BIOPROTA

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

Representation of Environmental Change in the Near-Surface Environment

Report of an International Workshop

London, 21 – 23 May 2014

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PREFACE

BIOPROTA is an international collaboration forum which seeks to address key uncertainties in the assessment of environmental and human health impacts in the long term arising from release of radionuclides and other contaminants as a result of radioactive waste management practices. It is understood that there are radio-ecological and other data and information issues that 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 to provide a transparent and traceable basis for the choices of parameter values, as well as for the wider interpretation of information used in assessments. A list of sponsors of BIOPROTA and other information is available at www.bioprota.org

The general objectives of BIOPROTA are to make available the best sources of information to justify modelling assumptions made within radiological and related assessments of radioactive waste management. Particular emphasis is to be 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 programme of activities 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.

This report describes presentations and discussions held during an international workshop held from 21st to 23rd May 2014. The workshop was hosted by RWM in London, UK. Technical inputs were provided by a wide range of organisations via presentations and discussions, as described in the report. Financial support was provided by ANDRA, ENSI, RWM, LLWR, NUMO and POSIVA.

The report is presented as working material for information. The content may not be taken to represent the official position of the organisations involved. All material is made available entirely at the user's risk.

Version History

Version 2.0: Final workshop report prepared by Karen Smith, taking into account comments received on the draft report from workshop participants. Distributed 7 November 2014 to workshop participants and sponsors.

Version 1.0: Draft workshop and review report prepared by Karen Smith and Graham Smith (BIOPROTA Technical Secretariat) based on participant presentations and workshop discussions. Distributed 29 September 2014 to workshop participants for comment.

Executive Summary

Post-closure assessment of radioactive waste disposal takes into account the distribution of radionuclides and other contaminants potentially released from underground into the surface environment, or biosphere. Previous activities within BIOPROTA have examined processes relevant to contaminant transfer in the geosphere-biosphere subsystem, leading to production of a generic methodology for how to address those processes. Work within the IAEA-sponsored MODARIA Working Group 6 (WG6) has in parallel been updating methods for addressing environmental change, with a focus on climate-driven changes. Both activities have drawn on the results of previous work at the site and project specific level, as well as the results of the IAEA EMRAS II WG3 report that considered different approaches to dose assessment under environmental change. A further factor to be taken into account is the range of future human actions that may need to be taken into account within an assessment.

This report summarises the presentations and discussion provided by the 18 participants from 8 countries, representing a range of operators, regulators, researchers and technical support organisations. Presentations were given on a range of subjects relating to environmental change in the near surface-surface environment, including drivers of environmental change and approaches to addressing such change. Ongoing work in related work programmes was also presented. Each of the presentations is summarised and potential further research areas are identified on the basis of the workshop discussions.

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1. INTRODUCTION

Post-closure assessment of radioactive waste disposal takes into account the distribution of radionuclides and other contaminants potentially released from underground into the surface environment, or biosphere. Previous activities within BIOPROTA have examined processes relevant to contaminant transfer in the geosphere-biosphere subsystem, leading to production of a generic methodology for how to address those processes (Thorne et al., 2014). Work within the IAEA-sponsored MODARIA Working Group 6 (WG6) has in parallel been updating methods for addressing environmental change, with a focus on climate-driven change. Both activities have drawn on the results of previous work at the site and project specific level, as well as the results of the IAEA EMRAS II WG3 report (as yet unpublished) that considered different approaches to dose assessment under environmental change. A further factor is the range of future human actions that may need to be taken into account within an assessment.

1.1 OBJECTIVES AND SCOPE OF THE WORKSHOP

The objective of this workshop was to provide a forum for discussion and review of all the above activities, with a view to developing suggestions for how all these different factors might be considered together in the representation of environmental change in the near-surface environment. The scope of the workshop included deep and near-surface radioactive waste repositories as well as other sites and facilities for which such representation is of interest, for example, in the context of site restoration and management. It was anticipated that shared assessment and site characterisation experience would be of interest, as would time series of site and environmental monitoring data, to inform future assessment developments.

1.2 PARTICIPATION

The workshop, hosted by RWM in London, was attended by 18 participants from 8 countries, representing a range of operators, regulators, researchers and technical support organisations. Participants are listed in Appendix A.

1.3 REPORT STRUCTURE

Section 2 of this report summarises the presentations made. Section 3 then summarises key discussion points and identifies potential research areas that could be taken forward as future work programmes.

2. PARTICIPANT PRESENTATIONS

The workshop opened with a presentation on the recently completed BIOPROTA project on approaches to representing the geosphere-biosphere interface (GBI) in assessment models. Various presentations relating to modelling the GBI and addressing environmental change were then provided by workshop participants. Summaries of each of the presentations made during the course of the workshop are presented below, including key discussion points.

2.1 EXPLORATION OF APPROACHES TO REPRESENTING THE GEOSPHERE-BIOSPHERE INTERFACE IN ASSESSMENT MODELS AND REMAINING AREAS OF UNCERTAINTY

Mike Thorne presented.

A BIOPROTA project 'representing the geosphere-biosphere interface (GBI) in assessment models' was started in 2012 in response to concern that biosphere and geosphere models may not always be appropriately coupled in assessment models. Aquifers, for example, sometimes are considered to be in the geosphere and sometimes in the biosphere; models are not always as well developed for this zone although there are exceptions such as for Forsmark, where the fracture network is well represented in the upper 40m of the assessment models by SKB.

Within the project, features, events and processes (FEPs) that should be included in models of this zone were identified and our understanding of those FEPs and how they could be represented in assessment models considered. The starting point for this was a review of how the GBI has been treated in recent assessments, including generic studies in the UK, Yucca Mountain in the US and Forsmark and Olkiluoto in Sweden and Finland, respectively. Studies undertaken in France, Canada and Switzerland were also reviewed. A draft report was prepared relating to this review and a workshop was held to discuss the content of this report. Subsequently, a conceptual method was developed and applied to a series of illustrative examples, with a further workshop being held to discuss this methodology. Only a limited amount of work has focussed on the transition between states although conceptual tools are available from the BIOCLIM (2004) framework including transition diagrams that show potentially relevant processes and their relationships.

For the methodology, two GBI types were considered – wells and groundwater discharge. For wells, there are various forms both in terms of the materials in which they are constructed and the depths, extraction rates and uses of extracted water. There is a tendency for wells to be treated as if they are idealised samplers into near-surface aquifers, but realistically they are dynamic systems. Water is pumped during the growing season (for agricultural irrigation wells) leading to a depression in the water table, leading to dynamic changes in the aquifer occurring on a seasonal basis with changes occurring on similar timescales to sorption and desorption processes. Few models consider the dynamics of the aquifer. In terms of groundwater discharge there are again different forms, sedimentary deposits will vary in structure and composition, as will fracture zones, the hydrochemical regime and the sizes and locations of discharge zones. Discharge zones are often structurally determined and this governs the biosphere system above; for example, structurally controlled depressions are likely to be overlain by lakes. The type of aquifer and whether or not the host rock is a fracture flow system must therefore be considered. It is recommended that a comprehensive narrative is developed as part of an assessment, which will lead to the identification of assessment scenarios that then determine the GBI that should be considered.

A key feature of the GBI is that it is less labile than the biosphere, but more labile than the deeper geology of the host system. Therefore, some, but not all aspects of the GBI may persist throughout the assessment period. Thus, for example, if fractures in the GBI currently exist, they will also exist into

the future although the overlying regolith may alter in response to climatic and/or land uplift events. Where an assessment is undertaken based on a selected site, site characterisation activities should enable the GBI to be described for the present time in 3-dimensions. This can then form the basis for considering how the GBI could evolve into the future, both in terms of likely evolution (geosphere) and possible evolution (biosphere).

In applying the developed methodology to illustrative examples, tools available for describing the GBI, such as interaction matrices (IMs), have been explored. Interaction matrices are a projection of the system and are useful for showing interactions when developing a conceptual model and can be applied at different stages of the assessment process, but with different levels of detail. In the early stages of assessment, IMs can be developed to help gain a broad view of how the GBI works within a broad landscape context. As the assessment programme develops and site characterisation work is undertaken, more detailed IMs can be developed to take account of the available site information. They can also be condensed to influence diagrams for illustrative purposes.

Whilst a 3-D representation of the GBI may be available as a result of site characterisation work, spatial detail may not ultimately be necessary for dose calculations; information from a 3-D system description could in such circumstances be collapsed to a 1-D model, with activity concentrations being averaged across a utilised area thus negating the need for detailed spatial considerations.

A staged methodology has been developed. In the initial stage, the geosphere-biosphere sub-system is identified with justification, environmental change is considered and narratives of environmental change developed. The same sub-components as given in the BIOMASS (2003) methodology can be used (up to stage 3) and no divergence in methods is therefore required in the early stages. The BIOMASS (2003) concept of regional hydrology can be extended to also consider regional hydrogeology and hydrogeochemistry. In considering environmental change and how this may affect the GBI, the overall intention is to identify qualitatively different features. Decisions as to how different parts of the disposal system are to be represented should also be made during the initial stage. Such considerations will help in understanding the output that will be available from the geosphere. Each narrative is examined, taking into account the assessment context, to determine the preferred approach to representing environmental changes that affect the GBI in an assessment. Consideration should also be given as to how other parts of the disposal system are to be represented and a decision should be made as to whether a sequential or a non-sequential approach to considering environmental change should be adopted. If a snapshot, or non-sequential approach to assessment is applied, there will be some limitations on what can be done in terms of GBI narratives; time variable releases will typically give rise to considerations as to whether a more detailed GBI representation is required such that the time variation can be appropriately propagated to the biosphere.

The second stage then involves the development of a detailed description of the GBI. Components of the GBI need to be characterised in specific terms and their inter-relationships identified. This can be done through the use of an IM. In developing an IM, it is useful to give descriptions of the diagonal and off-diagonal elements (the IM contains only names) and to develop an influence diagram to help in describing how different processes interact with each other.

Stage 3 then involves characterisation of the GBI, including development of an illustration of the site topography and stratigraphy, the hydrology and hydrochemistry of the system, and how climate change and humans will influence the system. To allow all interactions to be considered, such as waters with different chemistries, interaction tables can be developed that show interactions in a coherent way rather than having processes repeated throughout the IM.

Mathematical models are then developed and applied. There are numerous models available, such as hydrogeological and nutrient cycling models, but interactions between these models are not always sufficiently recognised and represented. Once the GBI has been conceptualised, a range of different tools can be applied to explore particular aspects, such as the influence of different climates on hydrology and specific examples may be explored without the entire GBI needing to be considered.

