository | WIPP |
| Inorganic colloid mediated transport | GBIZ | TILA-96, AECL |
| Intake by drugs | Biosphere | AECL |
| Intensification of natural climatic change | GBIZ | HMIP, TVO-92 |
| Interfaces (Interface of oxidising and reducing conditions is considered in some scenarios) | GBIZ | AECL, TVO-92, TILA-96 |
| Intrusion (Animal, deliberate, human, inadvertent) | Biosphere | TVO-85, TVO-92 |
| Ion exchange in soil | GBIZ | AECL |
| Irradiation | Biosphere | WIPP |
| Irrigation | Biosphere | NEA, NAGRA, AECL, WIPP, BIOPROTA |
| Isostatic rebound | GBIZ | SKI/SKB, TVO-85 |
| Isotopic exchange | GBIZ | BIOPROTA |
| Lacustrine deposition, formation, infilling, mixing, usage | GBIZ | AECL, HMIP, WIPP |
| Land and surface water use | Biosphere | BIOPROTA |
| Land slide | Biosphere | NEA |
| Land use changes | Biosphere | NEA, WIPP |
| Leaching | Biosphere | BIOPROTA |
| Leaf fall | Biosphere | BIOPROTA |
| Life processes (Anabolic and catabolic) | Biosphere | BIOPROTA |
| Marine transgressions and regressions | GBIZ | SKI/SKB, TVO-85 |
| Magmatic activity (Very low probability in Finland) | Geosphere | NEA |
| Marine sediment transport and deposition | GBIZ | NEA, WIPP, AECL, TVO-92, TILA-96, SKB |
| Matrix diffusion | GBIZ | NEA, WIPP |

APPENDIX 1 (10)

| PARAMETER | FEP | REFERENCE |
|---|-------------|---|
| Mineralization | GBIZ | BIOPROTA |
| Mineral dissolution and co-dissolution | GBIZ | NEA, WIPP |
| Mineral precipitation and co-precipitation | GBIZ | NEA, WIPP |
| Mechanical weathering | GBIZ | NAGRA, TVO-85, BIOPROTA |
| Meteorite | Biosphere | NEA, HMIP, AECL, SKI/SKB, TVO-85 |
| Microbes (Growth, interactions, transport) | GBIZ | AECL, NAGRA, WIPP, SKI/SKB, TVO-92, SITE-94, TILA-96 |
| Microbiological effects | GBIZ | NEA, AECL, TVO-92, TILA-96 |
| Mineralogy | Geosphere | NAGRA |
| Mutagenic contaminants | Biosphere | AECL |
| Natural and semi- natural environments | GBIZ | NAGRA |
| Natural ecological development | Biosphere | WIPP |
| Non-ice age (Most scenarios of TVO-92 and TILA-96 assume non-glacial conditions) | GBIZ | SKI/SKB, NEA, TVO-92, TILA-96 |
| Organics (ligands, complexation) | GBIZ | NAGRA, WIPP, TVO-92 |
| Oxidising conditions | GBIZ | SKI/SKB |
| Ozone layer (Very low consequences) | Biosphere | AECL |
| Outdoor spraying of water | Biosphere | AECL |
| Particle transport | GBIZ | BIOPROTA |
| Peat and leaf litter | Biosphere | AECL |
| Pedogenesis (Very low consequences) | Geosphere | NEA |
| Percolation | GBIZ | NAGRA |
| Permafrost | GBIZ | NEA, SKI/SKB, NAGRA, WIPP, TVO-92, SITE-94 |
| Physical weathering | GBIZ | TVO-85 |
| Photosynthesis | Biosphere | BIOPROTA |
| Plant and animal evolution Plant root Plant uptake Plants | Biosphere | NEA, NAGRA, AECL, WIPP |
| Pollen and Seed release | Biosphere | BIOPROTA |
| Precipitation and dissolution, temperature | Biosphere | NAGRA, NEA, AECL, WIPP, SITE-94 |
| Present day biosphere | Biosphere | NAGRA |
| Present day climatic conditions | Biosphere | NAGRA |

APPENDIX 1 (11)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|---|
| Pressure pumping | Geosphere/repository | BIOPROTA |
| Radioactive gases | GBIZ | HMIP, WIPP |
| Radionuclide accumulation in sediments and in soils | GBIZ | NAGRA |
| Ranching | Biosphere | WIPP |
| Recycling (Deals with contaminated materials) | GBIZ | AECL |
| Redox front (Movement of redox front in the near-field and geosphere is modeled in TVO-85. In the oxidising near-field scenarios of TVO-92 and TILA-96, redox front is assumed to be at the interface of the near-field and geosphere) | GBIZ | SKI/SKB, TVO-85, TVO-92, TILA-96 |
| Reduction-oxidising fronts (Movement of redox front in the near-field and geosphere is modeled in TVO-85. In the oxidising near-field scenarios of TVO-92 and TILA-96, redox front is assumed to be at the interface of the near-field and geosphere) | GBIZ | WIPP, TVO-85 |
| Regional uplift and subsidence Regional vertical movements (Postglacial uplift is taken into consideration in the groundwater flow modelling of the Olkiluoto site at the coast of Baltic Sea. TVO-92 also includes a scenario where the major postglacial fault is assumed to intersect the repository) | GBIZ | WIPP, NAGRA |
| Release due degradation | GBIZ | BIOPROTA |
| Release of organic matter | GBIZ | BIOPROTA |
| Release from solution | GBIZ | BIOPROTA |
| Removal mechanism | Geosphere/repository | NAGRA |
| Reservoirs | Biosphere | WIPP, TVO-85 |
| Respiration | Biosphere | BIOPROTA |
| Re-suspension | GBIZ | BIOPROTA |
| River flooding River flow and lake level changes River meandering River rechannelling River, stream, channel erosion River course meander | GBIZ | NEA, WIPP, SKI/SKB, AECL, TVO-85 |
| Root exudation, respiration, uptake | Biosphere | BIOPROTA |
| Runoff | GBIZ | AECL |
| Sabotage | Biosphere | NEA, AECL, TVO-85 |
| Saline intrusion | Geosphere/repository | WIPP, TVO-92, TILA-96 |

