BIOPROTA

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

THEME 2: Task 7:

Modelling Processes in the Geosphere Biosphere Interface Zone

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FOREWORD

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

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

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

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

BIOPROTA Concept

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

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

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

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

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

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

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

General Objectives

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

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

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

The work programme has been organised in three themes:

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

Theme 2: Modelling Testing and Development Tasks

Theme 3: Site Characterisation, Experiments and Monitoring.

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

Objectives of the Geosphere-Biosphere Interface Zone Task

The objective of Task 7 within Theme 2 is to support a better account of the treatment of radionuclide transfer through the geosphere-biosphere interface zone, and the related accumulation/dispersion/dilution processes which should be considered in order to provide appropriate confidence in PA results.

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

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1. INTRODUCTION, SCOPE AND OBJECTIVES

Historically, Performance Assessments (PAs) simulating the evolution of geological repositories for radioactive waste have considered the repository system in three basic parts, namely the near-field, the far-field (or geosphere) and the biosphere. This tripartite arrangement is commonly reflected in the assessment models and codes used to evaluate the transport behaviour of radionuclides released from the waste, through the surrounding engineered and natural barriers into the biosphere.

Conceptual and mathematical models of the transfer of radionuclides from the geosphere to the biosphere underpin the assessment codes, but they typically represent these transfers in a simplistic manner. The flux of radionuclides assessed to leave the domain of the geosphere model is often assumed to discharge directly into a part of the biosphere, such as soil or a surface water body, with little explicit consideration of the processes involved. In reality, the transfer of radionuclides across this geosphere-biosphere interface (GBI) could be very complex, involving numerous inter-linked 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 the geosphere model. On the other hand, in certain circumstances, some of these processes have the potential to re-concentrate radionuclides at or near the surface. Changes in the system condition may remobilise such accumulations, and thus might cause larger exposures of people than would otherwise be projected.

It can be argued that this GBI is no more than an artefact of the structure of PAs referred to above. There is no specific interface within the system being modelled, only a need for an interface between the components of the model used for PA. It is, therefore, more appropriate to recognise that there is a region of space that overlaps the geosphere and biosphere model domains. This is referred to in this report as the geosphere-biosphere interface zone (GBIZ).

The objective for Theme 2 Task 7 is to support a better account of the treatment of radionuclide migration in the GBIZ. This means exploring the related accumulation/dispersion/dilution processes which should be considered in order to provide appropriate confidence in PA results. Such detailed work is especially justified at this time as more countries consider specific sites for radioactive waste repositories.

Present site-specific conditions can be studied as within the BIOMOSA [2003a; 2003b] and BIOMASS [2003] projects. Alternative groundwater flow conditions can also be considered, for example, as in Wörman *et al.* [2004]. Changes in environmental conditions may also be relevant, as considered within the BIOCLIM Project [BIOCLIM, 2004] Climate change may result, for example, in redistribution of previously deposited radionuclides, due to hydrological or geochemical changes.

The Task Group has considered previous examples of assessment assumptions for:

- How source term(s) from the geosphere to the biosphere have been represented, including advective and diffusive transport in water, gaseous phase transfer and erosion from the surface of a contaminated geosphere, e.g. outcropping rock;

- The main geosphere transport features, events and processes (FEPs) as well as the geosphere model boundary conditions, which need to be consistent with the biosphere component of the system; and,

- The biosphere media and FEPs through which radionuclides reach the biosphere, giving rise to radiation exposure.

Section 2 reviews previous treatments of the GBIZ in particular PAs. The modelling issues and scenarios related to different aquifer types and different biosphere receptors are identified and discussed in Section 3, taking account of the FEP material in Appendix A and other inputs. The FEP list included in Appendix A is taken from Hooker *et al.* [2002] and has been considered as a basis for screening those FEPs. The intention was to identify whether a particular FEP should be considered further in any analysis, and how; or, if it is not to be considered further, to explain why not. Provisionally, this allows the identification of those areas to take into account in further stages of analysis. Section 4 summarises ideas for improving models, taking into account material presented at a BIOPROTA workshop, which is summarised in Appendix B. Conclusions and ideas for future work are also presented. References are given in Section 5.

2. PREVIOUS APPROACHES TO GBIZ

The degree of dilution at the GBI, as usually considered in PA exercises, was analysed and summarised in Pinedo *et al.* [1999]. Assumed water flows at the GBI, depending on specific assumptions range from 1 10^4 m^3/y for a minimal viable aquifer, 1 10^6 m^3/y for a small surface water body, 1 10^9 for a large surface water body or 1 10^{11} m^3/y for a marine release to a topographically constrained zone such as a bay or inlet. The review did not necessarily reflect the latest developments, but the objective was to understand alternative treatments of the interface. Conclusions based on those from the review, but drawing on additional considerations, are summarised below.

- PAs (even so-called Total System Performance Assessments, TSPAs) do not treat the system as a whole. The near field, far field and biosphere have been treated separately, and in some cases the boundary conditions between the geosphere and biosphere have not been well documented. Dilution in the biosphere can be significant depending on the way in which the source term to the biosphere is defined.

- Well interfaces are common, but the treatment of near-surface groundwater flow and related radionuclide transport are not modelled very precisely in most of the cases reviewed. Sometimes a lot of detail is included in the biosphere modelling, based on present day conditions, but no corresponding detail is given for the aquifer. A key issue in the evaluation of this interface is where the well is situated relative to the distribution of contamination in the aquifer. Usually the peak concentration is assumed (pessimistic) or some average concentration over the whole aquifer (possibly optimistic) is considered. This difference in location can have a big effect on results. The assumed abstraction rate can also be important, to the extent that it perturbs the underlying flow field and hence the degree of dilution and dispersion in the associated aquifer. If a large user population is assumed then this implies larger flow requirement. Flows assumed range from a few thousand to about 5 10^5 m^3/y. However, if dilution in the aquifer has been appropriately represented and the exposure pathways are pre-defined and parameterised, the assumed abstraction rate has negligible effect on the results obtained.

- Direct discharge to the surface is considered in some PAs, especially for geologies saturated to the near-surface. Release is either to a surface water body or to an area of subsoil. The assumption for volumetric flow in surface freshwaters is higher than the abstraction rates assumed for wells, ranging from about 1 10^6 to 1 10^9 m^3/y. For soil release, the area of soil contaminated is important. In the past, geosphere models were not usually capable of estimating either the location of soil release or the associated area. However, approaches such as particle tracking in 2D and 3D fracture-network or equivalent porous medium representations can now give useful indications of release locations and areas. In dry areas, direct discharge to the surface would dry out, resulting in the potential for high accumulation. Flow into the marine environment results in high dilution and much lower doses than the equivalent discharge to a terrestrial or lacustrine environment. For some sites, sea-level change could result in terrestrial releases becoming marine, and *vice versa*.

- It could be interesting to consider the flow through a repository near field (say 100 m^3/y), flow through the geosphere (say 1000 m^3/y), flow through a viable aquifer (1.0 10^4 m^3/y), flow through a small surface water body (1.0 10^6 m^3/y), flow through a large surface water body (1.0 10^9 m^3/y), flow in a small marine bay (1.0 10^{11} m^3/y), and then see how the potential impact is moderated according to each assumption.

- Solid and gaseous releases have been considered, but not commonly. Erosive releases (and comparison with natural erosive fluxes) have been considered, e.g. in the Radiation Protection and Nuclear Safety Authorities in Denmark, Finland, Iceland, Norway and Sweden [1993], but not in the PAs reviewed by Pinedo *et al.* [1999]. Natural fluxes may provide analogue data for repository derived radionuclide behaviour in the GBIZ [Miller *et al.*, 1996].

- Reasons for different treatments of the GBI can be found in the different site information (geology, surface environment, etc), but also due to other things, such as: different purposes of assessment, e.g. barrier system evaluation as compared to regulatory compliance. Details of regulatory requirements can also be important. These can be considered as part of the assessment context, as discussed in BIOMASS [2003].

- The most common interface considered is a well abstracting from a contaminated aquifer. In temperate climates, assuming the soil is uniformly porous and permeable; precipitation water infiltrates and saturates the rock up to the water table. Unconfined aquifers are at or near the land surface and hence easy to exploit as a water resource. However, exploitation of confined aquifers also occurs. Dug wells may be only a few metres deep, but boreholes for water abstraction are typically a few tens of metres deep and may extend down to around 200 metres deep for industrial water abstraction.