The GBI is system specific although wells and groundwater discharge are considered the main forms. In the case of wells, there is little evidence that the time development of the environment needs to be taken into account, but for groundwater discharge the timescales of landscape development may be comparable with the timescales over which radionuclides move through the GBI and an explicit representation of that landscape development may be required. This leads to the need to develop rules for mapping radionuclides from one component of the environment to a different component as the landscape changes.

Whilst wells and groundwater discharge are considered to be the primary forms of GBI, alternative scenarios can be envisaged. For example, a groundwater plume of radionuclides may be subject to mass transport as a result of surface incision due to erosional processes. Alternatively, radionuclides could be released in gaseous form. Incision processes may occur on a much shorter timescale than previously thought, potentially with valley systems being formed on timescales of a few thousand years. Till laid down following a glaciation can be subject to rapid and active hydrological regimes with glacial melt water potentially giving rise to high rates of incision.

A key benefit of the proposed methodology focussed on the GBI and IM's is that auditing can be readily performed to ensure all aspects of interest have been considered and major gaps are not evident. One approach to avoiding gaps would be to start conceptualisation from a point considerably below the surface to ensure that emphasis is on the key components. A wide range of computational tools is available that can be applied to address issues relating to the GBI, but more work is required on semi- and fully-quantitative models. Similarly, whilst geochemical modelling is considered to be broadly understood, even if data are sometimes unavailable, hydrobiological aspects of the system require further consideration. There is a need therefore to consider what the weakest component is in terms of models as this will be the weakest link in evaluating GBI processes. Once modelling of a system has been taken far enough it may be justifiable to make model simplifications.

In terms of further work requirements, it is recommended that priorities for focussing on specific radionuclides of common interest are explored so that well-posed questions can be developed relating to the geochemical and biological processes controlling their transport and distribution in the GBI (defined to include both surface soils and the associated vegetation). Furthermore, it is suggested that a test system be identified to which the approach could be applied which may facilitate engagement with other groups with the expertise required for assessment. A wetland site such as Duke Swamp is considered interesting in this regard.

2.2 ADDRESSING GEOCHEMISTRY IN A CHANGING NEAR-SURFACE ENVIRONMENT

Jorge Molinero presented.

Amphos 21 has undertaken a range of work to address issues relating to geochemistry. Most of this work has focussed on the deeper geosphere and there is therefore a need to consider how to transfer knowledge gained to the near-surface environment. An initiative for an iMaGe (interfacing multiphysics and geochemistry) platform has been developed that aims to provide an interface between multi-physics and geochemistry. Several different geoscience codes are available, but there is often a need to couple models to address different issues, such as a coupling of hydrothermal models with nutrient models.

Currently there is no one tool that allows all aspects to be considered at one time. Initially consideration was given to the development of a single code, but this was rejected due to the amount of effort that would be required. The focus therefore shifted to the development of a model interface that would allow models to be coupled. Currently there are six partners involved in iMaGe plus a number of additional collaborators. Additional partners and collaborators are invited.

Within the platform there are a number of different projects that allow the sharing of resources between partners, including three key interface projects: COMSOL and PHREEQC; FASTREACT and MARFA; and DARCYTOOLS and PFLOTRAN.

The intelligent Kd approach is being applied in the project. Kd, as a single parameter, lumps together many complex retention processes under the assumption that the Kd value for each radionuclide is constant in time. In reality retention will be affected by a number of factors such as pH, redox conditions and the local geochemistry; as geochemical conditions change, Kd will also change. The intelligent Kd approach allows for variation in geochemical conditions such that, as geochemistry varies, so too does Kd.

The intelligent Kd approach has been implemented in MARFA (efficient solute transport modelling along flowpaths) based on a random walk theory. FASTREACT is similar to MARFA, but is a coupled reactive transport model for multiple flow paths. FASTREACT is used to solve reactive transport equations. Equations are solved for each flow path to derive a matrix of the major chemistry in each position along that flow path. The output is then used within PHREEQC to evaluate Kd values at each position for radionuclides of interest. Variation in Kd over different time steps is then fed into MARFA.

The approach has been tested assuming a release from a disposal facility during glacial conditions with a change in the surface environment after 20,000 years resulting in more saline conditions. Under the intelligent Kd approach, one Kd value is maintained for the first 20,000 years, but then changes in response to changing conditions leading to a peak rapid release, which is in contrast to the classical Kd approach for which a more constant release is modelled (Figure 2-1).

It has been proposed that the intelligent Kd approach could also be applied to the near-surface environment by interfacing between COMSOL and PHREEQC models to obtain a powerful tool for coupling biochemistry, geochemistry, geology and geomorphology, surface hydrology and physics. The approach has to date been applied in a feasibility study based on SKB's geochemistry conceptual model (as published in SKB report R-08-107 - Complementary modelling of radionuclide retention in the near-surface system at Forsmark). GIS data on tills, glacial clay, organic matter etc. have also been imported and a mesh grid created to represent the area in 3-dimensions. The model allows a 3-dimensional representation of water and radionuclide flows, allowing for all key processes that govern differences in behaviour (e.g. retention and precipitation) and accounting for the complexity of changing geochemical conditions. The behaviour of Cs has been evaluated. Previously it has been assumed that Cs is efficiently absorbed to organic clays, but the model demonstrates that this is not the case as a result of hydrology being more accurately represented; water primarily flows through tills and sands rather than clays. The results indicate that understanding of processes does not equate to system understanding. It is intended that a paper will be produced to illustrate the difference between process and system understanding. Further development work is also required; only a simplistic representation of the interactions between groundwater and surface water is so far included and further processes are due to be incorporated.

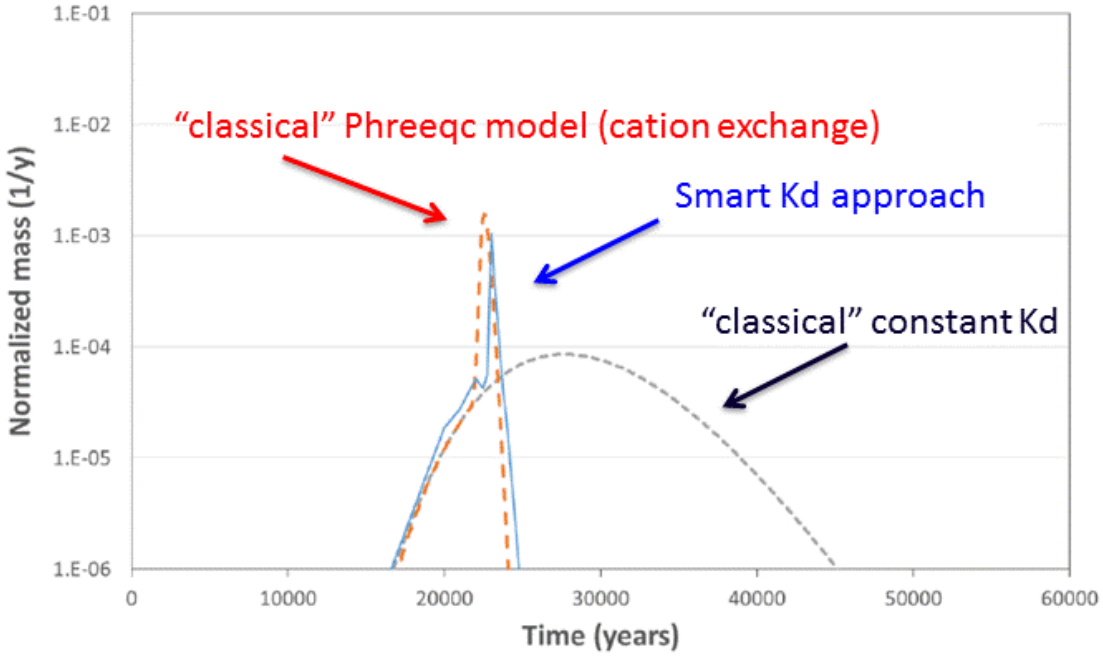

Figure 2-1. *Geochemistry in a changing environment – comparison of the intelligent Kd approach with a classical constant Kd.*

A paper 'Interface COMSOL-PHREEQC (iCP), an efficient numerical framework for the solution of coupled multiphysics and geochemistry' has recently been published in the journal Computers and Geosciences, volume 69.

2.3 CONSIDERING NEAR-SURFACE CHANGE IN THE UPDATED ASSESSMENT FOR EL-CABRIL

Danyl Perez-Sanchez presented.

There is some 176 m^3 of lower activity waste and 23 m^3 of higher activity wastes in Spain. A disposal facility for lower and intermediate activity wastes (L/ILW) has been operational at El Cabril in the Cordoba province since 1992. There will be continued disposal capacity until 2020. It is planned that cells will also be constructed for the disposal of very low level waste at the site.

L/ILW arrives at a conditioning building or, if already conditioned, at a temporary storage building prior to being placed in disposal cells. The waste drums received are placed in concrete containers. When a container is full, its drums are immobilised by means of injected mortar. The compact block is placed in the disposal cell, which is a structure of reinforced concrete. Each disposal cell has seepage control and leachate monitoring is undertaken. Once the disposal cell is filled, an upper reinforced concrete closure slab is constructed and weatherproofed and landscaped. Upon closure, the facility will be subject to a 300 year site surveillance and control phase.

Disposal of VLLW is different as wastes are of variable shape. Large scrap and rubble arrive in sacks, drums or containers and can be disposed of directly. As disposal areas are filled they will be covered by various layers including topsoil to allow landscaping into the environment. A 60 year surveillance and control phase will begin upon closure of the facility. The difference in surveillance period with that for L/ILW is due to the radioactive half-life of the wastes in each facility.

ENRESA requires that Ciemat should undertake an update of the safety assessment for El Cabril that is to take into account a variety of different scenarios including groundwater contamination and human intrusion. Climate evolution will be considered in light of the work of MODARIA WG6 and effects on drainage at the bottom of the earth cover and groundwater recharge.

The disposal facility, geosphere and biosphere are all treated independently in the assessment, but interactions between them are considered. For the biosphere, a small river is assumed to which groundwater discharges, this river then connects with a larger river; extraction of water from a well is also considered with irrigation of agricultural crops and drinking water being the key exposure pathways.

