BIOPROTA

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

Report of the 2022 BIOPROTA Annual Meeting

16-19 May 2022

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3 October 2022

PREFACE

BIOPROTA is an international collaborative forum that 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 radioecological and other data and information issues that are common to assessments required in many countries. Collaborative research within commonly focused projects is intended to make efficient use of skills and resources, to draw on international experience 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 primary objectives of BIOPROTA are:

- to provide a forum for exchange of information to support the resolution of key issues in biosphere aspects of assessments of the long-term impact of contaminant releases associated with radioactive waste disposal and contaminated land management; and
- to make the best sources of information available to justify modelling assumptions required within long-term safety assessments.

Particular emphasis is placed on key data for the assessment of long-lived radionuclide migration and accumulation in the biosphere, and the associated radiological impact, following discharge or release to the surface environment.

The programme of activities is driven by needs identified from previous and on-going assessment projects, as discussed at BIOPROTA meetings. Where common needs are identified amongst BIOPROTA members, a collaborative effort can be applied to finding solutions.

This report describes presentations and discussions held during the 2022 BIOPROTA annual meeting. As a result of the ongoing COVID-19 pandemic, the meeting was held as a series of web-hosted sessions via Microsoft Teams, from 16 to 19 May 2022. Technical inputs were provided by a wide range of organisations via presentations and discussions, as described in this report.

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 1.0: Draft meeting report prepared by Karen Smith (RadEcol Consulting Ltd) based on participant contributions and reviewed by Russell Walke (Quintessa Ltd) prior to distribution to meeting participants on 31 August 2022.

Version 2.0: Final meeting report prepared by Karen Smith (RadEcol Consulting Ltd), taking into account participant comments on version 1.0. Distributed to meeting participants and forum members 3 October 2022.

Version 3.0: Final meeting report prepared by Karen Smith (RadEcol Consulting Ltd), taking into account additional participant comments following distribution of Version 2.0. Distributed to meeting participants and forum members 4 October 2022.

CONTENTS

1. INTRODUCTION

The annual BIOPROTA meeting is designed to provide a forum for continuing exchange of information and discussion on topics of special interest in national programmes, and an opportunity to update participants on progress on the various projects and activities supported through BIOPROTA. It also aims to provide an opportunity for discussion of topical issues, with the intention that, where there is sufficient collective interest among member organisations, discussions could lead to collaborative research and assessment via specific BIOPROTA workshops and/or projects.

In light of the ongoing Covid-19 pandemic, the annual BIOPROTA meeting for 2022 was organised as a series of 3-hour web-hosted sessions over 4 days that focussed on updates concerning individual programmes and research from member organisations, progress with ongoing BIOPROTA work programmes and discussion of common themes and ideas for future collaborative work programmes. This report provides an overview of the presentations and discussions throughout the meeting.

1.1 OVERVIEW OF THE BIOPROTA FORUM

BIOPROTA is a forum for exchange of information to support the resolution of key issues in biosphere assessments of the long-term impact of contaminant releases associated with radioactive waste disposal and contaminated land management. A key objective is to make available the best sources of information and the latest research to justify modelling assumptions and help build confidence and reduce uncertainties in long-term assessments.

BIOPROTA members are the heart of the forum with membership aimed at national authorities, agencies and other organisations, including technical support organisations and independent research institutions, with shared interests in biosphere studies related to achieving safe and acceptable radioactive waste disposal and contaminated land management.

There are currently two grades of membership. Full members pay a membership fee that is used to support the role of the technical secretariat in providing technical and administrative support to the forum and coordination of meetings. Full members have a seat on the Sponsoring Committee that decides on the direction of the forum and its work programme. Academic members do not pay a membership fee, but do not form part of the Sponsoring Committee. The Sponsoring Committee is headed by a chairperson who is elected each year during the annual BIOPROTA meeting. The current chairperson is Alex Diener (BfS). The structure of the forum is illustrated in Figure 1.

One general meeting of the BIOPROTA forum is held annually, providing an opportunity for organisations to provide updates about biosphere related activities within their programmes and to identify challenges and uncertainties where collaborative efforts through projects and/or workshops could help their resolution.