Maul *et al.* [1999], as part of a collaborative agreement with CIEMAT/PIRA, addressed the main parameters that need to be taken into account in characterising the GBIZ. These are the groundwater discharge zone and the transport time scales (transit time through the geosphere, through the aquifer and to reach equilibrium in the biosphere).

The <u>area</u> over which radionuclides enter an aquifer from the geosphere is a key parameter in determining the additional radionuclide dilution produced by the aquifer. The area can vary greatly depending on whether the geosphere flow is through porous or fractured media, and for a wide variety of other reasons, such as variations in topography, and contrasts in the hydraulic conductivity of porous rocks. The importance of this area arises because of the degree of dilution which can occur, and because the nature of the aquifer 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. Flow calculations or estimates have to be made before biosphere concentration estimations are performed, and parameter variations within the biosphere model should only be undertaken in a way that is consistent with the assumed water balance. The importance of this consideration is reflected in the examination of generically based BIOMASS reference biospheres reported in Birkinshaw *et al.* [2005].

Generically, three <u>timescales</u> are identified in Maul *et al.* [1999] as relevant: (i) the timescale over which the flux from the geosphere remains reasonably constant, close to the maximum value, τ_g; (ii) the transport time for radionuclides through the aquifer, τ_a; and (iii) the time for radionuclide concentration equilibrium conditions to be established in the biosphere, τ_b. The typical cases, with regards to their relative magnitudes, are summarized in Table 1, as well as the implications in modelling.

Table 1: Transport timescales and the GBI [Maul *et al.*, 1999].

Case	Description	Suggested Approach
1. $\tau_g >> \tau_a$ and $\tau_b >> \tau_a$	The geosphere flux timescale is much longer than the aquifer transport timescale (so that the source term is effectively constant).The biosphere equilibrium timescale is also much longer than the aquifer transport timescale.	The GBI can be placed where the geosphere flux enters the aquifer, and simple calculations can be used to estimate dilution in the aquifer before reaching the biosphere receptor.
2. $\tau_g >> \tau_a \cong \tau_b$	The geosphere flux timescale is long, so that the source term is essentially constant. However, the transport time through the aquifer is comparable with the biosphere equilibrium timescale.	The GBI can be placed at the base of the aquifer, but the model of the aquifer should be included explicitly in the biosphere model, for example by compartmentalising it.
3. $\tau_g \cong \tau_a \cong \tau_b$	The transport time in the aquifer is comparable to the geosphere flux and biosphere equilibrium timescales.	The lower regions of the aquifer should be included in the model for geosphere transport, with the GBI placed in the upper regions of the aquifer so that transport time through the upper aquifer is short compared with the geosphere flux time. Transport through the upper aquifer is then modelled as in Case 2.

3. MAIN MODELLING ISSUES

A summary of PA assessment scenarios, the release mode and biosphere receptors relevant to high level waste disposal are presented in Table 2.

Table 2 Scenario and Release Modes relevant to High Level Waste Disposal, from Watkins and Smith [1999].

Scenario type	Release Mode	Biosphere Receptor
Central	Dissolved in groundwater	Well Soil Sediment (marine or freshwater) River water Sea
Alternative. Early release due to: canister failure; altered evolution in the near-field or the far-field;	Dissolved in groundwater Gases	As for central scenario Atmosphere
Inadvertent human intrusion.	Solid Material	As for central scenario

The radionuclide transport processes as well as the conceptual and mathematical approaches to activity concentration estimations based on the flux of activity from the geosphere (Bq/y) are the object of analysis. The geosphere models can provide information about:

- Radionuclide fluxes, without any additional information on the spatial distribution;
- Radionuclides activity fluxes, spatially distributed in 1 or 2 dimensions;
- Activity concentrations spatially distributed in 2 or 3 dimensions.

There are ambiguities in the definitions of these estimates that are discussed below.

3.1 Source Term Definition

For the well pathway, the source term to the biosphere is usually defined as a constant activity concentration in irrigation water (Bq/m^3) for each radionuclide. Those radionuclides with short half-lives that are present as progeny in decay series are only represented explicitly in the biosphere (and even there explicit representation of their in-growth and decay is not always undertaken). In the geosphere, the progeny radionuclides are generally assumed to be in secular equilibrium. This, in some cases, may not be very appropriate, due to the different mobility of parents and progeny. For example, if Th-232 is taken to be the parent radionuclide in the geosphere, Ra-228 is assumed to be in secular equilibrium with it. However, such secular equilibrium may not actually occur in well water, due to different mobility of Th-232 and Ra-228 from the rock into the well water. Ra-228 is usually explicitly modelled in the biosphere model, but these calculations may be inappropriate if the Ra-228 source term in the well water is under-estimated or over-estimated because its mobility in the surrounding rock is not identical to that of its parent, Th-232.

The Dose Conversion Factor for the biosphere (Sv/y to an individual per Bq/m^3 in source water) is estimated from the hypothesis of a (near) constant activity concentration in the source term groundwater. This approach allows the geosphere and biosphere calculations to be done independently. Steady state (or quasi-steady state) is assumed in the receptor compartments. This means that equilibrium is considered to exist between the source term and the biosphere, such that the activity in each compartment can be considered independently from the history of the activity released before. This can be considered to be valid whenever the variations at the release area and release rate are slow in comparison with the time to reach equilibrium (see Table 2). The comparison between the time for steady state and the duration of the peak release rate for a radionuclide can support and validate this assumption.

The radionuclides considered to be of more relevance for a deep disposal repository from a radiological point of view have been prioritised within BIOPROTA [2002] as follows: H-3, C-14, Cl-36, Se-79, Tc-99, Nb-94, Sn-126, I-129, Np-237 and the uranium series.

3.2 Transport Processes

The importance of individual processes controlling radionuclide transfer to the biosphere is dependent on the characteristics of the site, in terms of the geology, hydrogeology, topography, soil system, climate and vegetation (see Hooker *et al.* [2002]). As such, radionuclide transfer processes are site and system specific. Although this much is clear, there remains, however, considerable uncertainty with regard to:

- Which processes are significant for radionuclide migration behaviour, and the nature of the interactions that occur between processes (conceptual model uncertainty); and,

- The rates of the transport and retardation processes that control radionuclide migration behaviour (parameter uncertainty).

Hooker *et al.* [2002] proposed the use of a FEPS list for the screening of what FEPs are to be considered. By use of standard tables, a record can be kept of FEPs to be included and excluded, and why. A third column ("significance") classifies the FEPs, having high, medium or low significance in terms of controlling radionuclide transport. Annex A shows an example of the processes relevant for a potentially relevant Spanish context (inland, granite). A summary of the processes identified as relevant in the Spanish study is presented in Table 3.

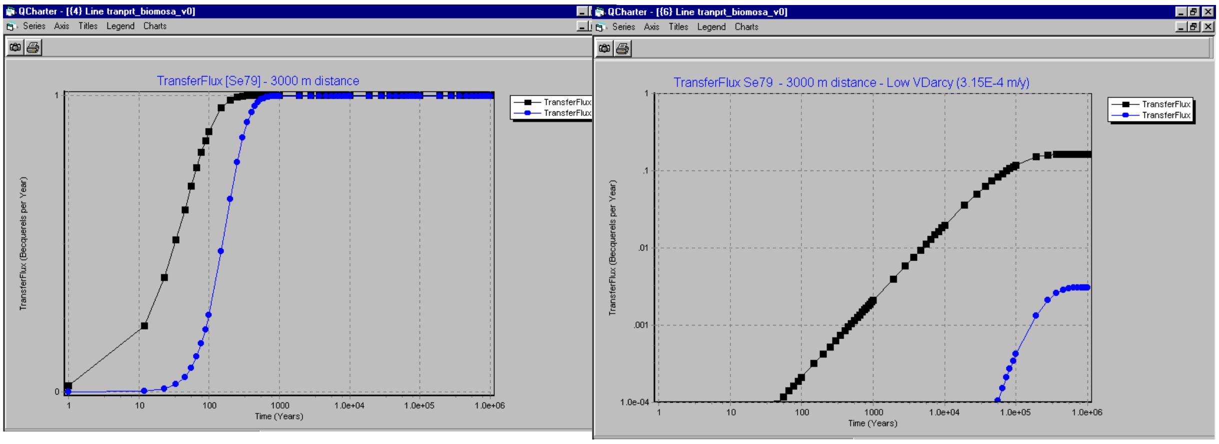
Table 3: Relevant FEPs for the GBIZ for a Spanish Case Study [based on Hooker *et al.*, 2002]