El Cabril is located in a region with a typical Mediterranean climate, but a rapid change in climate over the next 300 years is expected resulting in climate class BWh in which temperatures would be significantly higher than at present. This climate period would then be followed by moderately rapid cooling and then a sequence of cooling and warming transitions over a period of 120,000 years. An interaction matrix approach has been adopted to look at the different climate transitions in relation to topographical conditions. Spain is influenced by three seas (the Mediterranean, Atlantic and Bay of Biscay) that affect the climate classification of different regions and the crops that can be cultivated; the climate and vegetable crop classification interactions are currently the focus of a PhD project. Having initially looked at meteorological trends in relation to evapotranspiration and precipitation in the short term to ensure process understanding, the focus will then move to longer term trends and how climate trends (temperature, precipitation etc.) interact with crop dynamics (e.g. growth period). Climate change will also influence vegetation cover, with primary production being relatively higher in cooler climate regions of Spain.

Most regions of Spain are in water deficit and tend to be subject to an event-driven climatology and erosional processes in response to storm events require consideration in assessments. Warmer regions of the country tend to be associated with greater drainage variation whereas more humid regions have a lower range in drainage and, hence, groundwater recharge.

It is recognised that near-surface processes and features must be understood, such as the structure of aquifers and the properties of granite-sediment-soil sequences, to fully evaluate the influence of climate on a given area. Geomorphological changes with regard to soil types and characteristics should be evaluated, but also how these influence vegetation cover. Once these factors are understood they will be linked to an irrigation model that will be parameterised with respect to Spanish conditions.

Annual average data are often used in radionuclide transport models. However, this neglects seasonality considerations relating to crop growth and harvesting periods. Monthly data are therefore considered to be particularly important for those radionuclides that are strongly influenced by the hydrological regime and prevailing redox conditions. In Spain the change in average monthly temperature is at most 8%, but a greater range in precipitation is observed. Where the movement of water from saturated through unsaturated zones and into an aquifer is governed by individual storm events then modelling is complex, requiring consideration of the strength and duration of a storm. Computation of the flux of infiltrating water is therefore complex for the Spanish situation.

2.4 PROGNOSTIC MODELLING OF GLOBAL CLIMATE

Eva Andersson presented.

Working Group 6 of the IAEA MODARIA programme aims to develop a common framework for addressing climate change in post-closure radiological assessment of solid waste disposal. The interest is not just in global climate, but also on how global climate affects climate and landscape at the regional and site scales. The overall objectives of the working group are to:

- Define **key processes** that drive environmental change (mainly climate), and describe how a relevant future may develop on a global scale. These drivers are quantitative and can be extracted from existing scientific consensus on global historical climate evolution.
- Develop a **conceptual framework** that is valid on a global scale, and consider how that can be downscaled to provide information that is needed for site-specific assessments.
- Apply the conceptual framework to case studies (sites), to illustrate evolution of site characteristics and the **implications for the dose assessment** models.

SKB has developed a methodology for evaluating how global climate change can be downscaled to regional and site scales and this is to be evaluated through the case studies.

Having recently completed a safety case (SR-Site), knowledge of the SKB site at Forsmark and the planned disposal facility for spent nuclear fuel (KBS-3 type) is available. The site proposed for the spent fuel repository is very close to (within 5 km) a facility for low and intermediate level waste (SFR). Whilst the facilities are located close to each other and the same overall approach to addressing climate change has been adopted for both assessments, other factors come into play that affect the handling of climate in the respective safety assessments. These include the different inventories and half-lives of the more significant radionuclides, the different containment concepts, the greater depth of the SR-Site repository and the required longer timeframe for that assessment. Such factors lead to differences in critical climate-related issues, for example, the maximum depth of permafrost in SR-Site and the earliest possible timing of permafrost for SR-PSU. This in turn leads to different treatment of climate scenarios in the assessments. Thereby, although they are based on a common set of futures defined in relation to different assumptions for CO_2 emissions, different climate cases are used in the main scenarios of SR-Site and SR-PSU in order to answer to the specific questions of the assessments.

A publication is available on climate considerations in long-term safety assessments for waste repositories (Ambio (2013), volume 42, 393-401).

2.5 IAEA MODARIA WG6: CLIMATE CHANGE INDUCTION OF GBI CHANGE

Graham Smith presented.

It is widely recognised that environmental change will affect the radiological impact arising from any eventual releases of radionuclides from radioactive waste repositories into the biosphere and this is reflected in international recommendations on post-closure safety that require the implications of climate change to be considered in assessments. There is nonetheless a requirement for clarification as to how natural and anthropogenic changes in climate should be taken into account.

Two broad approaches have evolved for addressing climate change. Analogue approaches involve identifying suitable sites that can be used to represent future climate conditions at the site of interest and an appropriate set of analogues for constant systems can be used to capture the relevant range of future systems. Alternatively, models can be developed to explicitly consider the dynamic change at a site as climate evolution occurs, taking into account sea-level changes and post-glacial land uplift. This dynamic approach relies upon integration between changes in climate, hydrology, landform evolution and radionuclide release and thus requires detailed characterisation of the biosphere and how this interacts with the geosphere (the geosphere-biosphere interface) which in turn yields relatively precise information on release points to the biosphere. Both approaches have been demonstrated to be useful and can be considered complementary. The analogue approach is particularly useful in the early stages of assessment as it is less reliant on site information. The need to dynamically model transitions in climate states can be driven by whether or not the site is particularly susceptible to change or whether

there are regulatory requirements to address such dynamics. Both approaches rely on understanding the likely scenarios for climate change, which was last considered more than 10 years ago within the BIOCLIM programme. There was therefore a driver to further analyse key processes driving environmental change (primarily climate change) and to identify a reference set of possible futures within the MODARIA programme. These futures are not intended to be predictions, but rather relevant examples that can be applied to address specific questions in safety assessments. There will be uncertainty associated with the reference futures; each is applicable broadly to what is expected to occur in a particular context (e.g. greenhouse-gas emissions scenario) and they are intended to be used as reference points.

The overall objective of WG6 is therefore to develop a conceptual framework that is valid on a global scale and to demonstrate how this can be downscaled to provide information that is required for site-specific assessments. The approach will be demonstrated in different case studies that will aim to identify what does and does not matter through evaluation of dose implications. It is also intended that transient effects, occurring during transitional phases, that could give rise to release of radioactivity or altered bioavailability will be considered.

To date, a roadmap of the method has been produced and a breakdown of the draft report structure prepared. A typography of facility types has also been established (Figure 2-2), but is still evolving. The objective is to ensure that the method developed is of practical relevance to realistic types of repositories.

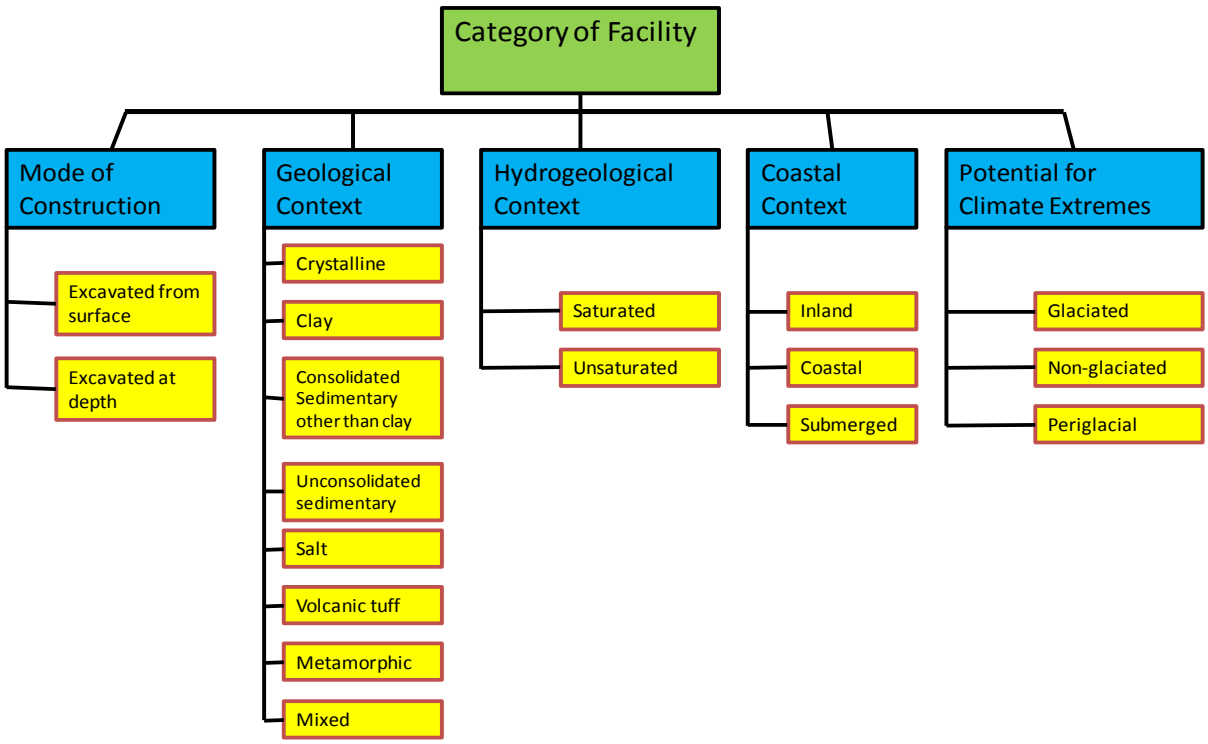

Figure 2-2. *Typography of facility types as developed by MODARIA WG6.*

Case study sites have been selected as Mol in Belgium, Forsmark in Sweden and lowland Britain. Additional sites are nonetheless invited.

A JER paper 'Influence of Climate on Landscape Characteristics in Safety Assessments of Repositories for Radioactive Wastes' has recently been prepared by members of the working group and has recently been published. The next meeting of the working group will be in November in Vienna with report completion due in 2015.

2.6 THE ATMOSPHERIC LIFETIME OF ANTHROPOGENIC CARBON DIOXIDE EMISSIONS

Natalie Lord presented.

There are a number of different mechanisms, operating over different timescales that drive climate change. These can be internal or external to the climate system and may be natural or anthropogenic in origin.