APPENDIX 1 (12)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|--|
| Saltation | Biosphere | AECL |
| Saturation (Saturation of sorption sites is not explicitly discussed in TILA-96, TVO-92 and TVO-85. The TILA-96 and TVO-92 sorption data is in general rather conservative when compared with other safety assessments) | Geosphere/reposition | SKI/SKB, AECL, TVO-85, TVO-92, TILA-96 |
| Sea level change (Changes in sea-level are taken into consideration in the groundwater modelling of the Olkiluoto site. In a scenario, the Olkiluoto is assumed to have become an inland site) | GBIZ | AECL, WIPP, SITE-94 |
| Sea water use | Biosphere | WIPP |
| Seas and oceans | GBIZ | WIPP |
| Seasonality in climate | Biosphere | NAGRA, AECL |
| Secular equilibrium of radionuclide chains (The stylised WELL-96 scenario takes into account all daughter nuclides with half-life greater than one day. Short-lived daughters are assumed to be in equilibrium with their parents. The effect of daughters procuring in vivo are accounted for in the ICRP dose coefficients) | GBIZ | NAGRA |
| Seepage | GBIZ | BIOPROTA |
| Sediment resuspension in water bodies Sediment transport including bioturbation Sediment/water/gas interaction with the biosphere Sedimentation in water bodies | GBIZ | AECL, HMIP, NAGRA |
| Seismic activity | Geosphere | NAGRA, WIPP, NEA, HMIP, TVO-92 |
| Sensitisation to radiation | GBIZ | AECL |
| Showers and humidifiers | Biosphere | AECL |
| Site flooding (Postclosure flooding of a coastal site likely has more beneficial than adverse effects on the performance of the disposal system) | GBIZ | NEA |
| Soil (Sediment bioturbation, depth, development, formation, leaching, moisture, evaporation, porewater pH, sorption, type) | GBIZ | AECL, NAGRA, NEA, WIPP |
| Solar insolation | Biosphere | NEA, TVO-92 |
| Solid discharge via erosional processes | GBIZ | HMIP, TVO-85 |

APPENDIX 1(13)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|---|
| Solubility and precipitation | GBIZ | SKI/SKB |
| Solubility limit/colloid formation | GBIZ | NEA, NAGRA, TVO-92 |
| Solubility constraints | Geosphere/repository | |
| Solution at boundaries | GBIZ | BIOPROTA |
| Sorption including ion-exchange | GBIZ | AECL, SKI/SKB, NEA, NAGRA, SITE-94, BIOPROTA |
| Sorptive surfaces | GBIZ | TVO-92, TILA-96 |
| Source terms | GBIZ | AECL |
| Space heating | Geosphere | WIPP |
| Stress changes – hydrological effects Stress changes of conductivity Stress field, settling, subsidence or caving, regime (Effects of particular type of drastic change are considered in the postglacial faulting scenario of TVO-92) | Geosphere/repository | NEA, NAGRA, TVO-92, SITE-94 |
| Surface denudation, disruptions | GBIZ | WIPP, NAGRA, TVO-85 |
| Surface pollution (Soils and rivers) | GBIZ | NAGRA, TVO-92 |
| Surface run-off water bodies | GBIZ | NAGRA, AECL, WIPP |
| Surface water chemistry | GBIZ | TVO-92, SITE-94, TILA-96 |
| Surface water flow, mixing, pH, sedimentation transport, suspension in air | GBIZ | NAGRA, HMIP, AECL |
| Symbiotic association | Biosphere | BIOPROTA |
| Suspension of particles | GBIZ | AECL |
| Technological advances in food production | Biosphere | AECL |
| Temperature Temperature rises | GBIZ | AECL |
| Tectonic contaminants | Geosphere | AECL |
| Terrestrial surface | Biosphere | AECL |
| Thermal effects on hydrochemistry, chemical and microbiological effects, effects on groundwater flow, thermo-chemical effects, thermo-hydro-mechanical effects, thermo-chemical change | GBIZ | NEA, HMIP, TVO-85, TVO-92, TILA-96 |

APPENDIX 1 (14)

| PARAMETER | FEP | REFERENCE |
|---|----------------------|--------------------------------------|
| Through-flow | GBIZ | BIOPROTA |
| Time dependence (In TILA-96 and TVO-92, the effects of the evolution of the disposal system are covered by a large number of scenarios. All variants dealing with release and transport of radionuclides assume, however, steady time-invariant circumstances and boundary conditions in the near field and the geosphere) | GBIZ | TVO-92, TILA-96 |
| Topography (Current, future) | GBIZ | BIOPROTA |
| Transpiration | GBIZ | BIOPROTA |
| Transport and release of nuclides | GBIZ | SITE-94 |
| Transport of radioactive gases | GBIZ | TVO-92 |
| Transport of radionuclides bound to microbes | GBIZ | TVO-92 |
| Transport of chemically-active substances into the near-field | GBIZ | TVO-92, TILA-96 |
| Tree sap | Biosphere | AECL |
| Tsunami (Very low probability) | Biosphere | BIOPROTA |
| Tundra climate | Biosphere | NAGRA, TVO-92 |
| Uncertainties (The set of scenarios in TVO-92 and TILA-96 aim to cover the uncertainties related to release and transport of radionuclides) | GBIZ | AECL, TVO-92, TILA-96 |
| Underground boreholes | Geosphere/repository | WIPP, TVO-92, TILA-96 |
| Underground rivers (e.g. during melting of the glaciers) | GBIZ | NEA, WIPP, SKI/SKB, AECL, |
| Uplift and subsidence | GBIZ | SKB/SKI TVO-85 TVO-92, TILA-96 |
| Uptake by crops Uptake by deep rooting species Uptake by livestock Uptake by fish | Biosphere | NEA, NAGRA |
| Urbanization on the discharge area (Potential adverse effects on hydrology are covered by the conservative flow model and data) | Biosphere | BIOPROTA |
| Vault heating effects | Geosphere/repository | AECL |
| Volcanism | Geosphere | SKI/SKB, WIPP, AECL, TVO-85 |

APPENDIX 1 (15)

| PARAMETER | FEP | REFERENCE |
|---|-------------|--|
| Warmer climate – arid Warmer climate – equable humid Warmer climate – seasonal humid | GBIZ | NAGRA |
| Water leaking into the basements (Deals with water leaking into the basement of a building) | Geosphere | AECL |
| Water producing well | GBIZ | SKI/SKB, AECL, NAGRA, WIPP, TVO-92, TILA-96 |
| Water resources exploitation, exploration | GBIZ | SKI/SKB, AECL, NAGRA, WIPP, TVO-92, TILA-96 |
| Water source | GBIZ | SKI/SKB, AECL, NAGRA, WIPP, TVO-92, TILA-96 |
| Water table fluctuation | GBIZ | SKI/SKB, AECL, NAGRA, WIPP, TVO-92, TILA-96 |
| Weathering of paths | GBIZ | SKI/SKB, TVO-85 |
| Well | GBIZ | AECL, TVO-92, TILA-96, BIOPROTA |
| Wetlands | Biosphere | AECL |
| Wind | Biosphere | AECL |

AECL=Atomic Energy of Canada Limited

HMIP=Her Majesty's Inspectorate of Pollution

NAGRA=Swiss National Co-operative for the Disposal of Radioactive Waste

NEA=Nuclear Energy Agency

SKB=Swedish Nuclear Fuel and Waste Management Company

SKI=Swedish Nuclear Power Inspectorate

APPENDIX 2

The various radionuclides of concern the key issues in geosphere-biosphere aspects of assessment of the long-term impact of contaminant releases associated with radioactive waste management (Leclerc-Cessac & Smith 2003).