FEP Number	Name	FEPs
1	Biological Activity	Biocatalysis, biochemistry, biocolloids, biocommunities, biogas, biological weathering (including fungi and lichen), bioturbation, ecosystem, evapotranspiration
2	Erosion, sediment movement and redistribution	Cliff recession, down cutting and gorge formation, dry lake bed remobilisation, landslides, liquefaction, physical weathering, river maturation (including meandering), rock-mass transport, sediment compaction and cementation, sedimentation and deposition, soil formation and development
3	Water movement and contaminant transport	Capillary action, diffusion, fracture flow (advection), groundwater discharge, groundwater mixing and dilution, groundwater recharge, inorganic colloid mediated transport, osmosis, percolation, physical retardation (filtration and anion exclusions), porous flow (advection), saline water interface, seismic pumping, underground rivers, unsaturated (two phase) flows, water table fluctuations (including flooding and lake drying)
4	Surface water body flow and contaminant transport	Inorganic colloid mediated transport, riverbank storage
5	Sorption and precipitation processes	Chemical aging and recrystalisation, mineral dissolution and co-dissolution, mineral precipitation and co-precipitation
6	Igneous and metamorphic processes and related hydrothermal activity	Hydrothermal systems
7	Seismic and tectonic activity	Fault movement, seismicity
8	Gas flow and contaminant transport	Biogas, gas transport, gas-water interactions, outgassing, unsaturated (two phase)
9	Groundwater and porewater chemistry, radionuclide solubility and speciation	Ground and pore water chemistry and evolution, inorganic colloid formation, organic complexants and their decay rates, radioactive decay, radionuclide solubility, radionuclide sorption

Depending on the release form and receptors, different emphases can be given to these various processes, as illustrated in the following comments.

Well (aquifer). The estimated transit time in geosphere models shows uncertainties which in some cases can be of significance or at least need to be known for the justification of hypotheses for the biosphere models. An example is shown in the BIOMOSA project [BIOMOSA, 2003a; 2003b] for the Spanish biosphere description. The information about the transit through the major water-conducting zone is given as ranges. The transit path is between 4600 and 11000 m and the Darcy velocity ranges between 3.15 10^{0} and 3.15 10^{-4} m/y. This implies uncertainty in the time to reach equilibrium in the biosphere. Figure 1 represents the activity flux for Se-79. The time to reach the steady state can range from some hundreds of years to thousands of years. As a consequence of this, the validity of the calculational hypothesis, i.e. the adoption of a constant biosphere and estimation based on invariant dose conversion factors, can be challenged.

Figure 1 Time for steady state in the biosphere (transit velocity in geosphere model fast – left – or slow – right)



Soil/subsoil. The subsoil lies immediately below the surface soil zone, where ploughing and growing of crops normally take place. The nature of the subsoil and its interaction with groundwater, and in general subsurface gases and biological organisms will influence upward transfer of contaminants into the topsoil. The processes that control the transport through the rainfall affected zone, as well as the time scales over which they take place, were analysed in INTRAVAL project (Phase 2) [NEA-SKI, 1996a; 1996b]. The results of this and other projects, such as the ones performed in Aspö area (Sweden) [SKB, 1995] can be considered for the purposes of evaluating the behaviour of the GBIZ.

The Uranium deposits in *Koongarra* (*Alligator Rivers* region) are located 225 km East from Darwin, in North Australia. The deposits are localised close to the Koongarra Reverse Fault (associated with quartz and chlorite). Studies in the zone have shown that timescales for uranium mobilisation from the primary mineral are of the order of some million years [NEA-ANSTO, 1994].

Studies at the Aspö site (granitoids) show the mobilisation of some elements by dissolution or physical erosion. Zr and Hf losses as well as those of Si and Al are due to physical erosion of minerals without significant chemical dissolution. For uranium and rare earths, erosion is again the main process, whereas for Na, Ca and Sr, it is a combination of dissolution and erosion. The results show that whereas Na, Ca and Cs are leached and transported as ions, Rb and Ba, which can substitute for K in minerals, are associated with only to negligible losses.

Sediments and surface water bodies. Surface waters are commonly addressed in HLW PA scenarios. Surface waters often overlie sediments, which can act as modifiers or retardation barriers for the upward movement of groundwater and contaminants. Groundwater contributing to the base flow of a river would have to pass through the sediments to reach the main water body. Equally, some lakes may have groundwater discharges into the lake sediments. Sediment characteristics such as thickness, composition and hydrological and geochemical properties can affect the transfer of radionuclides into the accessible free surface water above and can act as activity accumulators when the groundwater flow discharges to the surface water body through sediments.

One of the issues identified in research supported by SSI [Egan *et al.*, 2003] is the validity of concentration ratios for aquatic organisms derived from field data due to effluent discharges rather than due to discharges through bottom sediments, as can be the case for deep disposal. The issue of radionuclide accumulation in marine ecosystems subsequent to discharges through the underlying sediments has been addressed by Kumblad [2004] in the context of a carbon-cycling model.

3.3 Dilution/accumulation

A PA would generally model the inputs into the biosphere compartments as releases from the boundaries of the geosphere (or far-field) model. Dealing with hard rocks, groundwater flow by advection is the predominant transfer process that is treated in geosphere models linked to biosphere models. Both porous flow and fracture flow are usually modelled in numerical codes.

In granitic media, the representation of the hydrogeological model is usually by means of a 3D network of interconnected faults, which is represented in a 2D or 3D flow model, and assuming the validity of Darcy's Law. The radionuclide transport modelling is through the determination of the main water conducting faults, according to the hydrological model results. The transport due to advection-dispersion is represented in 1D, adding another differential equation to account for diffusion and sorption in the rock matrix.

Migration pathways from a repository for spent nuclear fuel that is placed in crystalline bedrock may significantly depend on the presence of Quaternary deposits. For some realistic assumptions, the residence time for radionuclides in Quaternary deposits can dominate over those in the bedrock. The Quaternary deposits can also exert a substantial control on infiltration and hence profoundly affect the characteristics of the deep groundwater flow system. Also, the migration time in surface hydrological system cam play a role, especially if the interaction of terrestrial and aquatic ecosystems is taken into account. As an example, results obtained for a granitic site by IPSN [Baudoin *et al.*, 2000] obtained with 3D finite elements (initially developed for porous media transport) showed that water transit times from the repository to the biosphere varied from some thousands to millions of years, with an average close to 20,000 years.

In unfractured clay formations, diffusion is the relevant transport process through the geosphere, with advection in the near surface aquifers, if present. As an example, transport times for poorly retarded radionuclides in the Belgium Boom clay, are estimated to be some tens of thousands years [Baudoin *et al.*, 2000], and through the aquifer not more than a few thousand years. In these formations, it is clear there is a difference between the transport models required on either side of the interface (i.e. diffusion in the vertical in the clay) and advection-dispersion in a horizontal plane in the aquifer.

Soil/subsoil. Wörman *et al.* [2004] emphasised the importance of including subsurface flows in the biosphere representation. A similar emphasis exists in both the SKB and Nirex programmes (see, e.g. Birkinshaw *et al.* [2005] and references therein). With improvements in detailed models of flow in Quaternary material, linked to deeper bedrock flow and transport, the emphasis is shifting to more realistic <u>interpretations of the mixing</u> between meteoric water and groundwater. An improved representation of these processes will enhance our understanding of the biosphere safety functions and provide a better basis for evaluating environmental impact and radiological dose consequences.

Sediments and surface waters. The use of a dilution volume is a common approach for the estimation of activity concentration in river/lake water. The radionuclide discharge through sediments has implicit potential for higher concentrations due to retardation on the sediment before dilution in the water column. Furthermore, some aquatic organisms preferentially accumulate contaminants from sediments rather than from the water column. Changes in the landscape due to human activities (such as reservoir building) or climatic changes, can cause modifications in properties and degree of saturation of sediments, so that they may be later used as agricultural land, BIOMOVS [1991]. More recently, Wörman *et al.* [2004] examined the effect of landscape evolution, estimating the doses due to agricultural practices in a lake area which has evolved in such a way that sediments can be used as land for cropping. The results in both studies showed that these system changes can result in higher doses for some radionuclides.

It follows from the above discussion that the conceptual and mathematical models used to describe radionuclide releases to the biosphere are simplified representations of ‘real’ systems and may be non-conservative under some conditions e.g. where dissolution and re-concentration processes can occur. This may lead to a lack of confidence in the assessment models used to quantify repository safety.