Short-term drivers include ocean circulation that affects the redistribution of heat between hemispheres; it has been suggested that ocean circulation can vary in response to glacial conditions. Where the polar front is extended southwards, lower sea-surface temperatures occur that reduce evapotranspiration which in turn causes lower salinity and affects the thermohaline circulation. Large meltwater inputs to oceans can also have such an affect. It has been suggested that changes in sea-surface temperatures may have been the driver behind the Younger Dryas cooling event. Changes in atmospheric composition can also affect global temperature by modifying the greenhouse effect. Changes in carbon dioxide and methane associated with glacial-interglacial transitions or volcanic activity can be drivers, as can anthropogenic influences such as the release of greenhouse gasses from fossil fuel burning or as a result of deforestation. There is also a feedback mechanism between the atmosphere and ocean in terms of carbon dioxide solubility that can be a short-term driver for climate change. As oceans are warmed, carbon dioxide solubility decreases leading to a greater concentration of carbon dioxide in the atmosphere that leads to further warming.

In terms of long-term drivers, orbital variations of the Earth relative to the sun, such as how elliptical the Earth's orbit is, can affect the total amount of solar radiation (insolation) received at the top of the atmosphere. This variation occurs primarily over 96 and 400 kyr periods. The tilt of the Earth's axis of rotation can also have an effect on climate by affecting the latitudinal distribution of solar radiation. The tilt of the axis of rotation can vary between 22º and 24.5º over a 41 kyr period. In addition, there is variability in the position in the Earth's orbit at which the axis of rotation is tilted towards the Sun.

A PhD project has been initiated to develop and run long-term carbon dioxide scenarios using the GENIE climate model for a period of 1 million years. Sensitivity analyses will be performed relating to the amount and timescale of carbon release, ice sheets etc. Downscaling will be applied to the results to produce regional and site scale climate projections. The overall aim is to update BIOCLIM using the full carbon cycle.

The GENIE model has a full representation of the carbon cycle in various modules, including atmospheric, marine biogeochemistry and sediment carbonate modules. There is also a weathering geochemistry module that considers terrestrial rock weathering and input to the marine system. A schematic representation of the relationship between the different model components is given in Figure 2-3.

The model was initially forced with historical carbon dioxide concentrations and then with carbon dioxide emissions from the IPCC SRES scenarios to the year 2100 (but further projected to 2300). Both gradual and pulse releases have been considered and time-dependent atmospheric carbon dioxide concentrations have been calculated for each scenario.

For the gradual release scenario, atmospheric carbon dioxide concentrations increase during the historical and projected future periods of projected human-induced enhanced emissions and then gradually decline as a number of processes work, over different timescales, to gradually reduce the artificially enhanced atmospheric carbon dioxide concentration. The processes and associated timescales are given in Table 2-1.

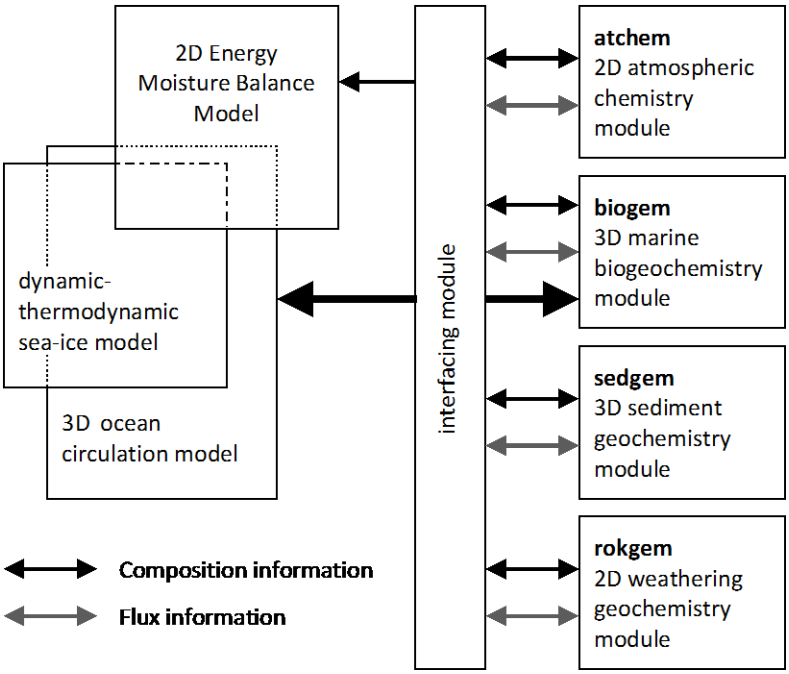

Figure 2-3. *Schematic representation of GENIE model components and interactions.*

Ocean invasion of carbon dioxide is affected by ocean surface pH and temperature. Inhibition of ocean invasion can occur as ocean temperatures rise and less carbon dioxide is able to dissolve. Surface oceans respond more rapidly than deep oceans in terms of dissolved inorganic carbon, hence transport and mixing of carbon dioxide in the deep oceans is a process operating on a longer timescale that surface ocean uptake. Seafloor neutralisation occurs as benthic waters become acidified which leads to calcium carbonate in solution that in turn affects carbon dioxide solubility; as carbonate increases in water, more carbon dioxide dissolves and this can bring atmospheric carbon dioxide concentrations down towards pre-industrial levels.

Table 2-1. *Processes acting to reduce atmospheric carbon dioxide concentrations and associated timescales.*

Process	Timescale (yr)
Ocean uptake, mixing with surface waters and reaction with saltwater	10-10^2
Transport and mixing in the deep ocean	10^2-10^3
Sea-floor $CaCO_3$ neutralisation	10^2-10^4
Carbonate weathering	10^3-10^4
Silicate weathering	10^5-10^6

Comparison of results from gradual and pulse releases show that, from around year 3000 onward, absorbed emissions are similar. It is, therefore, the total carbon dioxide input to atmosphere that matters

rather than the period over which the release occurs. The total amount of fossil fuels that can be burnt is less variable that the time over which burning and release of carbon dioxide occur; this finding therefore helps to constrain the assumptions that can be made with regard to the atmospheric life time of fossil-fuel-derived carbon dioxide.

Multi-exponential analysis of the fraction of carbon dioxide removed by the different processes has been performed for a range of emission scenarios. When plotted (Figure 2-4), non-linear variability is observed.

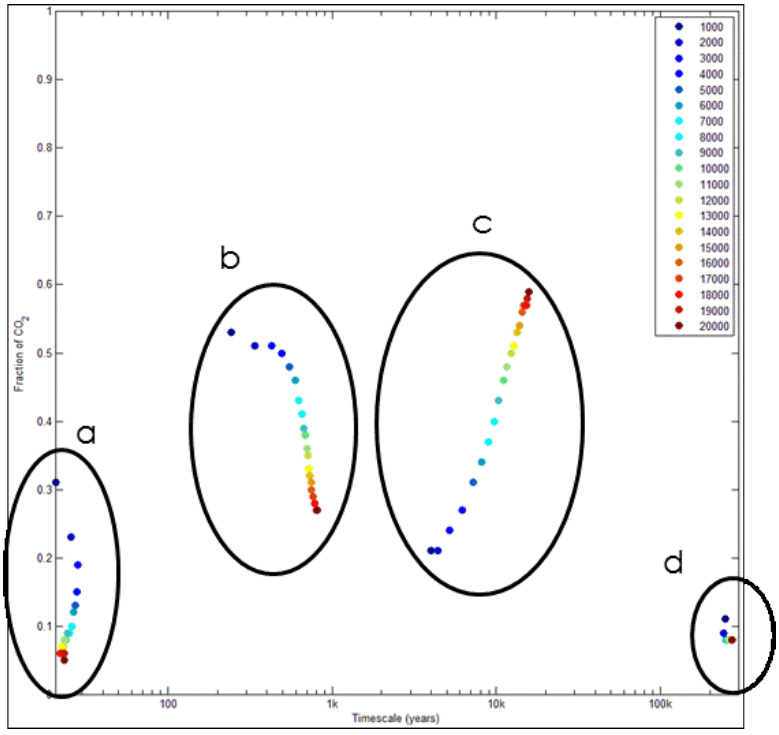

***Figure 2-4**. Multi-exponential analysis of the fraction of atmospheric carbon dioxide removed by the processes of ocean uptake and mixing with surface waters (a), transport and mixing with deep ocean (b), seafloor and terrestrial neutralisation (c), and silicate weathering (d).*

From the work undertaken to date, it is evident that there are a variety of processes that force climate change and many of these work in conjunction and over different timescales to restore atmospheric carbon dioxide toward pre-industrial levels. Multi-exponential functions have been shown to be useful in identifying and evaluating the relative importance of these different processes.

2.7 FUTURE HUMAN ACTIONS: HIDRA PROJECT AND EXAMPLE FROM THE CURRENT SAFETY ASSESSMENT AT SKB

Eva Andersson presented.

Human behaviour can affect the landscape and is therefore a relevant consideration in assessments for long-term disposal of radioactive waste. There is an international consensus that future human actions, especially human intrusion resulting in some disruption of the repository, should be considered in a safety assessment as part of a safety case for a repository. However, it is difficult to determine future human actions and what communities will be present in the long term; currently there is no international position on how human intrusion assumptions should be incorporated in assessments.

HIDRA (human intrusion in the context of disposal of radioactive waste) has therefore been established as an IAEA project. The objectives of the project are:

- To share experience of and practical considerations for development and regulatory oversight of assessments of impacts of future human actions, primarily human intrusion, in the context of the safety case during the lifecycle for a disposal facility.
- To provide specific information regarding technical, societal and design considerations to support development of a structured process or methodology for developing scenarios for site-specific application.
- To describe the role of assessments of human intrusion for siting, design and development of waste acceptance criteria in the context of a safety case.
- To provide suggestions for communication strategies to describe the rationale for assessments of human intrusion and for interpretation of the results of those assessments for the public.
- To provide supporting information for the IAEA PRISM and GEOSAF projects, and to provide clarification and support for requirements in existing IAEA Safety Requirements and Guides relevant to the assessment of future human actions and human intrusion.

Human intrusion can be considered throughout the lifetime of a safety case and the lifecycle of a disposal facility. Overall, the objective is to provide an appropriate method for addressing human intrusion in assessments and the project is therefore interacting with a number of related groups and drawing on a range of relevant reports, including the human intrusion report produced by BIOPROTA.

There are four working groups, one setting up stylised scenarios for both near-surface and deep disposal and considering the types of intrusion that could occur for each; one looking at societal factors such as the level of technology that should be considered; one on protective measures and a final one acting as an integrating group. Preservation of knowledge will ultimately prevent inadvertent intrusion so the project will look at ways of prolonging knowledge preservation through both active and passive processes and how long knowledge can reliably be preserved for, whereas the protective measures group will look at ways in which the implications of intrusion can be minimised. Optimisation of the waste to minimise the risk of intrusion is also a consideration. Safety cases are being evaluated in general to look at where human intrusions should be considered with regard to the different components of an assessment and it has been concluded that human intrusion considerations should begin in the early stages of the safety assessment process.