| RADIONUCLIDE Contaminant | KEY PROCESS ISSUES |
|-----------------------------|--|
| H-3 | Nature of waste source term Extreme mobility Organically bound forms affecting accumulation and dosimetry Gaseous/liquid exchanges |
| C-14 | Aspersion model parameters CO ₂ to bicarbonate system in soil Soil gas exchange with canopy (photosynthesis and respiration, growth, C ₃ /C ₄ plants) Root uptake and recycling Use of so-called specific activity models, appropriate choice of temporal and spatial averaging Uptake to freshwater fish, concentration ratio, dynamic biota models |
| Cl-36 | Aspersion model parameters Understanding of conditions for high apparent soil to plant transfer Animal product concentration dependent on level in fodder Halophytes and technical crops; organic interactions Distinctions among spatial distribution of Cl-36 and stable chlorine Previous modelling of Cl as Br assumed conservative, but may not be |
| Se-79 | Aspersion model parameters Soil – plant uptake Soil – plant – animal product uptake Methylation and volatilisation Speciation issues; selenite, selenate, elemental selenium, organics |
| Tc-99 | Soil-plant uptake very high in some circumstances Potential long accumulation in soil and relationship to bioavailability; redox sensitive and affected by micro-anoxic regions in soil Aspersion model parameters |
| Nb-94 | External exposure, hence long-term accumulation in soil and sediment Sensitivity to assumptions for environmental change over centuries or longer |
| Sn-126 | Organic forms and volatilisation Butyl forms in aquatic environment |
| I-129 | Soil: plant uptake and long-term accumulation linked to bio-availability, both affected by organics and microbes in soils and sediments, redox sensitivity, and interactions with dead plant material Aspersion model parameters Animal products – concern over use of empirical data |

| RADIONUCLIDE Contaminant | KEY PROCESS ISSUES |
|-------------------------------------|--|
| Np-237 | Soil to plant to animal products, and drinking water to animals Accumulation in soil dependent on assumptions for environmental change |
| Uranium series | Natural quantise in soil Long-term accumulation in soil and sediments External irradiation for Ra-226 and others in series Soil intake by animals Th isotopes and inhalation Rn-222 – Pb-210 – plant deposition Aspersion model parameters Suspension from soils and sediments, activity distribution between suspendable fraction and bulk soil Aeolian redistribution, following long term irrigation and ash deposition from volcanic eruptions Radon emanation Respiratory and inhalation dosimetry, activity distribution on particles of different size and chemical form Pb-210/Po-210 accumulation in aquatic organism in general |
| Pb | Chemo-toxic data Metallic and sulphate (more mobile) – can have high concentration in cement Main transfer parameter f_w Pb, potatoes, cereals and fruit, aspersion Based on Pb-210, solubility limit issues Issues of flooding and irrigation of pasture |
| B | Chemo-toxic data Aspersion, drinking water mobile, uptake by animals |

APPENDIX 3

The main long-lived radionuclides of concern (ANDRA 2002).

| Radionuclide (half-life in years) | Type | Impact | Transmutation Potential | Transmutation Problems |
|--------------------------------------|----------------------------|--|-------------------------------|--|
| Tin-126 (100 000) | Long-lived fission product | Groundwater release | Difficult | Difficult to separate from spent fuel/HLW. Long time to transmute. Lower isotopes result in new production of radionuclide |
| Selenium-79 (60 000) | Same | Same | None | Same |
| Cesium-135 (2.3 million) | Same | Same | None | Formation of more Cs-135 from Cs-133. Isotopic separation difficult due to presence of Cs-137 |
| Zirconium-93 (1.5 million) | Activation product | Groundwater release | None | Presence of stable Zr isotopes would produce more Zr-93. Would require expensive isotopic separation. |
| Carbon-14 (5 700) | Activation product | Groundwater release and/or air release as CO ₂ ; incorporation into living matter | None | Small neutron capture cross-section. Often released as gas from reprocessing operations |
| Chlorine-36 (300 000) | Activation product | Groundwater | None | Presence of natural Cl-35 would generate more Cl-36 |
| Technetium-99 (210 000) | Long-lived fission product | Groundwater release. Affects thyroid | Yes Requires slow neutrons | Would require several transmutation cycles |
| Iodine-129 (16 million) | Long-lived fission product | Same | Yes Requires slow neutrons | Same. Also, difficulty in capturing during separation. Difficulty in fabricating targets. Could pose corrosion problems |

| Radionuclide (half-life in years) | Type | Impact | Transmutation Potential | Transmutation Problems |
|--|--------------------------|--|---|--|
| Uranium (mainly U-238, (4.5 billion)) | Actinide source material | Forms bulk of spent fuel (~94 percent by weight). Has higher radioactivity than TRU waste slated for geologic disposal | None Would be separated and disposed of as LLW or used like depleted uranium | U-238 transmutation would result in the generation of more Pu-239 defeating the purpose of transmutation as a waste management strategy. Would essentially create a breeder reactor economy. |
| Carbon-14 (5 700) | Activation product | Groundwater release and/or air release as CO ₂ ; incorporation into living matter | None | Small neutron capture cross-section. Often released as gas from reprocessing operations |
| Americium-241 (430) | Actinide | Gamma-emitter. Human intrusion. Groundwater release (parent of U-233). Radiotoxicity | Preferably in fast reactors | Would require multiple separation and irradiation cycles. Would result in creation of curium which would make subsequent cycles more difficult |
| Neptunium-237 (2.1 million) | Actinide | Groundwater release | Preferably in fast reactor | Formation of more radioactive shorter-lived Pu-238 |
| Curium-244 (18) | Actinide | Highly radioactive alpha and gamma emitter. Contributes to heat of spent fuel. | Difficult Requires fast reactor | Difficult to separate from other actinides in HLW due to handling and chemistry problems. Would require multi-recycling along with other actinides. Could require storage of decades or even a century. More Cm-244 and other Cm isotopes created in irradiation of lower actinides (Pu and Am). |

| Radionuclide (half-life in years) | Type | Impact | Transmutation Potential | Transmutation Problems |
|--|---------------------------------|---|--|---|
| Plutonium (mainly Pu-239 (24 000)) | Actinide | Pu-239 Fissile. Radiotoxicity. Goes to bones | Fast reactor required for non- fissile isotopes. | Neutron capture forms higher isotopes and higher actinides (e.g. Am and Cm). |
| Strontium-90 (29) | Medium-lived fission product | Contributes to initial heat of waste. Determines repository capacity. Intrusion scenario dose. Behaves like calcium in the body | None | Cannot be transmuted due to small neutron cross-section. Forms a large part of the heat of spent fuel and high level waste and therefore limits increase in repository capacity from transmutation. |
| Cesium-137 (30) | Same | Same except behaves like potassium in the body. Also radiation barrier to proliferation. | None | Same. Also, separation from fissile materials eliminates radiation shielding for proliferation prevention. |

APPENDIX 4.

The main transport processes (IUR Report 2006)

Advection. Advection is the phenomenon in which dissolved substances are carried along by the movement of fluid displacement. The velocity of fluid displacement depends on the hydraulic conductivity, kinematical porosity and hydraulic gradient of the aquifer.

Adsorption. Sorption and/or adhesion of a layer of ions from an aqueous solution onto a solid surface and subsequent migration into the solid matrix. The process by which atoms, molecules, or ions are taken up from the soil solution or soil atmosphere and retained on the surfaces of solids by chemical or physical binding. Radionuclides present in the soil atmosphere can potentially adsorb directly onto organic matter. However, adsorption will typically occur following transfer from soil atmosphere to soil solution.