3.4 Environmental Change Implications

The impact of climatic changes on hydrological and topographical characteristics, amongst others, as well as the influence of some human actions on the hydrological regime will have implications on the surface water balance, the hydrogeological regime (recharge and discharge zones), and the biosphere receptors. Current and recent international collaborative projects addressing this issue are PADAMOT (PAlaeohydrogeological Data Analysis and MOdel Testing) and BIOCLIM (Modelling sequential biosphere systems under climate change for radioactive waste disposal) [EC, 2003]. The first of these provides guidance and data on varying geosphere conditions in response to changing climate; knowledge acquired throughout the project will be interpreted and synthesised in order that it can have direct application to PA. BIOCLIM provides a practical methodology for assessing possible long-term impacts due to climate change on the safety of radioactive waste repositories in deep formations [BIOCLIM, 2004].

4. CONCLUSIONS AND SUMMARY OF IDEAS FOR FUTURE ACTIVITIES

4.1 Assessment Issues and FEPs

From discussion at the workshop (Appendix B), it was recognised that assessment models should be kept as simple as possible, consistent with the objectives of the assessment. At the same time, there is a wider need to demonstrate a good understanding of the system under assessment. This can involve a relatively detailed consideration of the issues, going beyond the immediate requirement of assessment models.

As in other aspects of safety case development, a distinction can be made between overall systems models used for assessment and underpinning detailed models, which may often have been developed in a research context and which are used to justify the simplifications made in the overall systems model or to provide parameter values for use in that model.

A large proportion of the issues identified concern modelling radionuclide behaviour in near surface aquifers which are subject to relatively high gradients in chemical and other conditions and also to environmental change. Other key issues concern transfer through the unsaturated zone above the aquifers, bearing in mind the scope for erosion and variations in the level of the phreatic surface. Key summary FEPs are identified in Table 4.

Table 4: Aggregated Key FEPs for the GBIZ

Aggregated FEP Number	Aggregated GBIZ FEP Name
1	Biological activity
2	Erosion, sediment movement and redistribution
3	Ground and pore water movement, and contaminant transport
4	Surface water bodies and flow, and contaminant transport
5	Sorption and mineral precipitation processes
6	Igneous and metamorphic processes and related hydrothermal activity
7	Seismic and tectonic activity
8	Gas flow and contaminant transport
9	Ground and pore water chemistry, radionuclide solubility and speciation

The issues discussed above are grouped below into the following items: radionuclides of interest; source term; consistency between conceptual models and effects of change; understanding of transport processes; and the consideration of environmental changes.

The intention is to focus on the relevant issues in a practical way, i.e. by setting up a series of exercises or research topics to deal with each item. To reach these goals and be as generic as possible in conclusions, and, at the same time, in order to conclude in a way practicable and valid for each specific site, there is a need to compile information from participants, showing the national case peculiarities. The purpose would be to determine whether differences highlighted in Section 3 are actually significant. The work would then go on to test approaches for the consideration of GBIZ by using the assessment context definitions in relation to the types of source term/s from the geosphere in the corresponding assessment exercises, taking note of the main geosphere transport processes, the geosphere model boundary conditions, the biosphere recipient media and processes through which radionuclides reach biosphere components.

4.2 Radionuclides of Interest and Source Term

The source terms for the biosphere calculations are sometimes given as constant unit fluxes or concentrations for a long list of radionuclides. To conclude on the adequacy of the definition of the source term, it would be useful to review the currently considered key radionuclides and key mechanisms (advection and/or diffusion in water, gas release, solid release) assumed for transfer into the biosphere. Not all combinations and not all radionuclides need to be examined in detail, so such a review would promote the best focus.

4.3 Understanding of Transport Processes

- Compilation of FEPs relevant for the various sites and PA assessment contexts to focus on those common processes identified. An approach to deal with this is the use of FEPs lists and tables in the form that has been suggested in this report to compile the information and a further analysis and development of a "common FEPs table".

- For the processes identified initially as more relevant, practical examples should be drawn for selected GBIZs (well, soil/subsoil and sediment/surface water body, different near-surface aquifers) in order to define which are the conditions that can give rise to accumulation of radionuclides or the assumptions made as to the interfaces that can result in higher doses.

- Analysis of radionuclide transport processes and requirements of data for the estimations. This includes checking the validity of parameters which represent radionuclide transfers within biota (e.g. concentration ratios for aquatic organisms). The types of organism that directly receive radionuclide influxes from the geosphere can be different from those for which transfer factors have been derived and reported in the literature. The task here indicated is directly related to the activities undertaken in BIOPROTA Theme 1 [BIOPROTA, 2002].

4.4 Consistency between Conceptual/mathematical Models

- Consider an example geosphere modelled and analyse the area of discharge and associated issues such as the level of dilution it provides.

- Set up a series of GBIZ examples for point or spatially distributed releases for a set of radionuclides of interest. The objective here is (i) the comparison of the approaches to estimating radionuclide concentrations in the biosphere receptor (e.g. Bq/m^3 in aquifer); (ii) consider uncertainties arising from the geosphere models and their influence on the biosphere conceptualisation and calculations.

4.5 Consideration of Environmental Changes

- Review the previous items listed to infer the key transfer processes identified under item 4.2 that may be affected by natural changes in the environment.

This task would in some sense be a continuation of the initial trial made in the BIOCLIM project.

- Based on conclusions from 4.3, analyse the influences of climate change (and other surface changes induced by human activities) on hydrogeology and hence on radionuclide migration.

4.6 Implementation and Future Work Steps

Noting the above, the objectives of the continuing GBIZ activities would be:

- To determine the potential to reduce uncertainties and/or conservative assumptions in assessment of radionuclide transfer from the geosphere to biosphere domains, taking account of environmental change.

- To develop guidance on site-characterisation needs at different types of site, as regards the near-surface features.

The following work steps are suggested to meet these objectives.

1. Develop a current statement of continuing problems, and hence clarify and justify the need to do more. Initially, all ideas should be placed on the table for subsequent screening. There would be a need to consider alternative assessment contexts, and to have a basis for removing items later. This step should answer the questions:

- Are there significant accumulation and remobilisation scenarios that we have missed, and

- Are there any processes where there are real weaknesses in our current analyses; if so, do we have good theoretical understanding of the issue and has this been validated?

2. Review site investigations as they have been done already, and ask the question, do they meet performance assessment requirements?

3. Identification of scenarios and FEPs considered in current treatments.

4. For the scenarios, use source-pathway-receptor analysis. This has the power of combining forward (source-pathway) and backward (receptor-pathway) analyses to demonstrate comprehensiveness of the overall scenario identification process. Thus, this approach would address both how could someone be exposed and how a release across the GBIZ could lead to exposure?

The steps could be investigated through the development of a structured FEP list and Interaction Matrices for the GBIZ, using the assessment approach in BIOMASS [2003].

One could then go on to consider:

- The degree to which the relevant FEPs and interactions are already addressed within specific programmes,

- Outstanding research issues, both in generic and site-specific contexts,

- How existing, enhanced or new mathematical models should be used to characterise the GBIZ in different assessment contexts. This does not mean models specifically representing the GBIZ, but rather the consistent deployment of geosphere and biosphere models such that the key characteristics of the GBIZ are adequately represented. The context issues would likely include different types of near surface aquifers, different assumptions for temporal evolution and different assessment endpoints,

- Geometrical aspects i.e. how does water flow from a repository with three dimensions (e.g. 100 m thick, 2 km long and 1 km wide) into the biosphere of two or three dimensions, where releases are sometimes considered as a point or line source?

- The chemical processes where deep groundwater mixes with surface groundwater.

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APPENDIX A: GEOSPHERE-BIOSPHERE FEPS

The following list was abstracted from a study by Hooker *et al.* [2002] performed for CIEMAT.

The GBIZ FEPs are listed alphabetically in Table A1 below. FEPs for both inland and coastal environments are given for the sake of completeness. Each GBIZ FEP has been correlated with a FEP from the NEA international FEP list [NEA, 2000]. The significance of each GBIZ FEP is indicated as high, medium or low. This was determined in terms of to what degree a GBIZ FEP, if it were relevant, could control radionuclide transport? A set of more relevant FEPs has been aggregated and presented in Table A2.

Table A1: FEP List for Geosphere-Biosphere Interface Zones.