The general view of the project is that probabilities for human intrusion are difficult to put an actual number on and therefore the approach should be to discuss likelihood in general terms. A database of measures that can be taken to minimise the likelihood and effect of human intrusion is being produced.

Whilst the HIDRA project will describe considerations for addressing human intrusion in post-closure safety assessments and describe how the use of those assessments can help in optimising the siting, design and waste acceptance criteria, different countries will have to make their own site-specific applications based on this material. This will include considerations such as land evolution, stylised scenarios appropriate for the site and use of probabilities as may be required by national regulations.

The first meeting of the HIDRA project took place in 2012 and the next plenary meeting will be held in Vienna in December to which new members are invited. Further information is available from the project website (http://www-ns.iaea.org/projects/hidra/).

SKB has addressed human intrusion within the SR-PSU assessment for L/ILW. The current facility (SFR-1) is mainly at a depth of 60 m with a planned extension (SFR-2) at 120 m. Within the assessment, future human actions analysis was performed by identifying the relevant barriers and societal and technical features, events and processes. This analysis was then used to develop scenarios. The process used is depicted in Figure 2-5.

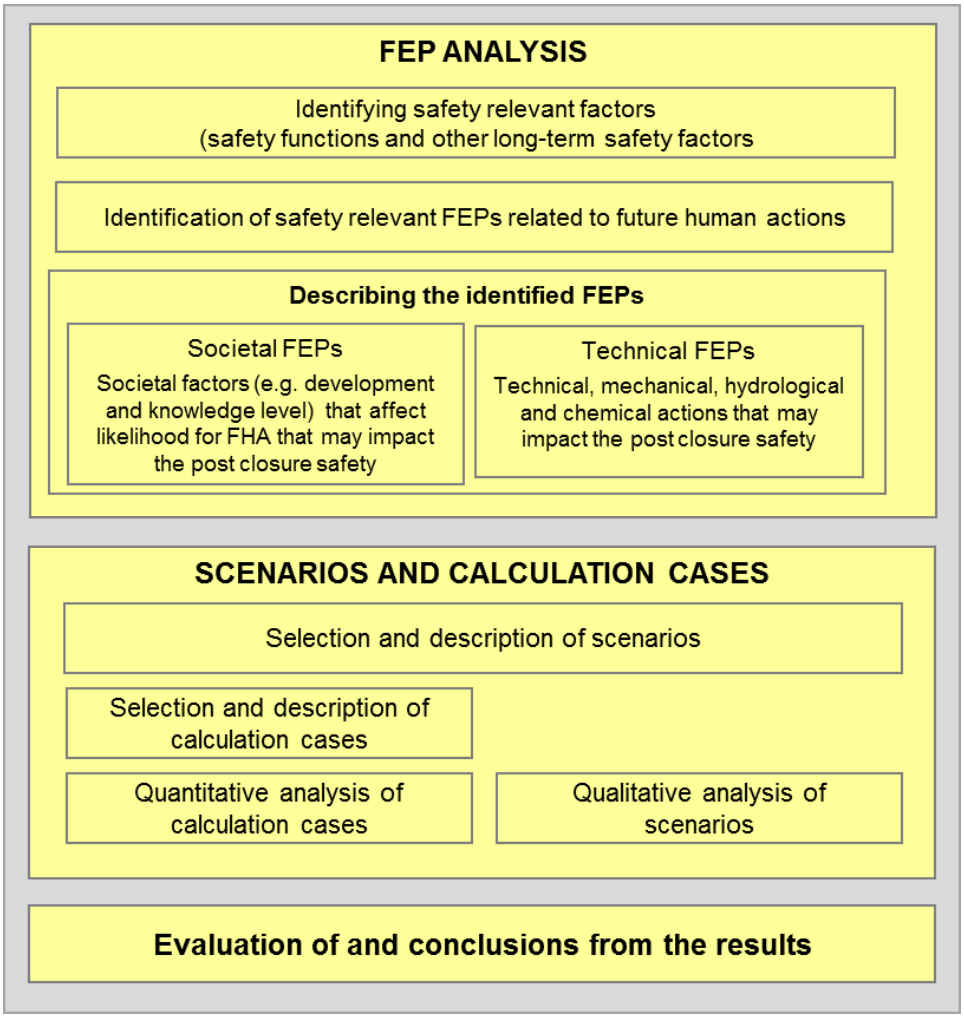

Figure 2-5. *SKB methodology for future human actions analysis.*

There were a number of general assumptions made in the analysis. Only inadvertent intrusion was considered and it was assumed there would be a loss of knowledge of the facility after 300 years. Overall, 17 FEPs were identified.

Whilst loss of knowledge was considered after 300 years, there were no immediate implications for intrusion into the facility due to the facility being located under the sea; future human actions are only of importance once the region of the facility has evolved to a terrestrial site. Once the site is located in a terrestrial setting, drilling of wells becomes an important consideration; a depth of 60 m is quite normal for wells in the region. Since wells are present in the region to repository depth utilisation of water from an intrusion well is not treated as a FHA “what if” case but instead included in the risk summation in the main assessment for SR-PSU. There, the probability of a well at the site location is based on current well frequency and risk is evaluated according to well frequency and the foot print of the repository. . However, the effect of the actual intrusion (e.g. on drilling personnel) is not included in the main

assessment but covered in the FHA assessment together with 2 more scenarios, i.e., three stylised FHA scenarios were developed:

1. Drilling into the repository, impact on:
   - Drilling personnel
   - Construction workers exposed to drill cuttings
   - Gardener using a garden plot developed on drilling cuttings mixed into soil
   - Individual utilising the well for drinking water and for watering animals (included in risk summation for the main safety assessment and not treated specifically as FHA)
2. Construction work,
   - mine in the vicinity of Forsmark
   - tunnel in the vicinity of Forsmark
3. Water management,
   - removing a pier that goes to the repository, i.e. potentially altering hydrological fluxes at the repository depth

All FHA-drilling scenarios resulted in annual effective doses much less than 1 mSv. For underground construction of a tunnel and mining, lots of fracture zones are present in the location and such activities are assumed to have only a minor e4ffect on the ground water flow through the repository. No doses were therefore calculated. For water management, a man-made pier could be removed once disposal is complete. Hydrological modelling has shown only a minor effect on the water flow through the repository by water management work, exemplified by removing the pier to SFR and thus doses were not calculated. It was concluded that both water management and underground construction activities in the vicinity of the repository or exposure to drilling personnel drilling into the repository will have little influence on safety. The only future human action resulting in significant dose rates is by utilising the drill hole as a well which is included in risk summation in the main assessment.

2.8 OVERVIEW OF THE COMET PROGRAMME FOR A LONG-TERM STRATEGY FOR RADIOECOLOGY

Mike Thorne presented.

COMET is a radioecology alliance for the long-term strategy for radioecology. Whilst the STAR programme is looking at what needs to be done in terms of radioecology research, COMET is the implementing programme. Within COMET there are a number of tasks related to radionuclide transport in the environment and one idea is to develop observation sites where extensive data sets could be obtained and analysed. This could result in long time series measurements and suggestions for the foci of these measurements are invited.

Challenge 1 is focussed on improvement of human and environmental dose assessment for which there are four research lines:

- Identify and mathematically represent key processes that play an important role in the environmental transfers of radionuclides influencing the exposures of humans and wildlife.

- Acquire the data necessary for parameterisation of the key processes controlling the transfer of radionuclides.
- Develop transfer and exposure models that incorporate physical, chemical and biological interactions, and enable predictions to be made spatially and temporally.
- Represent radionuclide transfer and exposure at a landscape or global environmental level with an indication of the associated uncertainty.

Each research line is comprised of a series of tasks and a range of modelling tasks are ongoing. Some of the radionuclides of interest to COMET are also common to the BIOPROTA programme. Any activities not completed in COMET will be handed to the overall alliance network in Europe.

Challenge 2 has a focus on research lines and aims to unravel the causes and mechanisms of radiation induced effects in wildlife from molecular and individual levels up to populations and ecosystems. There is also an objective to develop understanding of co-stressors. One hypothesis that will be tested is that exposure to gamma irradiation results in changed radiosensitivity (or resistance) within and over generations. Epigenetic changes will also be evaluated. Challenge 2 therefore comprises a range of laboratory and field studies. If broad signals are observed in terms of effects then these will be explored in more detail. Whether or not taxonomic relationships can be used to constrain transfer factors is one field of interest as is whether low activity concentrations of radionuclides are a stressor in the environment.

Challenge 3 is then to develop an integrated approach to enhanced risk characterisation and communication.

COMET operates on several levels. There are projects internal to COMET and others that are organised by COMET (e.g. via OPPERA calls). Projects are also coordinated by COMET as a means of building relationships. The projects are funded in part from European Community funds plus money in kind. All work produced will be publicly available.

2.9 REVIEW OF MODELLING OF LAND UPLIFT AND LAND USE IN BIOSPHERE ASSESSMENTS.

Ari Ikonen presented.

Land uplift has consequences for land formation and different approaches have been taken to modelling land uplift in assessments. Assessments can be based on dynamic geophysical modelling. Alternatively extrapolation of past development from, for example, shore-level displacement curves can be applied. For biosphere assessments, extrapolation tends to be applied as this approach is less data intensive, but this approach can attract criticism.

Shoreline displacement curves comprise dated observations of past shore levels that can be used to extrapolate to the future. For crustal movement, formulae are available that take into account how much the Earth's crust was depressed by ice sheets and also the bedrock properties and their potential for movement. There are also equations available for eustatic sea-level change which allows net sea level change to be computed. The spatial distribution of shoreline displacement curves allows coastal uplift to be evaluated with uplift having important consequences for factors such as sediment distribution, the formation and development of lakes, peat growth and soil formation, and vegetation succession, all of which must be taken into account in biosphere assessments. Together these factors gradually change the potential for land use and the habits of both people and biota, which are also affected by climate.

Sediment redistribution is affected by grain size and can be taken into account using sediment dynamics models. For safety assessments, it is largely extremes that are of interest. For example, an evaluation may be required of how much sediment can be transported. As such, extremes of processes are largely considered like maximum wind speeds. For the Olkiluoto site in Finland, it is more conservative to assume that fine sediments are not washed away, since these can develop into agricultural areas with land uplift unless there is transport to a single area where greater accumulation could occur.