Biofilms. Microbial populations generally live within biogenic polysaccharide films (biofilms) on surfaces. A biofilm will only exist as long as there are sufficient nutrients and energy sources and available water. Biofilms can vary in depth (from one cell thickness to several cm) depending on the environment and will contain biocommunities. The physico-chemical environment changes within the biofilm enable a variety of microbial species to live together, often with each species being dependent on another. Given sufficient nutrients, energy sources and available water, biofilms will form on surfaces. The biocommunity present will affect the water chemistry, influence mineral dissolution and mineral precipitation and generate inorganic colloids with resulting influences on radionuclide speciation. Biofilms will also have physical impacts e.g. physical retardation, which will influence water movement in the soil system.

Biological weathering can be caused by macro and micro organisms. On the macro scale, plant roots can penetrate cracks and fissures in rocks, forcing them apart. On the micro scale, rock surfaces are often colonised by a biocommunity of algae, fungi, lichens (algae and fungi living together) and bacteria, which often live together in a biofilm.

Bioturbation. The redistribution and mixing of soil or sediments by the activities of plants and burrowing animals. All living organisms can bioturbate their environment as a result of their normal biochemistry and life processes. Bioturbation effects are, in general, likely to increase the transport of radionuclides.

Capillary rise. Upward movement of water through soil layers above the water table as a result of capillary forces related to evaporation and transpiration. Water transport process that is the result of water adhesion and surface tension in a porous medium. Water adhering to the walls of a soil pore will cause an upward force (surface tension) on the liquid at the edges. Capillary action occurs when the surface tension is stronger than the cohesive forces between the liquid molecules. A capillary fringe is the soil area just above the water table where water can rise up slightly through capillary action. This layer ranges in depth from a few centimetres to a couple of metres, and it depends on the pore sizes of the soils/rocks involved. Fine-grained materials produce larger capillary action effects. The rise of water in a capillary fringe may cause the upward

migration of dissolved radionuclide solutes and possible mineral precipitation or dissolution at the edge of the capillary fringe.

Carbonate production. C-14 may be incorporated directly in inorganic soil solids by precipitation as carbonate.

Chemical weathering. The breakdown of rocks and minerals due to the presence of water and other components in the soil solution or changes in redox potential

Colloid transport. The complexation of materials can form colloids. Biocolloids are stable dispersions of biological particles in groundwater. They can be produced by a number of microbial metabolic processes e.g. by generation of organic by-products. Microbes themselves can also act as biocolloids and can be transported passively and/or actively (where they can control their own movement e.g. towards a nutrient source). Some biocolloids may be introduced to the Geosphere-Biosphere interface zone (GBIZ) with groundwater from the biosphere. Consequently, biocolloid populations will be higher in the near-surface ground and in pore waters than in deeper groundwaters from more stable environments. Radionuclides can adsorb onto biocolloids in a similar way to inorganic colloids. Thus, if a radionuclide is poorly soluble but is adsorbed onto a mobile biocolloid, its transport will be greatly enhanced. However, most microbes tend to attach to surfaces in biofilms thus, in this mode; a biocolloid will tend to decrease radionuclide transport.

Complex formation. A complex is a combination of two substances which normally remains dissolved.

Death. Animals that die release radionuclides to their immediate environment after decomposition .

Degassing (out-gassing). Soil gas emission. Out-gassing is the mechanism by which gases are released from the Earth's surface into the atmosphere. Out-gassing may lead to bubble-mediated transport or gas-driven groundwater flow. Out-gassing potentially increases radionuclide transport rates to the surface. Degradation of organic matter can lead to gas production and releases of gases containing radionuclides to the soil atmosphere. Radionuclides such as C-14 and Se-79 have the potential to be involved.

Deposition. The removal of gaseous or particulate material from the atmosphere by precipitation, causing deposition of material onto surfaces. Radionuclides can be deposited directly from the atmosphere as a result of dry deposition of particles or gases and vapours, or by wet deposition in which the radionuclide is either captured by rain or snow during its formation or fall. Occult deposition from mists is included in the wet deposition category. Particles containing radionuclides will generally be microscopic aerosols of organic or inorganic material, typically derived from soil. However, macroscopic plant parts, e.g. pollen, seeds and leaves, can be significant vectors of radionuclide transport.

Desorption. The migration of adsorbed entities off of the adsorption sites. The inverse of adsorption. Radionuclides may desorb from soil organic matter by reversible processes. However, decay of the organic matter may also result in radionuclide releases that are not characterised as reversible.

Diffusion. Physical process whereby chemical species move under the influence of a concentration gradient. Diffusion is the result of thermal movements in the solution (Brownian motion) and effectively causes a net flux of solutes from a zone of higher concentration to a zone of lower concentration. Diffusion can occur in the pore water or interstitial water of saturated porous media such as soil. Fick's Law is usually applied to the phenomenon and the effective diffusion coefficient for a diffusing contaminant will be controlled by factors such as the concentration gradient, temperature and the tortuosity of the interconnected porosity in the porous medium

Diffusive exchange. Radionuclides present in gas or vapour form in the above-ground atmosphere can exchange with the soil atmosphere by diffusion.

Droplet production. Radionuclides can be released from the surfaces of water bodies such as rivers and lakes by the creation of droplets either from bubble bursting or from waves.

Eructation. Release of radioactive gases produced in the gastrointestinal tract (notably C-14-methane in ruminants) during digestion.

Evaporation. Transfer of water from the ground directly to the atmosphere. Tritium in soil solution could be released to atmosphere directly by evaporation. Other radionuclides might be transferred to the gas phase in soil atmosphere and then released. However, this is an indirect route via soil atmosphere. Radionuclides can be released from the surfaces of water bodies such as rivers and lakes by evaporation.

Excretion. Although most of the material excreted by animals is organic in nature, inorganic materials such as soil particles are ingested, pass through the gastrointestinal tract and are eventually excreted¹.

Exhalation. Animals may release radionuclides to atmosphere by immediate exhalation of inhaled activity that is not deposited in the respiratory system, by exhalation of radioactive gases produced by metabolic processes in tissues.

External contamination. Solid organic matter from soils may be present on the external surfaces of vegetation.

Fermentation. See Respiration.

Fertilisation. The import of artificial fertiliser to enhance crop productivity.

Fixation. Radionuclides present in soil solution may be irreversibly incorporated in soil inorganic matter by chemical or biological processes.

Gas evolution. Radionuclides can be released from the surfaces of water bodies such as rivers and lakes by gas production within the water body and release from it (e.g. C-14).

¹ Excretion of gut microbiota. Animals contain an active microbiota in their gastrointestinal tract. Uptake of radionuclides can occur into this microbiotic community and some of the microbiota can be excreted. Urinary excretion can directly contaminate soil solution, as can the liquid component of faecal excretion. Faecal excretion will result in direct entry of radionuclides incorporated in organic solids into soil. Similarly, the death and decomposition of animals results in the incorporation of organic solids in soils. These comments apply both to animals present on soils and to the soil macrofauna (e.g. burrowing mammals and earthworms) present within soils.