GBIZ FEP Number	GBIZ FEP Name	Corresponding NEA FEP Number	Significance	Corresponding GBIZ Aggregated FEP Number (see Table A2)
1	Biocatalysis	3.2.06	High	1
2	Biochemistry	3.2.06	High	1
3	Biocolloids	3.2.06	Medium	1
4	Biocommunities	2.3.09	High	1
5	Biofilms	3.2.06	High	1
6	Biogases	3.2.06	Medium	1, 8
7	Biological weathering (including fungi and lichen)	3.2.06	Medium	1
8	Bioturbation	3.2.11	High	1
9	Capillary action	3.2.07	Medium	3
10	Chemical ageing and recrystallisation	3.2.01	Medium	5
11	Cliff recession	2.3.12	High	2
12	Contact metamorphism	1.2.05	Low	6
13	Diffusion	3.2.07	Medium	3
14	Down cutting and gorge formation	2.3.12	High	2
15	Dry lake bed remobilisation	2.3.12	Medium	2
16	Dual porosity	3.2.09	High	3
17	Ecosystem	3.2.13	High	1
18	Estuarine systems	2.3.04	High	4
19	Evapotranspiration	2.3.09	Low/medium	1
20	Fault movement	1.2.03	High	7
21	Fracture flow (advection)	3.2.07	High	3
22	Gas exsolution	3.2.09	Low	8

GBIZ FEP Number	GBIZ FEP Name	Corresponding NEA FEP Number	Significance	Corresponding GBIZ Aggregated FEP Number (see Table A2)
23	Gas transport (including bubble-mediated radionuclide transport)	3.2.09	Medium	8
24	Gas-water interactions	3.2.09	Medium	8
25	Ground and pore water chemistry and evolution	3.2.05	High	9
26	Groundwater discharge	3.2.07	High	3
27	Groundwater mixing and dilution	3.2.07	High	3
28	Groundwater recharge	3.2.07	Medium	3
29	Hydrothermal systems	1.2.06	High	6
30	Inorganic colloid formation	3.2.04	Medium	9
31	Inorganic colloid mediated transport	3.2.04	Medium	3, 4
32	Landslides	2.3.12	Medium	2
33	Life processes (anabolic and catabolic)	3.2.11	High	1
34	Liquefaction	2.3.12	Low	2
35	Marine transgressions and regressions	1.3.03	High	4
36	Matrix diffusion	3.2.07	High	3
37	Mineral dissolution and co-dissolution	3.2.01	High	5
38	Mineral precipitation and co-precipitation	3.2.01	High	5
39	Organic complexants and their decay rates	3.2.05	Medium	9
40	Osmosis	3.2.07	Medium	3
41	Outgassing	3.2.09	High	8
42	Percolation	3.2.07	High	3
43	Physical retardation (filtration and anion exclusions)	3.2.07	Medium	3
44	Physical weathering	2.3.12	Medium	2
45	Porous flow (advection)	3.2.07	High	3
46	Radioactive decay	3.1.01	High	9
47	Radionuclide solubility	3.2.02	High	9
48	Radionuclide sorption	3.2.03	High	9
49	Radionuclide	3.2.02	High	9

GBIZ FEP Number	GBIZ FEP Name	Corresponding NEA FEP Number	Significance	Corresponding GBIZ Aggregated FEP Number (see Table A2)
	speciation			
50	River maturation (including meandering)	2.3.04	Low	2
51	Riverbank storage	2.3.04	Low	4
52	Rock-mass transport	2.3.12	High	2
53	Saline water interface	2.3.06	High	3
54	Sediment compaction and cementation	2.3.12	High	2
55	Sedimentation and deposition	2.3.12	High	2
56	Seismic pumping	3.2.07	Medium	3, 7
57	Seismicity	1.2.03	Medium	7
58	Soil formation and development	2.3.02	High	2
59	Tsunami	2.3.06	High	4, 7
60	Underground rivers	3.2.07	High	3
61	Unsaturated (two phase) flow	3.2.09	High	8, 3
62	Volcanism	1.2.04	High	6
63	Water table fluctuations (including flooding and lake drying)	3.2.07	Medium	3

Table A2: The aggregated FEP List for the GBIZ

Aggregated FEP Number	Aggregated FEP Name
1	Biological activity
2	Erosion, sediment movement and redistribution
3	Ground and pore water movement, and contaminant transport
4	Surface water bodies and flow, and contaminant transport
5	Sorption and mineral precipitation processes
6	Igneous and metamorphic processes and related hydrothermal activity
7	Seismic and tectonic activity
8	Gas flow and contaminant transport
9	Ground and pore water chemistry, radionuclide solubility and speciation

APPENDIX B: GEOSPHERE BIOSPHERE INTERFACE ZONE, WORKSHOP 16-17 DECEMBER 2003, ANDRA, PARIS

B1 Workshop Scope and Objectives

The objective of the Workshop, as set out in the invitation, was to determine whether further investigation at a detailed level, generically or at specific sites, can usefully improve confidence in performance assessments, especially if this means reduced conservatism.

To meet this objective, the Workshop set out to:

- Determine the couplings between environmental change and processes affecting radionuclide transfer across, and accumulation within, the GBIZ. This would be done for a variety of site and facility types (both deep and near-surface) and initial environmental circumstances selected by participant organisations.

- Investigate the quality of information regarding these processes over various timescales and at different site types, and hence determine where key uncertainties remain. Then, identify potential options for improvements in the treatment of the GBIZ within a total PA context. Options may include:

    - ◇ Field research topics,
    - ◇ Experimental research topics,
    - ◇ Research model development, including coupled models of climate, geomorphology and human action change, groundwater flow and radionuclide migration in the GBIZ,
    - ◇ PA model improvements, including coupling of climate, geomorphology and human action change, groundwater flow and radionuclide migration in the GBIZ,
    - ◇ Methods of abstraction of PA models from research models.

- For the potential modelling options, determine the feasibility and value, in terms of improved confidence, of constructing coupled models of climate change, groundwater flow and radionuclide migration in the GBIZ, and identify those options worth further development.

These objectives were expanded upon during the introduction to the meeting, by reference to previous projects which have produced relevant input material, notably:

- Pinedo *et al.* [1999], which discussed the significance of, and apparent arbitrary nature, of the assumptions in the GBIZ. The volumetric flow rate, m^3/y, in receiving freshwater water bodies in the biosphere ranges over several orders of magnitude, with the degree of dilution arising clearly having a significant effect on the assessed doses. In addition, the effects of near-surface geochemistry were not generally taken into account in determining the radionuclide flux into the biosphere.

- BIOCLIM – This project has addressed the application of long-term climate modelling output, and down-scaling from global to regional scales, to the development of assumptions for the biosphere part of a PA. The primary inputs were the history of climate change, as determined from a variety of data sources. These were used as a basis for illustrative assessments of future climate and vegetation conditions in different regions within Europe. The nature, scale and timeframes for climate change and the more likely relevant change processes for inclusion in PA models have been identified. [BIOCLIM-BIOMOSA, 2003]

- PADAMOT – This project addresses the effect of climate change on deep groundwater flow systems. Paleohydrogeological data are being used to inform assumptions for flow and other factors which may affect radionuclide transport through the geosphere, as they may be affected by climate change. It is due to complete in June 2004. For more information, see http://www.bgs.ac.uk/padamot/home.html.

- BIOMOSA – This project has been testing the BIOMASS methodology at the site specific level, including the current treatment of different site specific, but assumed constant, GBIZs. [BIOCLIM-BIOMOSA, 2003].

- BIOPROTA – This project has a Task Group which is compiling updated information on the treatment of assessment model assumptions in the zone between deeper [1] (geosphere) radionuclide transport and transport in the biosphere – i.e. in the GBIZ [BIOPROTA, 2003].

Paul Degnan (Nirex) highlighted the need to:

- Develop ‘common ground’ between biosphere and geosphere workers;

- Identify GBIZ characteristics that are important for PA/SA;

- Propose a set of objectives that would address current limitations in knowledge; and,

- Propose approaches and methodologies to achieve the objectives.

Potentially relevant issues include:

- Characterising hydrogeology and hydrology;

- Near-surface diagenesis - effects on sorption and retardation;

- Soil ageing - effects on Kd and properties;

- Redox gradients – controls; and,

- Timescales for change - links to climate and environmental change, and time independency.

Paul invited the meeting to consider the question. ‘What are the detailed pathways and processes of concern?’

Detailed modelling issues might include:

1 It remains to be defined what is meant by deeper. In some assessment models, water is indeed abstracted from “deep” groundwater. In others the surface groundwater interacts with river water.

- Investigation of fluxes and water balance in the GBIZ (two-way interaction, includes recharge under different climate states, dilution);
- Handling time scales in coupled models (geosphere-biosphere); and,
- Hydrochemical studies in the near-surface including:
  - ◇ spatial variability;
  - ◇ diagenesis;
  - ◇ dissolution, erosion and other removal processes; and,
  - ◇ temporal patterns.