In terms of lake formation and development there is a succession of events as coastal bays become land locked. GIS data can be used to evaluate where lakes, streams and rivers will form, but assumptions around overburden hydrology are required. Basic dimensions of lakes and rivers can be used to evaluate water discharge and the geometry of a basin and chemistry of that basin will determine the ultimate fate of lakes. If a basin is deep and of low nutrient status then a lake is likely to remain open. Shallower lakes or those that are nutrient rich are more likely to be subject to vegetation growth both in terms of macrophytes and surface vegetation mats resulting in the formation of peat over time. Ultimately such areas can develop into peat bogs.

Sedimentation in lakes can be evaluated using physical/dynamic models or by applying stylised models. This latter approach has been used both by SKB and Posiva whereby the relationship between sedimentation rate and the basin water volume (decreasing rate with decreasing volume) is established based on observations of sediment deposits. The filling of lakes by vegetation has been considered by SKB by using an empirical relationship between littoral vegetation extent and lake basin area, whereas Posiva has applied a fetch-based model that has been calibrated with present reed bed locations to identify the possible future locations for reed beds. In both approaches, it is assumed that littoral vegetation will only form in water bodies that are less than 2 m deep.

Peat development occurs in areas where the groundwater table is close enough to the surface (peat cannot form if an area is too dry) or where infilled lakes are colonised by mosses, leading to the development of wetland and, ultimately, peat bog. Peat formation is therefore affected by land topography.

In terms of human land use, the main interest for assessments is agricultural areas. Mineral and organic deposits and landscape conditions (topography etc.) can be used to evaluate likely agricultural areas with only those areas that are not feasible for such use being excluded. This would include stony soils, gravel, coarse till and large boulder areas. Very wet areas are also likely to be excluded unless drainage of wetlands or peat bogs is assumed. In the Posiva assessment for Olkiluoto, it was assumed that total field area remained in the same proportion as at the current day and very small areas were excluded as agricultural areas.

The cultural level of the most exposed group can be driven by regulatory requirements. For Posiva, it has been outlined in the regulations that similar agricultural practices to those at present were to be assumed, whereas for SKB the regulations do not specify the most exposed group and a range of different potentially exposed groups may be considered. Future human actions may also be considered such as the construction of dams to form large lakes or the draining of lakes to obtain more agricultural land. Each of these actions can be used to develop scenarios that form the basis of calculation cases.

Land use assumptions are largely driven by human requirements, but these may not be limiting cases for wildlife dose assessments. Additional calculation cases may therefore need to be considered whereby biota are allowed to inhabit most areas. In the SKB SR-Site assessment, the most penalising of several lines of landscape development was selected as the basis for the biota dose assessment. Posiva in their assessment considered a range of calculation cases with biota dose assessment being performed for many. Whilst a ‘no agriculture’ scenario had at one time been considered, this was not

propagated through to the final calculation cases performed; such a case may have been of interest for biota dose assessment.

A range of references are available from the websites of both SKB (www.skb.se) and Posiva (www.posiva.fi) relating to land uplift and land use in biosphere assessments.

2.10 LEGAL FRAMEWORK FOR THE DECONTAMINATION PROGRAM AFTER THE NUCLEAR ACCIDENT OF FUKUSHIMA DAIICHI NPP

Takashi Nakamura presented.

Following the nuclear accident at Fukushima Daiichi nuclear power plant, a contamination map has been produced based on equivalent air dose modelling (Figure 2-6). Countermeasure areas have been established. There is an evacuation zone, corresponding to the higher levels of contamination. Dose rates of over 50 mSv/y correspond to areas where residents are unlikely to be able to return for some time whereas where dose rates are lower than 20 mSv/y it is likely that evacuation orders will be lifted in the short term.

Modelling has been undertaken to look at the movement and transport of radionuclides through the biosphere, taking into account human activities. This includes evaluating the transport of radioactivity in sewage and how to dispose of contaminated material.

An Act on Special Measures has been implemented following the accident, which aims to quickly reduce the impact of environmental pollution on human health and the living environment. The Act was produced five months following the accident and came into force in January 2012. It is a temporary law with a lifetime of three years, but may be continued after this time if necessary. Under the Act, the Minister of the Environment is made responsible for handling off-site pollution; radionuclides in the environment previously being excluded from his remit. Confidence in the nuclear regulators was damaged following the accident and this move of responsibilities to the Minister of Environment aims to improve public confidence in the handling of clean-up operations. The Minister of the Environment will be responsible for setting standards for decontamination and disposal of waste, including soils, contaminated by radioactive material and generated by decontamination works. All materials in the immediate zone of the Fukushima plants (the evacuation zone) are considered contaminated whereas for other areas, designation is made according to Cs-134 and Cs-137 concentrations in excess of 8 kBq/kg for the waste, and areas where the additional dose rate is over 1 mSv/y for the designated areas where the decontamination work should be implemented. The local government normally handled such wastes in Japan, but following the accident, the national government has been made responsible for the disposal of such wastes. Contaminated materials with activity concentrations below 8 kBq/kg can be treated as conventional wastes. The cut off is based on a dose assessment performed for workers and members of the public; an activity concentration of 8 kBq/kg corresponds to a dose constraint of 1 mSv/y for most severe scenario (workers working at landfill site). Decontamination measures undertaken by the local government are performed under the guidance of the national government.

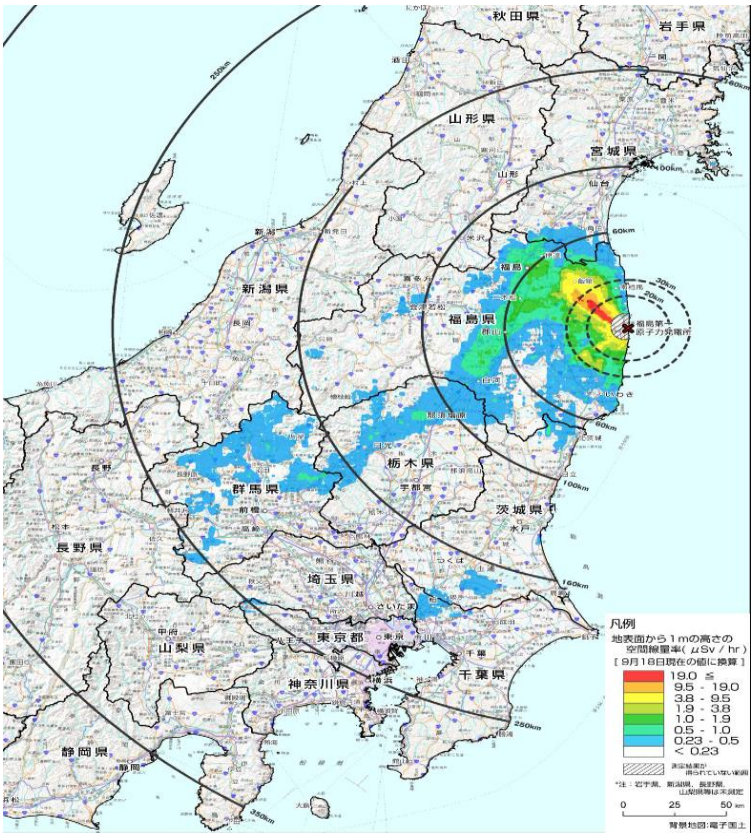

Figure 2-6. *Contamination map produced following the Fukushima Daiichi nuclear power plant accident. Blue areas correspond to a dose rate of 23 µSv/h and red to 190 µSv/h. (Air-born survey conducted by the ministry of education, culture, sports, science and technology in October 3011)*

The decontamination policy aims to reduce the additional exposure of people to less than 1 mSv/y as a long term goal for the lower contaminated areas whereas for higher contaminated areas the objective is to reduce dose in residential and farmland areas to below 20 mSv/y. Under the Act, the national government is required to take the steps necessary to establish facilities to allow decontamination activities to take place. These include facilities for:

- Temporary storage (allowing for the storage of waste for 3 years in principle);
- Volume reduction, such as by the use of incinerators;
- Intermediate storage (allowing for the storage of waste for 30 years);
- Transportation of wastes; and
- Final disposal of wastes.

A flow chart has been produced to indicate how different wastes should be treated. The wastes include both tsunami-associated wastes (e.g. houses) and radionuclide contaminated wastes (e.g. domestic wastes) as well as contaminated soils generated as a result of decontamination. In principle, no human wastes are being generated in the exclusion zone, but such wastes are generated elsewhere. Those wastes with activities in excess of 100 kBq/kg following incineration and all the contaminated soils

generated by decontamination works in Fukushima prefecture are to be placed in interim storage facilities. Those below this level can go to leachate-controlled landfill sites for domestic and industrial waste with some additional and specific measures, such as monitoring of radioactive material in groundwater to store the wastes with activities in excess of 8 kBq/kg.

A communication page for the Ministry of Environment has been created (http://josen.env.go.jp/en/) and progress on decontamination activities is reported. A concept for the design of an interim storage facility has been produced. Groundwater monitoring will take place and leachate will filtered to prevent the migration of radionuclides from the facility. Currently, negotiations are taking place for land acquisition that will allow the construction of the facility structure.

Decontamination activities can be quite destructive, which is not good for biota. As such, decontamination works are carried out in minimal degree in forest ecosystems. A marine contaminated zone of around 20km from the coast has been designated. Fish within this zone and which might pass through this zone are monitored to ensure they are fit for human consumption. To prevent further contamination, it is intended to reduce the new income of groundwater into the highly contaminated zone especially in the Fukushima Daiichi nuclear power plant site, by installing groundwater pumps in the upstream side in order to bypass the concerned zone, and by installing an underground ice wall encircling the highly contaminated area.

2.11 CHALLENGES OF MODELLING C-14 IN FORESTS AND MIRES

Ari Ikonen presented.

Carbon-14 modelling has been identified as a key issue for the soil-plant pathway and, in northern latitudes, forests and mires are common biotopes that may require consideration in assessment models. The wetter forest and mire areas are, the more likely they are to receive groundwater inputs and, potentially, radionuclides from underground waste disposal facilities. Whilst C-14 was the focus of the presentation, it was noted that issues may be relevant to other radionuclides.