Gas sorption. Radionuclides in gas or vapour form may be taken up directly into soil solution present at the soil surface, though it would be more usual for such uptake to be indirect via the soil atmosphere.

Groundwater recharge. The percolation of incident precipitation and other surface waters to groundwater systems.

Ingestion. Incorporation of radioactivity into the body in water or other contaminated substances by ingestion. Animals may deliberately or adventitiously ingest soil and, therefore, soil microbiota, soil solution and soil inorganic matter. Herbivores and omnivores ingest living vegetation. Detritivores ingest senescent vegetation. Animals may ingest radionuclides present in drinking water also.

Inhalation (burrowing animals). Incorporation of radioactivity into the body in the form of aerosols, vapours or gases as a result of breathing. High concentrations of radionuclides in air may build up in the excavations of soil-inhabiting macrofauna. These high concentrations may be inhaled. Rn-222 and its progeny originating from Ra-226 present in soil may be of particular interest in this context.

Inhalation by animals. Animals can inhale radionuclides present in particulate form (as micron or sub-micron size aerosols) or as gases and vapours.

Ion exchange. Ion exchange may be considered a special case of sorption. It occurs when an aqueous radionuclide ion displaces a counter-ion in the substrate surface layer and is retarded. This process is especially important for positively charged radionuclide species interacting with clay minerals that have a high cation exchange capacity (CEC).

Irrigation. Use of abstracted water to supplement natural supplies to gardens and/or agricultural crops. Irrigation waters containing radionuclides may be applied directly to plants. Strictly, spray irrigation occurs via the atmosphere. However, it may be more convenient to treat it as a direct transfer from water bodies to the external surfaces of plants. Radionuclides present in surface water bodies may be transferred directly to soil solution in irrigation waters, either applied directly to the surface or by spray techniques. The latter pathway is strictly via the atmosphere, but it may be more convenient to treat it as a direct route of contamination.

Isotopic exchange and solution. Radionuclides may move from the soil atmosphere to soil solution either by isotopic exchange with other atom of the same element or by dissolving in the soil solution.

Leaching. The removal of soluble materials from one zone in soil to another via water movement in the profile.

Litter fall. During senescence and death, plant material enters soil. This is often initially into the litter layer. However, the material then decomposes and bioturbation processes mix it into soil organic matter. This material may be rapidly degraded in soil, or it may be either physically or chemically stabilised and only slowly degrade.

Mechanical weathering. Mechanical disintegration of a material. Physical weathering may be a precondition of any chemical weathering of a rock. The physical agents that can cause mechanical disintegration of an exposed material are temperature fluctuations, wind, water and ice flow. Diurnal and seasonal temperature changes may

cause repeated expansion and contraction leading to exfoliation or spalling of a rock surface. If a material is wet, then a freeze-thaw process (frost shatter and frost wedging) may disrupt its physical integrity. Freeze-thaw processes depend on ice expanding as the water freezes in the joint or fracture. The process of mechanical weathering breaks down a rock into smaller fragments; no chemical change is involved.

Microbial metabolism may convert radionuclides in soil inorganic matter to being in organic matter. However, this would usually involve the intermediate step of incorporation of the radionuclides in the microbial biomass, so this is probably best represented as an indirect pathway. Metabolism is a basic characteristic of all living systems; metabolic reactions (particularly those producing energy) keep the cell alive. Metabolic reactions occur in small steps (metabolic pathways) so that the organism can derive as much benefit from each reaction as possible. Many of these reactions are catalysed by enzymes. Two types of reactions occur in living systems: synthetic and breakdown. Synthetic reactions comprise anabolism and breakdown reactions that of catabolism. Anabolic reactions require energy (and build up structures etc within an organism) whereas catabolic reactions produce it (to drive anabolic reactions, to provide energy for work and for maintenance of the organism).

Mineral Dissolution and Co-dissolution. Process by which material in the solid phases is incorporated into the liquid phase. Affected by local Eh, pH, solubility limits and the presence of other chemical species. Involves the aqueous removal of elements from the crystalline lattice of the mineral surface. This solid-water interaction process is controlled by thermodynamic factors and the water composition, including pH. The dissolution of the different constituent elements may proceed in a congruent fashion that follows the stoichiometry of the lattice structure or in a non-congruent way when certain elements are preferentially dissolved first. Co-dissolution refers to the process whereby co-precipitated trace elements or radionuclides are released from their positions within the lattice during the dissolution process. Once freed these soluble trace constituents may be free to migrate. The dissolution of minerals occurs when rocks suffer chemical weathering. It may also occur when meteoric water percolates down through the **unsaturated zone**.

Mineral Precipitation (mineralisation) and Co-precipitation. Involves the assembly of dissolved aqueous elements into a crystalline lattice to form a solid phase. This solid-water interaction process is controlled by thermodynamic factors and the water composition, including pH. Co-precipitation refers to the process whereby trace elements or radionuclides are incorporated into the lattice structure. A trace element is incorporated either because it can form an ideal solid-solution or because its size and charge are thermodynamically favourable for inclusion. Mineral precipitation may occur during weathering when a new phase may immediately form following mineral dissolution. It may also occur when mineralised water percolates down through the unsaturated zone. Mineral precipitation may affect the net radionuclide retardation capacity of a soil.

Particle transport. Natural transport processes causing movements of solid material between environmental media.

Photosynthesis. If C-14 is present in the atmosphere it can be incorporated directly into plants as a result of photosynthesis. Also, other gases and vapours, such as sulphur dioxide, can penetrate directly into plants through the stomata and be taken up by the

leaf mesenchyme. This could be relevant to the deposition and uptake of radionuclides such as S-35 and Se-79.

Pollen and seed release. Radionuclides incorporated in solid parts of plants can be transferred to atmosphere with those plant parts. In some cases, it may be convenient to treat such transfers as directly from plants to organic matter in soils (see release of organic matter). However, some plant parts such as pollen, seeds and leaves may be transported considerable distances through the atmosphere before deposition.

Precipitation. Rain, snow, hail etc. as part of the natural hydrological cycle. Radionuclides may be dissolved in wet precipitation and, therefore, enter soil solution directly.

Pressure pumping. Radionuclides present in gas or vapour form in the above-ground atmosphere can exchange with the soil atmosphere by advective pumping induced by changes in air pressure forcing gas into or out of the soil zone.

Recharge by surface waters. The percolation of incident precipitation and other surface waters to groundwater systems. Surface waters may flow across the soil surface, e.g. as a result of infiltration excess or flooding. Such waters could contain radionuclides in solution (or attached to suspended solids) that could be transferred to soil solution. Surface waters could flow over outcrops of bedrock. If the outcrops were unsaturated at the surface, recharge would occur carrying radionuclides into the bedrock. The rate of groundwater recharge depends on the type of subsurface rock materials in a given area. Saturated permeable layers capable of providing a usable supply of water are known as aquifers. Typically, they consist of sands, gravels, limestones, or basalts. Layers that tend to slow down groundwater flow, such as clays, shales, glacial tills, and silts, are instead called aquitards. Impermeable rocks are known as aquifuges, or basement rocks. In permeable zones, the upper surface of the zone of water saturation is called the water table. Recharge is from atmospheric precipitation and percolation of the water through the overlying soil and rock sequence. The rate of groundwater recharge depends on the type of subsurface rock materials in a given area.