Wider PA/SA issues could include:

- Giving more credit to the GBIZ as a partial barrier (importance of redox conditions and diagenesis);
- Developing a more ‘realistic’ treatment of hypothetical biospheres, in particular spatial descriptions of discharge areas and system evolution; and,
- Use of Evidential Support Logic (ESL).

There were 21 meeting participants, from 6 countries and 11 organisations. The presentations given are summarised below. All the material presented represented the technical views and suggestions of individuals at the meeting and does not represent any position of particular organisations.

B2 Presentations

B2.1 Representation of Surface and Near-surface Hydrology and Radionuclide Transport at the Catchment Scale (M Thorne)

SHETRAN Version 5 is used to model surface and near-surface hydrology and radionuclide transport on a catchment scale. Some features of SHETRAN Version 5 are:

- 3-D hydrology and contaminant transport;
- Multi-gridding (to allow accurate representation of features such as boreholes and stream banks);
- Ground and channel freezing;
- No sediment transport (but this is included in other versions of SHETRAN, e.g. Version 4);
- Explicit representation of vegetation (both for hydrological properties and contaminant uptake); and,
- User ports for special models, e.g. nitrate or radiological impact.

The spatial scale for which it is typically used is a hillslope to basin surface water catchment of 1 to 100 km^2. The grid size used is typically 0.25 km horizontally and 0.02 to 5 m vertically and the model depth is typically 30 to 100 m.

In future, SHETRAN will be used to:

- Implement the hypothetical BIOMASS Example 2B catchment in 3D;
- Calculate hydrological flow patterns within the catchment;
- Impose internal boundaries within the representation of the catchment corresponding to the discretisation adopted in the BIOMASS Example 2B analyses that have already been reported and compute the seasonal water fluxes across those boundaries;
- Compare the water fluxes with those assumed in the reported analyses to determine the realism and self-consistency of those analyses;
- Perform inverse modelling to identify the catchment hydraulic parameters needed to provide output closely resembling that from BIOMASS ER2B;
- Compute, for illustrative 2D hillslopes within the catchment (as in BIOMASS Example 2B), transport of those radionuclides included in the Example 2B analyses;
- Calculate average concentrations of those radionuclides over appropriate regions of the catchment and compare the results obtained with those from the reported Example 2B analyses; and,
- Perform inverse modelling to examine the steps necessary to minimise any identified inconsistencies between radionuclide transport results from the SHETRAN and BIOMASS simulation approaches.[2]

Conclusions:

- Surface and near-surface hydrology require explicit consideration in assessments;
- 3-D models exist for representing that hydrology;
- Coupling to models of the deep hydrological system is an issue because of the different spatial and temporal scales involved; and,
- Variations in hydrological conditions should be taken into account both in the routing of radionuclides and in evaluating biotic uptakes.

During discussion, the need for such complicated models was questioned. What is lost by imposing simplified hydrological assumptions? It may be that there is a need to undertake illustrative examples of such detailed modelling to demonstrate that a simpler approach is generally fit-for-purpose in PA.

[2] Subsequent to the Workshop, this work has been completed and reported in Birkinshaw *et al.* [2005].

B2.2 Key Characteristics of the Deeper Biosphere and Upper Geosphere (R Klos)

Results comparing the *TAME* [Klos *et al.*, 1996] approach to a simple biosphere model for a simple release scenario (well release and irrigation) show that the same characteristics in the top soil (traditional biosphere) can have different implications for the results obtained depending on the assumptions for the deeper system.

The main influence of the deeper system on biosphere concentrations is the storage capacity of contaminants in the different parts of the system and the time required to come into equilibrium – steady state can always be reached, the question is when. Is the timescale long or short compared with the driving forces for surface evolution and of release from the geosphere? How does it compare with anticipated changes in radionuclide transport into the biosphere? Both capacity and timescales depend on the assumed structures in the biosphere and geosphere-biosphere interface.

Geosphere models largely deal with water flows. This is in part also the case for contemporary biosphere assessment models. With *TAME*, the effects of solid material mediated contaminant transport are seen via bioturbation between deep and top soils. Erosive processes have been neglected here to conform to the BIOPROTA irrigation scenario (see BIOPROTA Theme 2 Task 4 Report). It may be helpful to consider the biosphere to be that part of the overall system for which bulk transport can be occasioned by *biotic* action – bioturbation, transpiration, well abstraction in addition to physico-chemical transport processes. This excludes the role of microbes in determining chemical conditions in the near-field or geosphere.

The numerical results presented here depend on the use of compartment models. The BIOPROTA approach is referred to as “simplistic” here, but the *TAME* approach represents only a marginal increase in complication. The irrigation scenario is only one kind of geosphere-biosphere interface. The question of “natural discharge” scenarios has not been attempted here. At issue is the representation of structures in the geosphere-biosphere interface zone (as well as in the biosphere and geosphere). Are compartment models suitable? Do they require more compartments? Are alternative analytical tools more suitable? If so, are they able to include mass conservation and to deal with solid and water flows?

The key characteristics of the deeper biosphere and upper geosphere are those which affect storage capacity and time to equilibrium. Sorption and structure are the key issues. Some thought should be given as to how such factors are dealt with when dealing in the long timescales inherent in waste disposal and management. The timescale to equilibrium is also important when considering how long the assumed biosphere conditions might remain constant.

The distribution of the activity in the components of the near surface is a key issue. During discussion, it was noted that the importance of distribution over wider areas would depend on whether the assessment is intended to consider the wider distribution of doses among populations, as well as doses to candidate critical groups.

B2.3 Current and Planned GBIZ Work in Sweden (U Kautsky and J-O Selroos)

This presentation provided the background to the systems of interest in SKB performance assessments and included examples of the potential for coupling the components of the system, e.g. soil, plant, atmosphere, climate, deep and near-surface groundwater flow.

The processes to consider at the GBIZ include; accumulation, redox reactions, sorption to organic matter, biological uptake, sedimentation, and retardation.

Morphometric parameterisation [Moore *et al.*, 1993] includes:

- Elevation,
- Slope,
- Aspect,
- Longitudinal curvature (intersecting with the plane of the slope normal and aspect direction),
- Profile convexity (intersecting with the plane of the Z axis and aspect direction),
- Plan convexity (intersecting with the XY plane),
- Cross-sectional curvature (intersecting with the plane of the slope normal and perpendicular aspect direction),
- Maximum curvature (in any plane),
- Minimum curvature (in any plane).

In Sweden, Stockholm University has developed a GIS-based surface water model of the Forsmark area on the basis of available geographic, hydrological and hydrogeological data in SKB's database, using the PCRaster tool kit. However, it is possible that a more complex tool may be required for detailed studies in future.[3]

The input parameters required for the model are: elevation, precipitation, temperature, land cover, vegetation, aquifer porosity and capacity, and evapotranspiration.

Two scenarios for evapotranspiration were considered, the first where E_a is a function of precipitation and temperature, and the second where evapotranspiration is empirically related to different soil cover and vegetation conditions. The methods are represented by the following equations:

$$E_p = 325 + 21T + 0.9T^2$$

$$E_a = \frac{P}{\sqrt{0.9 + \frac{P^2}{E_p^{\,2}}}}$$

[For reference, E_p is potential evapotranspiration, E_a is actual evapotranspiration, T is mean annual air temperature (°C) and P is the mean annual precipitation (mm). This is the empirical formula of Turc, see Shaw, E M, Hydrology in Practice, Van Nostrand Reinhold, UK, 1983, page 259.]

[3] The MIKE SHE surface-water catchment model is now being used for this purpose.

On the basis of site-specific model input parameters for the Forsmark catchment, the GIS - surface hydrologic model PCRaster yielded stream flow values that agreed well with available, independent hydrologic stream flow data.

It was shown how the model in its present state can be used for predicting seasonal, average, differences in stream flow values. Results for summer and winter showed that whereas there are differences in the absolute stream flow values between the seasons, the relative distribution of flow between different stream outlets remained the same.

On the basis of the present analysis, SKB identified possible ways of model development with respect to evapotranspiration estimation and the coupling of surface water – groundwater flows.

In addition to the above, SKB are coupling deep and near-surface groundwater flow to study the distribution and movement of groundwater from depth in the near-surface deposits. They are simulating:

- High resolution of both rock mass and Quaternary deposits,

- Steady-state and transient conditions.

The Forsmark site (Fiskarfjärden) provides a general context, but real site data are not used and the model size is 40.5 km^2 area, 600 m deep (undulating). The grid resolution is 25 × 25 to 50 × 50 m in the horizontal direction, and 0.5 to 360 m in the vertical direction. Lakes and Quaternary deposits have been explicitly included.