Forests can vary considerably from sparse tree stands to dense forests in areas from dry to very moist types. Whilst forests growing in moist areas are more likely to receive a deep groundwater release, previous agricultural use or emerging from sea or a lake could have led to soil contamination with forests then developing. Drier forest types tend to be rocky and are less likely to be used for agriculture, but could still become contaminated if the area is subject to land uplift with previous sea contamination. Upland forests are largely considered to be sinks for atmospheric methane. Patches of contamination may occur and these may be relevant for biota exposure (e.g. bird nesting areas etc.). Some literature data are available for degassing and foliar uptake for a number of radionuclides in forests, including C-14, but these data are not comprehensive; particle deposition and incorporation are more commonly addressed.

There are a number of different sinks and sources of carbon in forests that form a layered system. Soil and understorey vegetation form lower layers with a gap then for tree trunks with an upper layer for tree crown (branches and leaves). Complexity can be increased through the presence of taller shrubs.

In terms of modelling atmospheric mixing of C-14 in forests, a logarithmic wind profile model could be applied for the upper atmospheric levels, but the canopy dynamics become more complex within the canopy due to turbulent mixing with the understorey further complicating wind movement. The understorey is largely the habitat of biota and is therefore an important component in forests. With understorey and higher tree canopies, the productivity zones are variable within a forest ecosystem.

Whereas forest ecosystems are particularly relevant for biota dose assessments, mire or wetland ecosystems are generally more relevant to dose assessments for people, although some mires are also inhabited by trees. Like forests, mires are similarly complex with various types having been identified. Mires with trees can affect wind dynamics, and variations in the density and type of trees present adds to complexities. Dead trees may also be present; whilst these affect the carbon system only very slowly they do have the potential to affect the wind profile. As with forests, mires are highly variable, ranging from those with some ground level vegetation with trees to open mires and raised peat bogs that may or may not contain open pools. There is not only variation in the type of mires, but also small-scale variability within any given mire. The rates of growth and productivity of mires are very variable and this will affect C-14 uptake to biological matter due to differing rates of photosynthesis. Open mires and peat bogs are more likely to be relevant to groundwater discharge, but wetter areas tend to be less productive than dryer areas. Most wetlands are considered to be sources of methane production. Representing the variability of a mire surface within a model presents a challenge, particularly with regard to how wind velocity and turbulence behave in such a mixed system.

The carbon balance in a mire is regulated by the production of organic material on the top and its decay deeper in the mire. The lateral extent of a mire is explained by the hydrological balance and hydrological conductivity. Plant communities in a peat-forming soil depend upon water availability. As peat forms, the groundwater table is raised and new growth forms above leading to the formation of lawns or hummocks. Thicker peat deposits can prevent or retard the formation of permafrost. Such areas are therefore not only of interest to biosphere assessments, but can also influence geosphere considerations.

There are a number of challenges therefore in linking biosphere models to reality, but solid data sets exist that could be used to evaluate different aspects of C-14 modelling, including consideration of biomass in different layers and compartments. For example, in terms of carbon balances, carbon dioxide assimilation is linked to photosynthesis, which is determined by primary productivity that is itself linked to biomass in different layers and compartments. Spatial variability could be addressed by mapping of the biosphere through tools such as remote sensing. Processes such as soil respiration and degassing are measureable, having been undertaken for climate studies and, as such, a greater database is becoming available. There are also data available on C-14 depth profiles for peat bogs that have been developed in order to reconstruct their development in land uplift studies performed especially both in Sweden and Finland. There is a further level of complexity to modelling C-14 behaviour in forests and mires in that there are cycles of microbial activity associated with seasonal changes; variations in temperature and soil moisture will affect microbial activity and hence emanation of carbon dioxide from soils. Daily variations will also be evident with greater emanation occurring during the day when temperatures are warmer, this coinciding with the period of plant photosynthesis.

A range of references has been identified that may be of interest in addressing some of the issues associated with C-14 behaviour in forests and mires, and it was proposed that a thorough review of this literature be undertaken, leading to the development of a detailed conceptual model for forests and mires.

2.12 RWM PERMAFROST WORK

[N.B. due to schedule conflicts, the presentation outlined below was given during the annual BIOPROTA meeting, held in the days prior to the workshop reported herein. Nonetheless, due to the relevance of the presentation to the workshop subject area, an outline of the presentation has been included herein].

Simon Norris presented.

RWM is interested in developing knowledge on how the geosphere responds to climate change and the potential impact that permafrost could have on a geological disposal facility (GDF). Such a facility in England and Wales could be located at a depth of between 200 and 1000 m. If located at the shallower depths, permafrost may impact directly upon the engineered barriers of the disposal facility. For a deeper GDF, permafrost formation could affect e.g. groundwater chemistry in the host rock. The impact of such permafrost-related changes would need to be assessed in a safety case.

Permafrost is defined as ground at a temperature below a 0ºC isotherm for at least two consecutive years, with ground temperature driven by cyclically changing air temperature.

In a recent study for RWM to ascertain possible depths of permafrost, ten locations around the UK with borehole and core records available were randomly selected (Figure 2-7), and site geology was considered along with heat flow data and thermal conductivity of rocks (these being important factors to represent when considering permafrost development). How temperature has changed over the past glacial cycle was reconstructed, including ice sheet development (Figure 2-8). Various data sets were available to support reconstruction, including sea surface temperature and land temperature studies with the combined data allowing a temperature-time dataset to be established for the UK over the last 140,000 years. Comparison with other climate datasets showed broad similarity with that developed as part of the RWM study. The temperature profile was used to evaluate when and where ice sheets may have been present in the UK, with the south of the country not thought to have been affected by ice sheets over the last glacial-interglacial cycle.

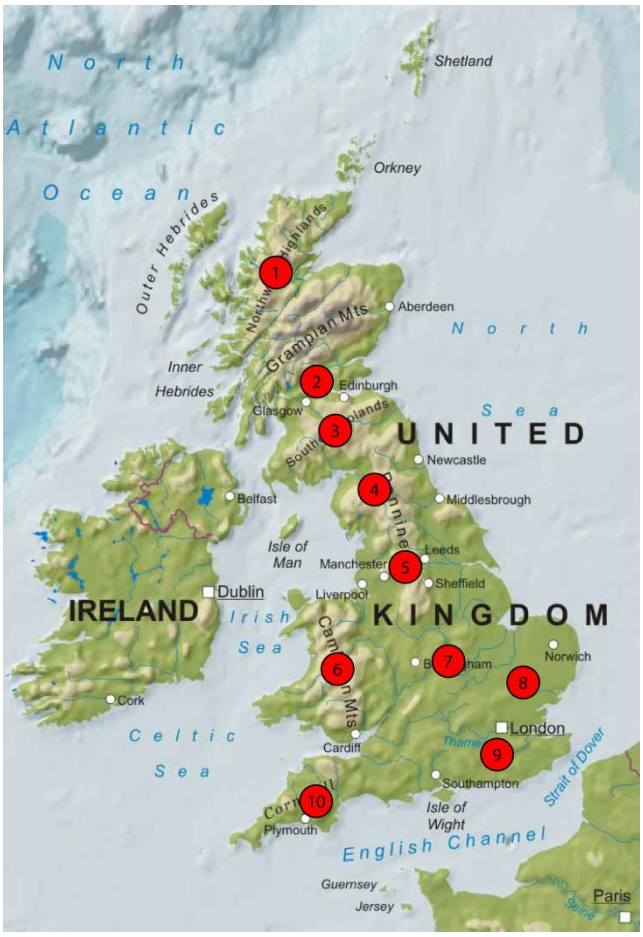

Figure 2-7. *Study locations in the RWM permafrost study.*

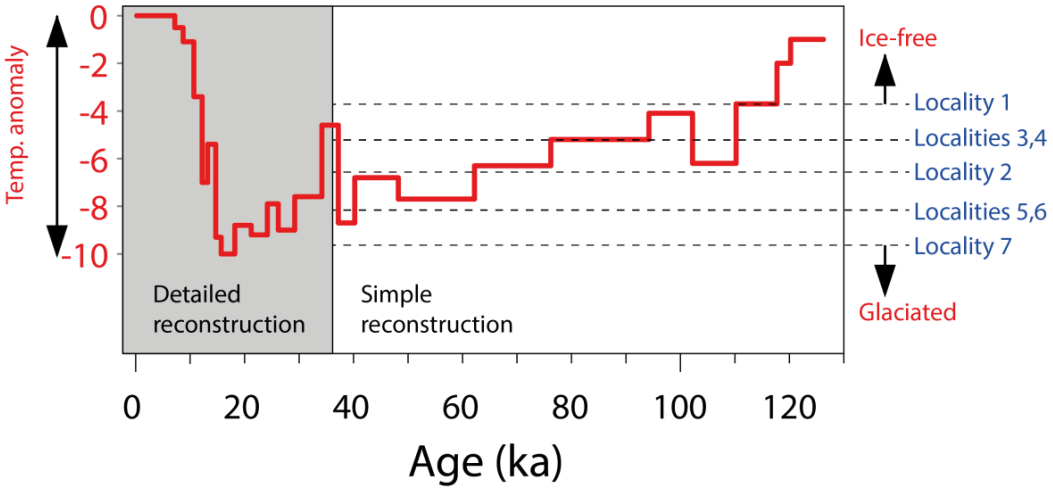

Figure 2-8. *Ice sheet coverage of different regions of the UK. Localities correspond to those depicted in Figure 2-7 (see also Table 2-2).*

Models have been run for each of the ten localities, taking into account basal temperature. Currently groundwater flow and its impact on sub-surface temperature have not been considered. Consideration was given however as to whether dry- or wet-based ice sheets would develop. Once the surface temperature is known, subsurface temperatures could be evaluated. Results of the model runs indicate that the greatest permafrost penetration would occur in the northwest Highlands (Table 1). A maximum penetration of 305 m was modelled for the Southern Uplands during a cold climate. An example from models run for the Dartmoor region (denoted 10 in Figure 2-7) is detailed in Figure 2-9. Uncertainty in permafrost development modelling requires consideration.