Release of Organic Matter. Organic matter may be carried downward in percolating water. This may be as particles or as colloidal humic materials.

Release during degradation. Decay of the organic matter may result in radionuclide releases that can not be characterised as reversible.

Release from solution. Water bodies present in contact with soil could degas at their boundaries, releasing radionuclides into the soil atmosphere. However, it would be more usual for water to enter soil, so becoming part of soil solution, and then degas.

Respiration and fermentation processes. Radionuclides may be released from soil microbial communities in gaseous form. This is potentially important for H-3 and C-14 (e.g. in methane and carbon dioxide), but may also be of significance for other radionuclides, e.g. Cl-36, Se-79 and I-129. Gases can be formed by microbial activity in three ways: direct biodegradation of organic materials (which act as a nutrient source); direct catalysis of anaerobic corrosion of metals; and indirectly by producing chemical environments which cause gas production e.g. production of acids which enhance metal corrosion. Carbon dioxide, hydrogen sulphide and methane are examples of biogases.

directly produced by a variety of different microbial species living together in a biocommunity within a biofilm.

Resuspension. Solid organic matter, microbial community and solid inorganic matter in soils may be resuspended to atmosphere by the wind and human activities. Parent material may also be resuspended to atmosphere. This could occur where it is exposed at outcrop and has been weathered to a fine enough consistency to make it susceptible to resuspension.

Root exudation. Roots may penetrate into parent material, so exudation can release organic compounds and radionuclides to this zone. In addition, plants can develop in pockets of soil on outcrops and can contribute biotic material on senescence and death. Vegetation with its roots penetrating surface water bodies or deep groundwater may transfer radionuclides by exudation into the water body. Organic compounds produced by roots are released into the soil. These compounds may incorporate radionuclides. However, in addition, such compounds may play a role in mobilising radionuclides present in the rhizosphere and making them more available for plant uptake.

Root respiration can release C-14-labelled carbon dioxide into the soil atmosphere. However, other volatile gases that are products of metabolism and are labelled with radionuclides such as S-35 and Se-79 may also be released.

Root uptake. Uptake of water and nutrients from soil solution and soil particles by absorption and biological processes within plant roots. Both active and passive uptake occurs, and soil moisture status is a major factor controlling the degree of uptake. Micorhyzal associations can also be important. Some plants have root systems that penetrate directly into surface water bodies. These roots may take up radionuclides directly from those water bodies. In addition, deep rooting plants may have roots that penetrate to groundwater within parent material, taking up radionuclides from that **source**.

Seepage. Radionuclides present in soil solution may be transferred to surface water bodies by advective flow through the soil with discharge at seepage faces or through spring discharge.

Senescence and death. Vegetation with its roots penetrating surface water bodies or deep groundwater may transfer radionuclides by death of the plant or senescence of parts leading to releases into the water body. This includes falls of branches. However, deposition of leaves, seeds and pollen onto water bodies is best considered as occurring via the atmosphere.

Solution. See isotopic exchange.

Solution at boundaries. Radionuclides present in the soil atmosphere may diffuse into surface water bodies across the soil boundaries and go into solution.

Sorption. The removal of an ion or molecule from solution by adsorption and absorption. It is often used when the exact nature of the mechanism of removal is not known. The forces responsible for sorption range from 'physical' interactions (van der Waals' forces) to the formation of specific chemical bonds. Sorption depends both on radionuclide speciation (dependent on valence state, hydrolysis, complexation and soil solution composition) and the solid phase composition and surface characteristics.

Desorption kinetics are generally slower than sorption kinetics and there may be instances where sorption is effectively irreversible.

Symbiotic association. The boundary between plant roots and soil microbiota is not well-defined. Mycorrhiza form a symbiotic association between fungi and plant roots, so nutrients and radionuclides may be exchanged directly between plants and the soil **microbiota by this route.**

Through-flow. General term for sub-horizontal flow through soils and such discharge. Alternatively downward seepage/infiltration can occur with radionuclides lost from soil in recharge of groundwater.

Transpiration and Respiration. Transpiration is the transfer of water from the soil to the atmosphere by plants. Vegetation can release radionuclides to atmosphere in the transpiration stream (H-3) or by respiration (C-14 as carbon dioxide and other radionuclides such as S-35 and Se-79 incorporated in gaseous products of metabolism).

Transport by microbiota. May move downward to invade parent materials as part of the process of soil formation. Migration may be by active or passive transport. Such migration can carry radionuclides with it. In addition, microbial populations present in parent materials may increase by reproduction.

Transport in aerenchyma. Plants can contain inter-connected gas-filled pathways (aerenchyma), particularly in water-logged soils. These are a potential route of transport for radionuclides from the soil atmosphere to plant tissues.

Uptake. Nutrients and radionuclides in the soil atmosphere may be directly available for uptake and incorporation in soil microbiota, but this is likely to be secondary compared with uptake from soil solution. Soil solution constitutes a primary source of nutrients for soil microbiota. Thus, radionuclides in soil solution may be highly available for incorporation in microbial biomass.

Utilisation. Soil organic matter may be directly utilised as a substrate by soil microbiota. Thus, radionuclides may pass directly from organic matter to microbiota without passing through soil solution.

The general interaction matrix for the terrestrial environment, the processes of potential importance for Np-237 is in bold.

| | | | | | | | | |
|---|-----------------------------|------------------------|-------------------|---|------------------------|--|-----------------------------|---|
| Atmosphere | Deposition | Deposition | Inhalation | Wet deposition | | Deposition | | Deposition |
| | Water bodies | Irrigation | Ingestion | Irrigation, Flooding | | Irrigation, Flooding | | |
| Leaf fall, Release of other organic matter, Biomass burning | | Vegetation | Ingestion | Root exudation | | Litter fall, senescence and death | | |
| | | | Animals | Excretion | | Excretion, Death and decomposition | Excretion of gut microbiota | |
| | Seepage, Throughfall | Root uptake | Ingestion | Soil solution | | Sorption, Fixation | Uptake | Sorption, Fixation, Diffusion, Mineral precipitation |
| | | | | | Soil atmosphere | | | |
| Resuspension | Run-off | External contamination | Ingestion | Desorption, Release during degradation | | Soil organic matter | Ingestion | |
| Resuspension | | Symbiotic association | Ingestion | Leaching, Mineralization, Excretion | | Death and decomposition, Biofilms | Soil microbiota | |
| Resuspension | Run-off | External contamination | Ingestion | Desorption, Mineral dissolution | | | Ingestion | Soil inorganic matter |

The general interaction matrix for the terrestrial environment, the processes of potential importance for C-14 is in bold.