In addition to the annual meeting, topical workshops are held on particular issues of common interest that provide an opportunity for organisations to discuss specific topics in depth and to which additional external expertise may be invited. Presentations and discussions are recorded in topical workshop reports and can, where there is sufficient interest and support among forum members, lead to technical projects to address issues or to undertake model-data and/or model-model comparisons. The workshops require a small amount of technical support to organise and to develop a workshop report with those organisations with an interest in the topic providing the necessary funding. All workshop reports are made available on the forum website.

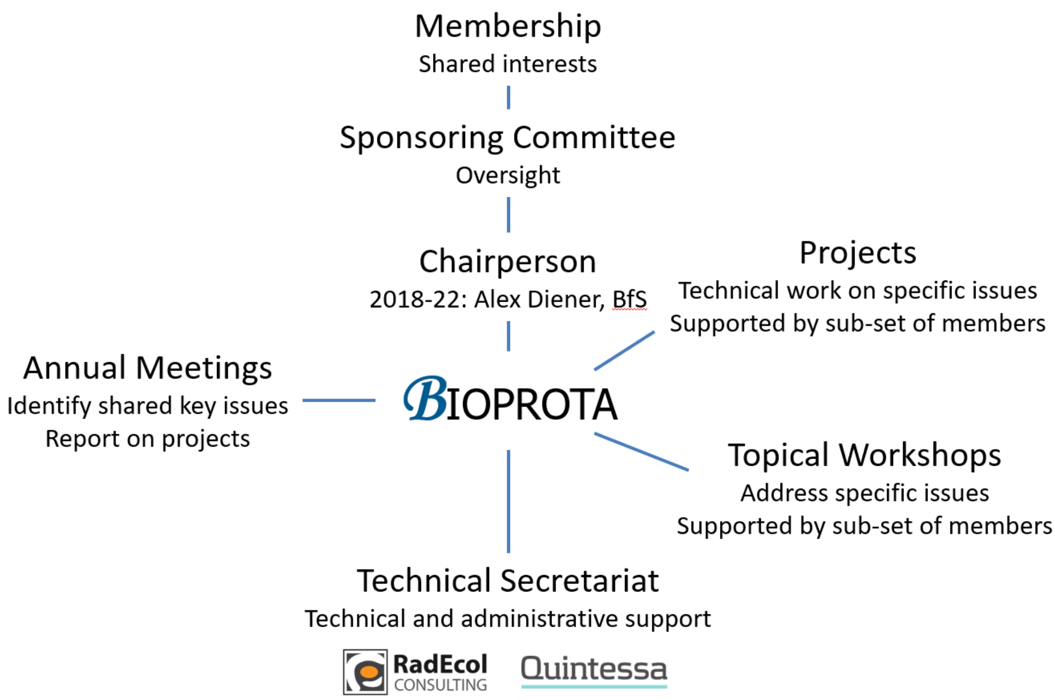

Figure 1. Structure of the BIOPROTA forum.

Proposals for collaborative projects or workshops are welcome from members of the forum at any time and are distributed amongst members for consideration. Proposals should detail the planned scope of work, deliverables and propose a technical support team to deliver the works and estimated project costs. Member organisations are then invited to consider supporting the projects financially and/or technically. If successful, sponsors are invited to form a project steering group to oversee the project and approve project deliverables prior to wider distribution. Results of the project are presented and discussed during the annual BIOPROTA meetings and final project reports are, where approved by sponsors, made publicly available on the BIOPROTA website.

Membership invites for 2022 have been sent out by the Technical Secretariat to 21 organisations that were full members in 2021. In 2021 there were also 5 academic members. Two organisations, SURAO and UJV from Czech Republic, did not renew membership in 2021. Membership invitations for 2022 are therefore as follows:

Full member organisations

- Andra, France
- ARAO, Slovenia
- BfS, Germany
- DSA, Norway
- EDF, France
- ENSI, Switzerland
- EPA, USA
- FANC, Belgium
- IRSN, France
- JANUS, Japan
- KAERI, Korea
- KORAD, Korea
- LLWR, UK
- Nagra, Switzerland
- NUMO, Japan
- NWMO, Canada
- Posiva, Finland
- RWM, UK
- SCK·CEN, Belgium
- SKB, Sweden
- SSM, Sweden

Academic members

- Oregon State University (OSU), USA
- Clemson University, USA
- University of Eastern Finland (UEF)
- University of Life Sciences (NMBU), Norway
- Royal Institute of Technology (KTH), Sweden

The membership represents a broad cross section of regulators, operators, technical support organisations and academic institutions.