The main conclusions of the modelling are:

- Discharge areas remain stable (with respect to permeability of Quaternary deposits and groundwater recharge);
- Discharge may occur through the lake sediment (advective or diffusive transport) or through the lake perimeter (mostly advective transport);
- Flow path lengths in Quaternary deposits are relatively short (typically 10 to 20 m);
- Flow in Quaternary deposits varies significantly during the year due to variability in groundwater recharge; and,
- Flow path characteristics (length, travel time, discharge area) are not sensitive to temporal variation.

B2.4 Mineralogical Aspects of Climate-Biosphere-Geosphere Interaction: Records of Past Changes and Implications for Movement across the GBIZ (T Milodowski)

Examples of output from PADAMOT were presented. These raised issues relating to the saline-freshwater interface and co-precipitation and use of natural analogues.

In the recharge zone it was noted that:

- Glacial recharge can mean that oxygenated waters are found at depth;

- Organic matter influences subsequent reduction in the deeper groundwater system; and,
- Porosity modification can occur, with the possibility of non-reversible changes due to precipitation/dissolution reactions.

In the discharge zone:

- Secondary accumulation processes can occur;
- Mn oxyhydroxides are associated with Ra, U, Sr;
- Calcretes are associated with U, Ra, Sr[4];
- Ageing occurs with the recrystallisation of unstable gels; and,
- Re-release to groundwater may occur.

The role of geochemical processes in accumulation of radionuclides in the near surface environment was discussed. High gradients in near-surface chemical and other conditions (notably redox) may result in locally high concentrations which may be released acutely into the biosphere as a result of environmental change, either naturally occurring or due to human activities.

B2.5 Long-term Transfers across the GBIZ: Geochemical Methods (A Bath)

The GBIZ could be defined on hydraulic and/or hydrochemical characteristics. There are few groundwater studies in low permeability rocks that focus on the GBIZ in the upper 10-50 metres. GBIZs have heterogeneous flow directions and discontinuous water compositions in recharge areas and discharge zones (note: discharge via soil zone interflow as well as at seeps and springs).

Do existing data sets identify GBIZs, what extra data are required, and how can mass transfers be estimated?

Methods for detecting directions of groundwater flow and solute transport in the GBIZ are:

- Depth variations of conservative solutes (e.g. Cl^-) and isotope ratios (e.g. $^{18}O/^{16}O$);
- Reactive transport modelling of natural solutes (e.g. pH, Ca^{2+}, HCO_3^-, SO_4^{2-}) and secondary minerals (e.g. calcite);
- Downwards penetration of anthropogenic solutes, isotopes and volatiles (NO_3^-, H-3, CFCs, Cl-36) and soil solutes (TOC); and,
- Shallow occurrence and dispersion of deep groundwater indicator species (Cl^-, C-14, He-4).

[4] The key point here is that both the Mn-oxyhydroxides and the calcretes can incorporate these elements during co-precipitation.

Baseline Study at Sellafield: a methodology for identifying the GBIZ?

- At Sellafield, a higher-K[5] sandstone aquifer formation overlies a fractured low-K basement formation.
- What are the responses of the shallow groundwater system to external pressure influences and infiltration?
- What evidence is there of hydraulic and chemical connection between deep (geosphere) and shallow (biosphere) parts of the groundwater system?

Observations about the GBIZ at Sellafield

Seasonal and long-term natural hydraulic effects on the shallow geosphere are (a) coherent vertically but waning with depth, and (b) strongly correlated with lateral location in the recharge-discharge system.

Salinity stratification defines interfaces within the deep geosphere and between the deep and shallow geosphere, but may not help to characterise transfers in the GBIZ.

Mass transport interfaces between geosphere and biosphere would be identified by reliable hydrochemical indicators (NO_3, Cl, H-3, CFCs, C-14, He-4, *etc.*) as well as hydraulic responses.

Some preliminary findings have been obtained about groundwater discharge and chemistry in the GBIZ (personal communication, P Shand/BGS and A Haria/CEH):

- Groundwater pressure profiles, flow directions and mixing zones indicate spatial and temporal variability of the 'discharge zone';
- Both convergent and divergent vertical flow occur with respect to an intermediate transmissive zone at the base of the soil;
- Locally confined zones are transiently artesian;
- Groundwater pressure gradient in parts of a conceptual 'discharge zone' below the stream indicates downflow, possibly due to faulting, i.e. both recharge and discharge may occur in a limited spatial domain along the stream channel;
- Detailed measurements have revealed a complex GBIZ which does not conform to simple concepts;
- Groundwater composition stabilises below about 20 m depth due to dominance of geosphere water and buffering by water-rock reactions;
- Electrical conductivity and total dissolved solids rise, pH rises, and Eh (redox) becomes negative (i.e. reducing); and,
- At shallower levels, chemistry is variable due to varying origins and reactions.

[5] K, the hydraulic conductivity

Conclusions about the GBIZ

It is often deeper than expected on the basis of simple conceptual models, because of the dominance of downflow and attenuation and/or diversion of upflow.

Long-term mass transfers are indicated (but not quantified) by Cl^- and He-4 for discharge, H-3, CFCs and TOC (total organic carbon) for recharge, as well as secondary minerals for immobilised solutes.

In discussion, it was noted that identification of the GBIZ was not an issue in itself. Rather, a clear understanding was needed of migration and accumulation processes within all parts of the system. However, a clear definition is needed to clarify discussion and to find a common basis.

B2.6 Hydrogeology of the Meuse/Haute-Marne Andra Site for Present-day (H Benhabderrahmane)

The groundwater flow system for the clay site being investigated by ANDRA was described, including the understanding of the near-surface groundwater flow system. This provided relevant background to the near surface dose assessment issues discussed below.

B2.7 Scenarios of Biosphere System Evolution for the Meuse/Haute-Marne region: Outputs of the BIOCLIM Project (D Texier)

Paleo-reconstructions show that during the last 440 ky, the successive Meuse/Haute Marne biosphere systems were of three major types: temperate, boreal and tundra. Scenarios of future evolution of the Meuse/Haute-Marne Biosphere System, provided by the BIOCLIM project (Modelling sequential BIOsphere systems under CLIMate change for radioactive waste disposal) are based on:

- Continuous climate simulations for the next 1 million years with an emphasis on the next 200 ky;
- Snapshots simulations for some chosen times (Near future, 67 ky AP, 178 ky AP); and,
- Three atmospheric CO_2 scenarios: one natural (A4) and two natural plus an anthropogenic perturbation (B3, B4).

Results were provided at the global and regional scales.

Natural evolution:

- Temperate Biosphere System persisting for the next 50 ky,
- Next occurrences of a Tundra Biosphere System around 100 ky AP and 178 ky AP (under glacial climate).

Then thirteen other periods of Tundra conditions.

Perturbed evolutions:

- Temperate Biosphere System persisting for the next 200 ky (climate either warmer or similar to that of the present-day),

- Next Tundra Biosphere System at around 178 ky AP (under periglacial climate conditions),
- Then, either five (B3 scenario) or three (B4 scenario) other periods of Tundra (but not before 600 ky AP).

B2.8 Choice of the Outlets: Impact on the Conversion Factors Used for PA (A Albrecht)

The geosphere-biosphere interface zone under a cold climate was considered with respect to its possible impact on dose assessment and biosphere conversion factors. The following considerations were identified:

- In a cold climate, permafrost modifies patterns of exchange between deep and near-surface groundwater;
- During cold climate periods abstraction of water from a deep well is unlikely, giving rise to enhanced interest in other kinds of geosphere – biosphere interface zones;
- For contamination of sediments and soils, a simple approach was adopted;
- Due to the presence of taliks, exchange between deep and surface groundwater is feasible even during periods of permafrost - to assess the maximum accumulation possible, direct contamination of soils, without leaching losses was investigated; and
- For modelling radionuclide accumulation in soils, the classical approach for a temperate climate was used.

Few adaptations to the original equations were necessary to compute soil accumulation as a result of ascending contaminated waters.

Preliminary results of modelling radionuclide accumulation in soils in cold climates suggest that:

- As leaching and harvest related losses are equal to zero (because they would be much lower in such conditions), soil accumulation can be very significant;
- For many PA-relevant radionuclides (I-129, Se-79, Tc-99, Np-237, Cs-135, Nb-94) equilibrium is not reached after an assumed cold period of 20,000 years; and,
- If, after such a period, the climate warms, doses to the incoming farmer would be greater by strongly varying factors compared with a return to uncontaminated land that subsequently became contaminated.