| | | | | | | | | | |
|--|---|--|--------------------------------|---|--|---|-------------------------------|---|---|
| Atmosphere | Deposition | Deposition, Photosynthesis | Inhalation | Dry deposition precipitation, Gas sorption | Diffusive exchange Pressure pumping | | | | Diffusive exchange Pressure pumping (both at outcrop) |
| Evaporation, Gas evolution, Droplet production | Water bodies | Root uptake Irrigation | Ingestion | Irrigation, Recharge by surface waters | Release from solution | | | | Recharge by surface waters |
| Transpiration, Respiration, Pollen and seed release, Leaf fall, Release of other organic matter | Root exudation, Senescence and death | Vegetation | Ingestion | Root exudation | Root respiration | Litter fall, Senescence and death | Symbiotic association | | Root exudation, Litter fall (at outcrop), Senescence and death, Biological weathering |
| Exhalation, Eructation | Excretion, Death | Excretion, Death | Animals | Excretion | | Excretion, Death, and decomposition | Excretion of gut microbiota | Excretion | Excretion, Death and decomposition (at outcrop) |
| Evaporation | Seepage, Through fall, Groundwater recharge | Root uptake | Ingestion | Soil solution | Ion exchange, Degassing | Sorption, Fixation | Uptake | Sorption, Fixation, Diffusion, mineral precipitation | Advection, Diffusion |
| Diffusive exchange, Pressure pumping | Solution at boundaries | Root uptake and transport in aerenchyma | Inhalation (burrowing animals) | Isotopic uptake, Solution | Soil atmosphere | Adsorption | Uptake | Adsorption, Carbonate production | Diffusive exchange, Pressure pumping |
| Resuspension | | External contamination | Ingestion | Desorption, Release during degradation | Degassing | Soil organic matter | Ingestion, Utilization | Complex formation | Particle transport, Colloid transport |
| Resuspension | | Symbiotic contamination | Ingestion | Leaching, Mineralization, Excretion | Respiration, Fermentation | Fertilization, Death and decomposition, Biofilms | Soil microbiota | | Transport, Biological weathering |
| Resuspension | | External contamination | Ingestion | Desorption, Mineral dissolution | Degassing | Microbial metabolism | Ingestion, Utilization | Soil inorganic matter | Particle transport, Colloid, Transport, Isotopic exchange |
| Resuspension (at outcrops) | Desorption, Mineral dissolution | External contamination, Irrigation | Ingestion, Bioturbation | Diffusion, Advection, Colloid transport | Degassing | Microbial metabolism | Ingestion, Utilization | Chemical and mechanical weathering, Isotopic exchange | Interface with geosphere |

The general interaction matrix for the aquatic environment, the processes of potential importance for C-14 is in bold.

| | | | | | | | | |
|--|--|--|---|--|--|---------------------------------------|--------------------------|---|
| Atmosphere | Deposition | | | | | | | Diffusive exchange, Pressure pumping |
| Evaporation, Gas evolution , Droplet production | Water | Adsorption, Complexation, Precipitation | Diffusion, Advection, Adsorption, Complexation, Precipitation | Uptake, Photosynthesis , Deposition | Uptake | Uptake | Uptake | Recharge by surface waters |
| Resuspension | Desorption, Dissolution | Abiotic suspended matter | Deposition | | Ingestion | Ingestion | Ingestion, Uptake | Particle transport, Colloidal transport |
| Resuspension | Desorption, Dissolution , Degassing | Erosion of bed sediment | Deposited matter (sediment) | Root uptake | Ingestion | Ingestion | Ingestion, Uptake | Biological weathering |
| Respiration, Release of other organic matter | Respiration, Release of other organic matter | | Death | Primary production (phytoplankton, macrophytes, aquatic plants) | Ingestion | Ingestion | Ingestion, Uptake | Excretion, Death and decomposition |
| Exhalation, Eructation | Exhalation , Eructation, Excretion | | Death , Bioturbation | | Consumers I (zooplankton, macropenthos) | Ingestion | Ingestion, Uptake | Excretion, Death and decomposition |
| Exhalation, Eructation | Exhalation, Eructation, Excretion | | Death , Bioturbation | | | Consumers II (omnivorous fish) | Ingestion, Uptake | Excretion, Death and decomposition |
| Resuspension | Resuspension, Excretion | | Death, Bioturbation | | Grazing/Uptake | | Decomposers | Excretion, Death and decomposition |
| Resuspension | Desorption, Mineral dissolution | Chemical mechanical weathering | Chemical mechanical weathering | | Ingestion, Bioturbation | Ingestion, Bioturbation | Ingestion, Utilisation | Interface with geosphere |

The general interaction matrix for the terrestrial environment, the processes of potential importance for CI-36 is in bold.

| | | | | | | | | | |
|--|---|---|--------------------------------|--|--------------------------------------|--|-----------------------------|--|---|
| Atmosphere | Deposition | Deposition, Photosynthesis | Inhalation | Dry deposition, Precipitation, Gas sorption | Diffusive exchange, Pressure pumping | | | | Diffusive exchange, Pressure pumping, (both at outcrop) |
| Evaporation, Gas evolution, Droplet production | Water bodies | Root uptake, Irrigation | Ingestion | Irrigation, recharge by surface waters | Release from solution | | | | Recharge by surface waters |
| Transpiration, Respiration, Pollen and seed releases | Root exudation, Senescence and death | Vegetation | Ingestion | Root exudation | Root respiration | Litter fall, senescence and death | Symbiotic association | | Root exudation, Litter fall (at outcrop), Senescence and death, Biological weathering |
| Exhalation, Eructation | Excretion, Death | Excretion, Death | Animals | Excretion | | Excretion, death and decomposition | Excretion of gut microbiota | Excretion | Excretion, Death and decomposition (both at outcrop) |
| Evaporation | Seepage, Through flow, Groundwater recharge | Root uptake | Ingestion | Soil solution | Ion exchange, Degassing | Sorption, Fixation | Uptake | Sorption, Fixation, Diffusion, Mineral precipitation | Advection, Diffusion |
| Diffusive exchange, Pressure pumping | Solution of boundaries | Root uptake and transport in aerenchyma | Inhalation (burrowing animals) | Isotopic exchange, Solution | Soil atmosphere | Adsorption | Uptake | Adsorption, Carbonate production | Diffusive exchange, Pressure pumping, (both for unsaturated parent material) |
| Resuspension | | External contamination | Ingestion | Desorption, release during degradation | Degassing | Soil organic matter | Ingestion, Utilization | Complex formation | Particle transport, Colloid transport |
| Resuspension | | Symbiotic association | Ingestion | Leaching, Mineralization, Excretion | Respiration, Fermentation | Fertilization, Death and decomposition, Biofilms | Soil microbiota | | Transport, Biological weathering |
| Resuspension | | External contamination | Ingestion | Desorption, Mineral dissolution | Degassing | Microbial metabolism | Ingestion, Utilization | Soil inorganic matter | Particle transport, Colloid transport |
| Resuspension (at outcrop) | Desorption, Mineral dissolution | External contamination | Ingestion, Bioturbation | Diffusion, Capillary rise, Colloid transport | Degassing | Microbial metabolism | Ingestion, Utilization | Chemical and mechanical weathering | Interface with geosphere |

The general interaction matrix for the aquatic environment, the processes of potential importance for Cl-36 is in bold.