1.2 MEETING PARTICIPATION

The organisation of the 2022 annual meeting as a series of web-hosted meetings allowed for greater participation from member organisations than would be feasible for a face-to-face meeting. The meeting was attended by 47 participants from 13 countries, representing a range of operators, regulators, researchers and technical support organisations. Participants are listed in Appendix A, along with affiliations.

1.3 REPORT STRUCTURE

Section 2 of this report summarises the presentations from meeting participants on progress and perspectives from member organisations. Section 3 provides and update on the current work programme and Section 4 summarises presentations and discussions around ideas for the forward programme. Feedback from the sponsoring committee and forum arrangements for 2023 are detailed in Section 5.

2. PROGRESS AND PERSPECTIVES FROM MEMBER ORGANISATIONS

Presentations from meeting participants on their biosphere programmes, issues and uncertainties are summarised in this section, including related discussions.

2.1 BIOSPHERE ASSESSMENT IN THE OPERATING LICENSE APPLICATION

Lauri Parviainen (Posiva) presented.

The biosphere assessment is just one part of the overall operating license application for the Olkiluoto repository for spent nuclear fuel in Finland. As the application has been progressed, so too have construction works at the site. The external construction of buildings is mostly complete and work is progressing to install the necessary internal machinery, with completion due by the end of the year. The first deposition tunnels are currently being excavated and should be ready in the summer.

The operating license application was submitted in December 2021. The application was made within a tight schedule and some reports are still in the publication process. Nonetheless, the regulator STUK has accepted the application and confirmed they will start to review and inspect the submitted reports and the first questions from the regulator are anticipated in the summer. A decision on granting the operational license is expected in 2024.

The license application consists of a safety case portfolio that will be publicly available from June. The portfolio contains numerous reports that themselves refer to many other background reports that have been produced over recent years. There are two groups of biosphere reports. The first are the description and data reports that detail the site description and present the data that are used within the biosphere models. There are five reports in this category:

- Lahdenperä, A-M. Kuusisto, J. 2021. Safety Case for the Operating License Application: Description and data of the surface environment 1 - Overburden Properties and Sorption. Working report 2019-11;
- Kirkkala, T., Mikkila E. 2021. Safety Case for the Operating License Application: Description and Data of the Surface Environment 2 - Aquatic Environment. Working Report 2019-12;
- Aro, L. 2021. Safety Case for the Operating License Application: Description and Data of the Surface Environment 3 – Forest and Mires. Working Report 2019-13;
- Salo, T. 2021. Safety Case for the Operating License Application: Description and Data of the Surface Environment 4 – Agriculture. Working Report 2019-14;
- Haavisto F., Toivola M. 2021. Safety Case for the Operating License Application: Description and Data of the Surface Environment 5 – Fauna. Working Report 2019-15.

The second are the biosphere modelling reports:

- Gunia, M., Gunia, K., Parviainen, L. Isoaho, A. 2021. Safety Case for the Operating Licence Application: Terrain and Ecosystems Development Modelling. Working Report 2020-22;
- Karvonen, T. 2021. Safety Case for the Operating Licence Application: Surface and Near Surface Hydrological Modelling. Working Report 2020-23;

- Broed, R., Kupiainen, P., Parviainen, L., Isoaho A. 2021. Safety Case for the Operating Licence Application: Biosphere Radionuclide Transport and Dose Modelling. Working Report 2020-24;
- Hjerpe, T. 2021. Safety Case for the Operating Licence Application: Biosphere Models for Screening Purposes and Simplified Dose Calculations. Working Report 2020-25;
- Smith, K. 2021. Safety Case for the Operating Licence Application: Dose Assessment for the Plants and Animals. Working Report 2020-26;
- Mäki, J. M. 2021. Safety Case for the Operating Licence Application: Modelling report for Simplified Landscape Dose Conversion Model. Working report 2021-23.

All reports are available from Posiva website (TVO - Reports and publications (posiva.fi)).

The repository is being constructed on Olkiluoto Island on the southwest coast of Finland. Whilst currently an island, post-glacial land uplift, at a current rate of around 6 mm/year, will result in the island joining with the mainland in a few thousand years. The coastline will, however, retreat once more with future glaciation events, the timing of which will vary depending on greenhouse emissions from some tens of thousands of years to hundreds of thousands of years after present.