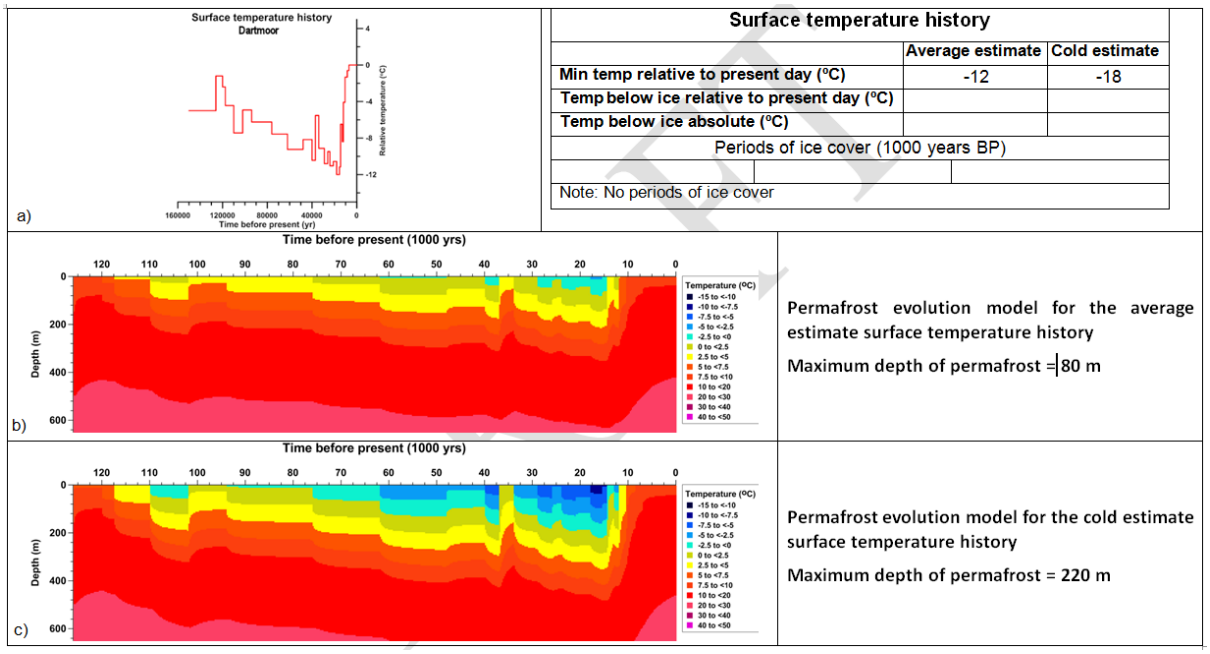

Figure 2-9. *Results of permafrost evolution at Dartmoor from the period from 126-0 kyr BP for the average estimate surface temperature history (upper) and cold estimate surface temperature history (lower)*

The past climate has been used to evaluate possible future climate conditions. On average, the maximum permafrost development across the UK is calculated as 180 m. If anthropogenic warming is considered, no permafrost impact on a GDF is likely to occur for the first 180,000 years post closure.

Geological evidence for permafrost during previous cold stages of glacial cycles is available from the investigation of near-surface geology, although only for shallow depths (a few tens of metres). Although there is no evidence for deeper permafrost penetration, this does not mean that it didn't occur. Rather, it could be that we just do not know what evidence to look for, or that a one-time present signal is now no longer present.

Further work is planned in relation to permafrost modelling following various recommendations made as a result of RWM's work programme to date, e.g. how permafrost could affect the mineralogy of rocks could be considered.

Permafrost is not always a negative consideration for geological disposal; it can affect the rate of groundwater recharge / discharge, giving a greater decay time in the geosphere or engineered barrier system for GDF-derived radionuclides. Furthermore, whilst people can live in areas affected by permafrost, larger subsistence areas are required; this could reduce exposure potential to GDF-derived radionuclides. The effect of permafrost growth and decay on the properties of the geosphere need be considered.

Table 2-2. *Modelled permafrost penetration at ten sites around the UK during average-estimate and cold-estimate climates.*

Location (location number from Figure 2-8)	**Maximum depth of permafrost (m) due to average estimate climate**	**Maximum depth of permafrost (m) due to cold estimate climate**
Dartmoor (10)	80	220
Weald (9)	65	245
East Anglia (8)	65	245
South Midlands (7)	30	180
Mid-Wales (6)	105	215
South Yorkshire (5)	90	180
Stainmore Trough (4)	20	205
Southern Uplands (3)	150	305
Midland Valley (2)	110	215
Northwest Highlands (1)	180	235

2.13 SUCCESSION OF ASSESSMENTS FROM THE PERIOD OF OPERATION

Graham Smith presented.

Regulatory requirements are often variable depending upon the phase of assessment for a disposal facility (construction, operation, post-closure). Whilst rules may change however, the system itself does not. There is therefore a need to manage risk transition; during the period of operation there is risk management, but once the facility moves to a post-closure phase, risk management ceases and the

possibility for inadvertent human intrusion begins. There are therefore a number of issues to consider in the transition between different phases of assessment. In particular, ensuring that assumptions are consistent with regard to human behaviour and land use is considered important. Exposure assessments for the operational phase are largely based on habit surveys, hence human behaviour is quite well understood in terms of food and water consumption rates and occupancy assumptions. Assumptions relating to the longer term are likely to differ however and the level of conservatism in assessments may therefore vary considerably.

In considering succession of assessments, it is not only in relation to modelling that the assumptions and approach may vary; monitoring programmes may also differ considerably. Monitoring activities for site characterisation programmes and those linked to assessments for operational assessments can differ considerably, with the latter often being designed to ensure discharges are consistent with regulatory requirements. Whilst the monitoring programmes may currently be considered separately there could be real merit in considering the data needs for further phases of assessment when monitoring programmes are developed. Site characterisation forms an important part of various stages of assessment and therefore maintaining communications between the different assessment groups could lead to important efficiency savings, both in terms of time and costs, by ensuring coordinated activities; such actions could prevent duplication of effort and would help to mitigate against data gaps whilst also maintaining consistency through the different phases of assessment.

During construction activities, land use will be restricted. It is suggested that models could be tested during this phase by undertaking an environmental impact assessment and evaluating whether or not models predict the impacts that do or do not occur. Data collected during this phase of assessment could prove useful for safety case development.

Whilst models can be used to evaluate likely discharge areas for radionuclides entering the biosphere, it is potentially important to consider monitoring other areas than those identified since there are uncertainties in model output. Well considered monitoring strategies could help avoid issues associated with model errors and help to improve public confidence in assessments. Extensive monitoring at a site is also likely to help maintain knowledge of a facility into the future by identifying the site as of real scientific interest.

There is further consideration that should be given to the availability of technologies in assessments. Whilst there may be plans for technologies to be available in the future, it may not be appropriate to place reliance on such availability. There may also be drivers for undertaking monitoring post-closure where, scientifically, there may be little justification; such activities could provide public confidence. Sensibly designed monitoring can be used to allay fears.

From assessments undertaken to date (both site specific and generic), it is considered that the waste community has sufficient experience to identify key monitoring activities for characterisation of a site. The sooner such activities begin at a site, the better for the assessment programme, allowing for potential efficiency savings as different monitoring requirements can be aligned.

The monitoring of human habits may be done in a single survey, but this survey may be affected by societal factors in force at that time; hence current human habits may not be fully applicable to future years. Such factors should be considered sensibly and inconsistencies in assessments considered and documented.

Finally, it was noted that, not only can regulatory requirements change in relation to the different phases of assessment, but rules may also evolve as regulations develop both nationally and internationally, with implications for assessment approaches.

3. DISCUSSION AND IDENTIFICATION OF FURTHER RESEARCH

A substantial report has been produced as a result of the BIOPROTA project on 'representing the geosphere-biosphere interface (GBI) in assessment models' that includes a detailed methodology. The application of this methodology to alternative sites and facilities to those considered in the report itself may have considerable merit in demonstration of the applicability of the approach, both in terms of site specific and generic applications. One approach could be to develop a proposal on the illustrative application of the method, enhancing the biological and geochemical aspects. It was suggested that Duke Swamp may be an interesting and applicable site-specific focus.

It was furthermore considered that the work completed to date could form the basis of a scientific publication. With the appropriate consideration of biological aspects of assessment, the Science of the Total Environment was suggested as a possible journal to gain a wider audience than just those working in the field of radioecology. Maintaining links with ongoing work in the IAEA MODARIA programme, particularly that of Working Group 6, was deemed important. In particular, the work of the group is important in exploring the use of simple versus complex models in relation to the evolution of the biosphere.

In a recent conference on geological disposal of radioactive waste, 30 out of 140 abstracts were related to biosphere assessments and sub-surface microbiology and there would be merit in considering how the work being done by various groups could be linked with the interests and work performed through BIOPROTA. Of particular interest would be work being undertaken in relation to micro- and macro-biology in the soil rooting zone and characterising microbiological interactions with plants in the rooting zone of soils. Understanding such interactions on a site-specific basis, particularly for wetlands, could be of interest and it was noted that there are substantial data for reference mires from the work of Posiva in characterising their reference area. It was suggested that a programme could be established to look at evolution of mires as a sub-system (ADMIRE) with C-14 assessment being included as a possible sub-task, potentially focussing on Duke Swamp if data were to be made available. Alternatively, information from the BIOPROTA GBI project could be used as input to a future C-14 project, which may allow greater links to be built with the wider C-14 community. Furthermore, developing links with the COMET programme was considered beneficial as this would allow opportunity for priorities in radioecology research to be highlighted for key radionuclides such as C-14, but also less well researched radionuclides such as Mo-93. Aspects such as landscape evolution and site characterisation in relation to radioecology research could also be discussed along with issues such as redox sensitive and volatile radionuclides. For such radionuclides it is considered that research activities are required rather than the capabilities of existing models being expanded. There are also links between intelligent modelling of Kd and the STAR research programme and further links could be made with COMET. Feedback is invited in terms of interest areas that may invite support.

The IAEA BIOMASS report on reference biospheres continues to be an important input to biosphere safety assessments. However, having been completed in 2002, this is now rather dated and indeed, the project did not progress how to address environmental change very far. There has been, and continues to be, substantial work that further develops the concepts and knowledge relating to reference biospheres and their assessment, such as work being undertaken within the IAEA EMRAS II, HIDRA and MODARIA projects and various BIOPROTA projects, notably work on the representation of the GBI. It may therefore be timely to consider updating the BIOMASS methodology to take account of new information and experience of the application of the BIOMASS methodology to real assessments and what this means for site characterisation activities, models and data. It was suggested that such an activity could be suggested as a logical succession to the current IAEA Working Group 6 programme. The success of such a suggestion would nonetheless depend on the level of support provided by the

waste community to such a proposal. Should this idea be taken forward, there may be merit in including semi-arid and arid landscapes and tropical and sub-tropical climates for which particular issues arise. Each of these could be described and climate downscaling performed.

APPENDIX A. LIST OF PARTICIPANTS

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