B2.9 Treatment of the GBIZ in Nagra Performance Assessment (F van Dorp)

This presentation concerned biosphere modelling for the safety assessment of a proposed deep geological repository in the Opalinus Clay in northern Switzerland. The effects of climate and surface environment in general on a repository were discussed. Effects of the host rock and the hydrogeology are considered in Nagra assessments, but were not discussed.

The aims of overall project Opalinus Clay is to demonstrate that disposal of SF/HLW/ILW is feasible in Switzerland. It is in preparation for a decision regarding the future Swiss HLW programme. The regulatory framework for biosphere modelling is HSK R-21 and ICRP 81. The radiation protection objectives are: 0.1 mSv/y, or risk of fatality of less than 1 in a million per year. Reference biospheres, indicators of impact, and stylised biospheres are all used.

Principles and procedures for defining the "biosphere" are as follows.

"Physical or transport" biosphere:

- Identify areas of expected discharge (present and future);
- Describe present state and evolution (climate and geological processes); and,
- Select areas/systems at the higher end of expected range of radionuclide concentrations for dose evaluation.

"Exposure pathways" biosphere:

- Define critical group(s) consistent with properties and evolution of the release area(s);
- Adopt present day habits (reference case);
- Consider an average person from a community of approximately 100 persons (order of magnitude value: 10 is too small, 1000 is too large); and,
- Assume all food and water is produced in the area with the highest radionuclide concentrations (no dilution with uncontaminated food and water).

Substantial discussions with geologists, hydrogeologists, hydrologists and climatologists have taken place leading to use of the following sources of information to describe the "Physical" biosphere.

Geology and Climate:

- Geological maps,
- Hydraulic potentials of geological aquifers,
- Historical information,
- Data on tectonic movements,
- Data on climate changes.

Topography and Geomorphology:

- Topographical maps,
- Geological maps,
- Historical information,
- Hydrological maps,
- Soil maps.

The expected climate evolution assumes continued glacial/interglacial cycling due to orbitally forced climate changes, i.e. Milankovitch cycles with a period of 100,000 years. Periods considered comprise an interglacial (like the present day but possibly with higher/lower temperatures and/or higher/lower precipitation and evapotranspiration), periglacial (e.g. tundra) and glacial (ice cover).

Conclusions from an historical analysis led to adoption of climatic and geomorphological evolution as in the past. Although the location of release is projected to move south, the properties of that location will be similar to those at the present day. Thus, the present situation is taken as the basis for model development.

The biosphere model used is implemented in the computer code TAME [Klos *et al.*, 1996]

The physical biosphere is represented in terms of compartments with fluxes of water and solids. Mass balance of water and solids is required and radionuclide transport includes sorption and decay to give concentrations in the compartments.

The food chain biosphere takes concentrations in soil and water to estimate:

- External radiation of humans;
- Doses due to inhalation of dust and ingestion of drinking water by humans;
- Radionuclide concentrations in water and fodder for animals; and,
- Radionuclide concentrations in food for humans and doses due to ingestion of food by humans.

Water fluxes are estimated on the basis of geomorphological, hydrological and climatic considerations. They can be provided either as numeric input or in equation form, but they must be in balance.

Solid material fluxes include those due to suspended material in water, erosion and bioturbation. Again, they can be provided either as numeric input or in equation form, but they must be in balance.

Considerations in the modelling of time independent systems are that the time for equilibrium can be larger than the timescale of changes to the system. This means that equilibrium will often not be reached. However, the modelling of constant biosphere states is considered to be conservative and different climates and geomorphological conditions can be covered by a range of cases.

Use of a compartment model implies that the time scale of release is longer than the time scale for equilibrium in the compartments. In defining compartment sizes, human diet and habits are averaging mechanisms. Overall the primary interest is in lifetime dose to members of a community, so seasonal variations and spatial variations on length scales of a few metres are of little interest.

Cases to be analysed require consideration of the following local geomorphological interfaces with the deeper system:

- Eroding river,
- Deep discharge into local gravel aquifer,
- Sedimentation area,
- Wetland,
- Deep discharge into a river,
- Spring at a valley side,
- Periglacial,
- Human intrusion / mineral water well.

No flooding of rivers or irrigation with river water is considered since the other release types considered are more cautious.

B2.10 Modelling of the Drigg LLW Disposal Site (M Willans)

The disposal facility is approximately 6 km south of Sellafield and within about 500 m of the coast at its nearest point on a former Royal Ordnance site. Radioactive waste was first disposed of by tumble tipping in clay-lined trenches in 1959. There are seven such trenches in total, which have been progressively capped. Trench disposals ended in 1988.

Vault disposals have taken place into Vault 8. This is concrete-lined and receives half height ISO-containers of waste. Concrete grouting is practised and the vault is scheduled to be full by 2005. It contains LLW from Sellafield and other sources, e.g. hospital wastes. Smaller-scale vault structures (9-22) are planned to take waste up to 2050 (Vault 9 is the subject of current planning) and site closure planned for 2150, i.e. 100 years of preparing the site for closure.

The most recent Safety Case for the site is the 2002 Drigg Post-closure Safety Case (PCSC). This is complemented by the 2002 Operational Environmental Safety Case and has been submitted to the regulators (Environment Agency) for Review of Authorisation.

The 2002 Drigg PCSC has developed a systematic approach including:

- EFEP analysis;
- Process System (Near Field, Geosphere, Biosphere) FEP analysis; and,
- Scenario derivation (Regional Glaciation, Valley Glaciation and Coastal Erosion scenarios).

Pathways considered comprise:

- Gas and groundwater pathways (studied in detail for the Regional Glaciation Scenario);
- Future human actions; and,
- Disruptive events.

Individual dose/risk and collective dose calculations have been performed.

The states for which the GBIZ had to be defined for the Regional Glaciation Scenario are set out below.

State	Time Post-closure	Agricultural Analogue	Comment
At Closure	0 y	Plymouth	Global warming
Altered State 1	200 y	Plymouth	Global warming
Altered State 3	4000 y	Drigg	Cooling
Altered State 5	11000 y	S. Finland	Marine boreal
Altered State 6	48000 y	N. Finland	Continental boreal

The near-field model used is DRINK. This is a point-scale geochemical model for source term (release rate) generation.

For groundwater flow, calibrated network models have been used. These are distinct for different engineering/climate state combinations and are applicable to near-field and geosphere.

Radionuclide transport in the geosphere uses a network model (as for flow) and employs a 1-D solution of the advection-dispersion equation that incorporates retardation and radionuclide chain decay and ingrowth.

The biosphere model is compartmental, but with different compartmental numbers and connections for various system states. The GBIZ comprises mapping of geosphere network nodes to biosphere compartments and compartmental dimensions are based on leg lengths and plume spread. Details of the GBIZ for various states are summarised below.

State	GBIZ
AC, AS1, AS3	Marine (intertidal zone, local coastal sediments, cliff erosion)
AS5	Marine (as above) plus terrestrial (emergent land), including streams/pools, overbank soils, banks and bottom sediments
AS6	Terrestrial (more extensive emergent land, but otherwise as above)

A sequence of states modelled. Transitions are treated as instantaneous, but with a degree of model-imposed smoothing. The transitions are particularly important in the coastal region.

Unit input studies on biosphere model dynamics established times to reach various proportions of equilibrium concentrations with input rates switched on/off).

Key Nuclides, States and Pathways were identified as:

- U-234 → Th-230 → Ra-226 → Pb-210/Po-210,
- Terrestrial environment (with freshwater fish and cattle milk and offal being the principal exposure pathways),
- Well water (abstracted from nodes of the geosphere network model) dominates doses to Local Resource Dominated Potential Exposed Groups (PEGs).

Conceptual Model uncertainty studies were undertaken on:

- Biosphere system change with time,
- The geosphere - near-field - biosphere Interface.

B2.11 Key GBIZ Issues from a Czech Perspective (A Laciok)

The Czech Republic has three operating near-surface repositories and is planning a deep granite repository for spent fuel. NRI carries out safety analyses for all of these in an iterative manner. The main radionuclides of interest include long-lived fission products and Nb-94. There are some important near-surface processes for which it would be useful to have improved information, for better confidence in assessment results:

- Structure of aquifers;
- Properties of granite-sediment-soil sequences; and,
- Hydrochemical zones.

These processes need to be better understood, taking account of environmental change within the time-frame of assessment. BIOCLIM output is supporting developments in this area.

B2.12 References for Appendix B

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