The continued evolution of the coastline prior to the next glaciation will see the shoreline retreat as new land areas form. Some bays will form around the island where there are topographical depressions. Much of the new land area is likely to be suitable as croplands.

Release points from the geosphere to the biosphere have been modelled using a fracture network model for groundwater flow and radionuclide transport through the geosphere. The release locations are, to some extent, dependent on time. For early releases, the locations occur close to Olkiluoto Island, whereas later releases are more focussed towards a bay to the north of the island with some smaller releases occurring to the south.

The information on release locations over time was used to inform the construction of the landscape model. A terrain and ecosystem development model informs the properties of the areas of land as they evolve with time which, combined with release areas, helps in the selection of biosphere ‘objects’ that may be contaminated as a result of releases. These biosphere objects are then carried forward to the hydrological and landscape (radionuclide transport and dose) models.

The hydrological model has a compartmental structure and considers the release of groundwater to the surface and groundwater recharge. The hydrological model is described in Working Report 2020-23. The landscape model then uses data from the terrain and ecosystem model and the hydrological model to evaluate radionuclide transport through the biosphere objects, with transport being modelled according to water fluxes and diffusion and uptake by plants. For carbon-14, a specific activity model is applied.

Since the last round of assessment for the construction license application in 2012, seawater exchange in the landscape model has been updated. This results in peak concentrations of radionuclides occurring in some landscape objects downstream of the release locations that then reduce when inputs to the area decline. There are only a few release areas during the terrestrial phase and only nearby landscape objects are affected as a result of releases.

The release scenarios have also changed since the 2012 assessment in which a pinhole release from a canister was the baseline scenario. In the current round of assessment, releases only occur from the

Low and intermediate level waste (LILW) repository in the base case as the canisters storing the spent nuclear fuel will remain intact. However, in the what-if cases, a complete loss of containment is assumed for a canister at either 300 years or 3,000 years post-closure. Resultant doses even from these calculation cases remain below the regulatory constraint. Alternative calculation cases have considered the implications of alternative release locations. The difference in calculated doses with release location is around 1 order of magnitude.

In addition to the landscape model, a simpler dose model has also been applied which gives rise to doses that are closer to the regulatory limit. Consumption of fish from the sea is the main exposure pathway and the key radionuclide is C-14. During the later terrestrial phase, consumption of cow milk is the main exposure pathway and Cl-36 is the main contributor to dose.

The main radionuclides contributing to dose for the spent nuclear fuel repository are C-14, Cl-36 and I-129. Over longer timescales, Ra-226 is also important. For the low and intermediate level (LILW) repository, the key radionuclides are Ag-108m, Mo-93, Ni-59, Sr-90 and Ra-226. Doses associated with the LILW repository are many orders of magnitude below the regulatory constraint and post-closure safety for that repository is not therefore an issue for the safety case. The main exposure pathways are consumption of cow milk, fish, cereals and well water.

Croplands can be allocated in different ways. They can be allocated according to dietary needs or based on current agricultural land use statistics. If croplands are allocated on the basis of dietary needs, then doses to the most exposed people are slightly increased relative to those calculated using a statistical allocation. However, for 'other exposed people', doses are slightly higher when a statistical allocation is used than if a dietary needs approach is employed. This is because a dietary needs based allocation requires a greater area of land to be allocated to livestock whereas if the allocation is based on current agricultural land use statistics then more cereals are produced in the contaminated area with those cereals being widely consumed throughout the population.

Dose rates to non-human biota associated with releases from the LILW repository are very low, being many orders of magnitude below the ERICA screening dose rate. Dose rates associated with releases from the spent nuclear fuel repository are higher, but still remain orders of magnitude below the screening value, even for the most conservative 'what-if' calculation cases. It should also be noted that no releases would be expected to occur from the spent nuclear fuel repository within the assessment time window of 10,000 years (this timeframe is defined in regulatory guidance).