| | | | | | | | | |
|--|--|---|---|--|--|---------------------------------------|--------------------------|---|
| Atmosphere | Deposition | | | | | | | Diffusive exchange, Pressure pumping |
| Evaporation, Gas evolution, Droplet production | Water | Adsorption, Complexation, Precipitation | Diffusion, Advection, Adsorption, Complexation, Precipitation | Uptake , Photosynthesis, Deposition | Uptake | Uptake | Uptake | Recharge by surface waters |
| Resuspension | Desorption, Dissolution | Abiotic suspended matter | Deposition | | Ingestion | Ingestion | Ingestion, Uptake | Particle transport, Colloidal transport |
| Resuspension | Desorption, Dissolution, Degassing | Erosion of bed sediment | Deposited matter (sediment) | Root uptake | Ingestion | Ingestion | Ingestion, Uptake | Particle transport , Colloidal transport |
| Respiration, Release of other organic matter | Respiration, Release of other organic matter | | Death | Primary production (phytoplankton, macrophytes, aquatic plants) | Ingestion | Ingestion | Ingestion, Uptake | Biological weathering |
| Exhalation, Eructation | Exhalation, Eructation, Excretion | | Death , Bioturbation | | Consumers I (zooplankton, macrobenthos) | Ingestion | Ingestion, Uptake | Excretion, Death and decomposition |
| Exhalation, Eructation | Exhalation, Eructation, Excretion | | Death , Bioturbation | | | Consumers II (omnivorous fish) | Ingestion, Uptake | Excretion, Death and decomposition |
| Resuspension | Resuspension, Excretion | | Death , Bioturbation | | Grazing/Uptake | | Decomposers | Excretion, Death and decomposition |
| Resuspension | Desorption, Mineral dissolution | Chemical and mechanical weathering | Chemical and mechanical weathering | | Ingestion, Bioturbation | Ingestion, Bioturbation | Ingestion, Utilization | Interface with geosphere |

The general interaction matrix for the terrestrial environment, the processes of potential importance for U-238 is in bold.

| | | | | | | | | |
|---|-----------------------------|------------------------------|-------------------|---|------------------------|--|-----------------------------|---|
| Atmosphere | Deposition | Deposition | Inhalation | Wet deposition | | Deposition | | Deposition |
| | Water bodies | Irrigation | Ingestion | Irrigation, Flooding | | Irrigation, Flooding | | |
| Leaf fall, Release of other organic matter, Biomass burning | | Vegetation | Ingestion | Root exudation | | Litter fall, Senescence and death | | |
| | | | Animals | Excretion | | Excretion, death and decomposition | Excretion of gut microbiota | |
| | Seepage, Throughfall | Root uptake | Ingestion | Soil solution | | Sorption, Fixation | Uptake | Sorption, Fixation, Diffusion, Mineral precipitation |
| | | | | | Soil atmosphere | | | |
| Resuspension | Run-off | External contamination | Ingestion | Desorption, Release during degradation | | Soil organic matter | Ingestion | |
| Resuspension | | Symbiotic association | Ingestion | Leaching, Mineralisation, Excretion | | Death and decomposition, Biofilms | Soil microbiota | |
| Resuspension | Run-off | External contamination | Ingestion | Desorption, Mineral dissolution | | | Ingestion | Soil inorganic matter |

The general interaction matrix for the aquatic environment, the processes of potential importance for U-238 and Np-237 are in bold.

| | | | | | | | | |
|--|--|--|--|--|--|---------------------------------------|-------------------------------|---|
| Atmosphere | Deposition | | | | | | | Diffusive exchange, Pressure pumping |
| Evaporation, Gas evolution, Droplet production | Water | Adsorption, Complexation, Precipitation | Diffusion, Advection, Adsorption, Complexation, Precipitation | Uptake, Photosynthesis, Deposition | Uptake | Uptake | Uptake | Recharge by surface waters |
| Resuspension | Desorption, Dissolution | Abiotic suspended matter | Deposition | | Ingestion | Ingestion | Ingestion, Uptake | Particle transport, Colloidal transport |
| Resuspension | Desorption, Dissolution, Degassing | Erosion of bed sediment | Deposited matter (sediment) | Root uptake | Ingestion | Ingestion | Ingestion, Uptake | Particle transport, Colloidal transport |
| Respiration, Release of other organic matter | Respiration, Release of other organic matter | | Death | Primary production (phytoplankton, macrophytes, aquatic plants) | Ingestion | Ingestion | Ingestion, Uptake | Biological weathering |
| Exhalation, Eructation | Exhalation, Eructation, Excretion | | Death, Bioturbation | | Consumers I (zooplankton, macrobenthos) | Ingestion | Ingestion, Uptake | Excretion, death and decomposition |
| Exhalation, Eructation | Exhalation, Eructation, Excretion | | Death, Bioturbation | | | Consumers II (omnivorous fish) | Ingestion, Uptake | Excretion, death and decomposition |
| Resuspension | Resuspension, Excretion | | Death, Bioturbation | | Ingestion, Uptake | | Decomposers | Excretion, death and decomposition |
| Resuspension | Desorption, Mineral dissolution | Chemical and mechanical weathering | Chemical and mechanical weathering | | Ingestion, Bioturbation | Ingestion, Bioturbation | Ingestion, Utilization | Interface with geosphere |

The general interaction matrix for the aquatic environment, the processes of potential importance for Tc-99 is in bold.

| | | | | | | | | |
|--|---|--|--|--|--|---------------------------------------|--------------------------|--|
| Atmosphere | Deposition | | | | | | | Diffusive exchange, Pressure pumping |
| Evaporation, Gas evolution, Droplet production | Water | Adsorption, Complexation, Precipitation | Diffusion, Advection, Adsorption, Complexation, Precipitation | Uptake, Photosynthesis, Deposition | Uptake | Uptake | Uptake | Recharge by surface waters |
| Resuspension | Desorption, Dissolution | Abiotic suspended matter | Deposition | | Ingestion | Ingestion | Ingestion, Uptake | Particle transport, Colloidal transport |
| Resuspension | Desorption, Dissolution, Degassing | Erosion of bed sediment | Deposited matter (sediment) | Root uptake | Ingestion | Ingestion | Ingestion, Uptake | Particle transport, Colloidal transport |
| Respiration, Release of other organic matter | Respiration, Release of other organic matter | | Death | Primary production (phytoplankton, macrophytes, aquatic plants) | Ingestion | Ingestion | Ingestion, Uptake | Biological weathering |
| Exhalation, Eructation | Exhalation, Eructation, Excretion | | Death, Bioturbation | | Consumers I (zooplankton, macrobenthos) | Ingestion | Ingestion, Uptake | Excretion, death and decomposition |
| Exhalation, Eructation | Exhalation, Eructation, Excretion | | Death, Bioturbation | | | Consumers II (omnivorous fish) | Ingestion, Uptake | Excretion, death and decomposition |
| Resuspension | Resuspension, Excretion | | Death, Bioturbation | | Grazing/Uptake | | Decomposers | Excretion, death and decomposition |
| Resuspension | Desorption, Mineral dissolution | Chemical and mechanical weathering | Chemical and mechanical weathering | | Ingestion, Bioturbation | Ingestion, Bioturbation | Ingestion, Utilization | Interface with geosphere |