A simplified dose assessment model was applied to evaluate doses to people over a longer assessment timeframe (1 million years). This is a relatively simplified and conservative grid-based model with 100 m by 100 m grid cells within which releases from the repositories can be distributed. For releases from the LILW repository, Mo-93 is the dominant radionuclide for the first few thousand years, followed by Ni-59 and then Ra-226 after around 50,000 years. For the spent nuclear fuel repository, a chemical erosion case was considered using the simplified dose assessment model where some tens of canisters failed. The releases from the canisters mostly occurred within a relatively small area of around 1 km by 500 m. Results exceeded the regulatory constraint, with the key radionuclides being I-129, Cl-36 and Ra-226. However, the regulatory constraint only applies during the first 10,000 years. The peak doses were associated with the next glaciation event, specifically during ice advance and retreat during which time it is unlikely that people would actually be present. The results were not, therefore, considered to be an issue for the safety case. Furthermore, subsequent erosion studies undertaken after the calculation case was completed strongly suggested that this case was improbable and, if scenario formulation were to be repeated in light of the new studies, would likely be dropped.

A trial run of final disposal operations will take place in 2023, which will be a full demonstration of how disposals will be made using the actual equipment and procedures that will be deployed in the operational phase but with four dummy disposal canisters. Fuel transport, encapsulation, final disposal (to include buffer, backfill and end plug installation) and retrieval of a damaged canister will all be part of the demonstration trial run.

Discussion

Landscape development has considered the general area around the repository but with special focus then being given to the release locations. None of the likely release locations are associated with mire habitats but one low probability release area in the centre of the Island could see a mire develop. Mire development has therefore been considered within the safety case.

2.2 DEVELOPMENT OF BIOSPHERE ASSESSMENT MODULE FOR GEOLOGICAL DISPOSAL SYSTEM

Minjeong Kim (KAERI) presented.

Work to develop a biosphere model for geological disposal in Korea began in 2021. Current understanding and ongoing work in developing the model was therefore presented.

The objective for the biosphere assessment is to assess the compliance of the geological disposal system against safety goals that are set out in regulatory guidelines for a high level waste repository in Korea:

- The total annual risk for the representative person resulting from radiation exposure should not exceed 1E-6/yr.
- The expected radiation exposure for the representative person for each scenario should not exceed 10 mSv/yr.

The assessment process involves three steps. Firstly, the past, current and future states of the biosphere are to be described. Secondly, the migration of radionuclides in the biosphere will be simulated based on hypothetical releases from a repository. Thirdly, dose and risk will be calculated based on the activity concentrations of radionuclides in the biosphere. Sufficient reasoning is required at each step.

KAERI's Performance Assessment Model (K-PAM) for radionuclide transport is being developed using GoldSim. Radionuclides are transferred between compartments according to transport rates for each transport mechanism.

A system-level compartment model requires the system of interest to be simplified in order for the model to be computationally efficient and many assumptions are needed. Process-level detailed models can be used to supplement the system-level model, with potential to provide more realistic and plausible simulations that are spatially distributed. Detailed models, however, require a lot of data and computational resources. In combination, system-level and process-level models can be used as complementary tools for assessments.

A process-level total system performance assessment model is being developed at KAERI that covers the whole disposal system, i.e. near-field, far-field, hydrogeology etc. A biosphere module is currently being developed which consists of three models:

- Simulation of the water balance is performed in a Soil and Water Assessment Tool (SWAT) model. Input to the model includes various surface environment data such as topography, land use, soil type and weather. Water balance output includes information such as recharge rate, river morphology and river discharge.
- Simulation of groundwater flow is performed using a COMSOL model with water balance components from the previous step being used as input data to derive the groundwater flow distribution in an aquifer.
- The final model component is then the simulation of radionuclide transport based on data output from the previous steps, again applying a COMSOL model with both 3- and 1-dimensional transport of diluted species in porous media to derive radionuclide concentration distributions throughout the aquifer and surface water bodies.

The surface environment changes over time. An independent snapshot approach is employed, based on future development data. For each snapshot, steady-state hydraulic conditions and time-dependent radionuclide transport are computed with radionuclide concentrations from one snapshot being used as input to the subsequent snapshot. This allows time-transient radionuclide transport to be simulated across the different hydraulic conditions in each snapshot over time.

A disposal site has not yet been selected so a virtual disposal system and associated biosphere have therefore been developed. The artificial disposal system (ADioS) covers 24 km^2 and is comprised of river, lake, sea, forest and cropland areas. Weather data are based on historical records.

SWAT is a semi-distributed watershed model that uses GIS input data. Watersheds are sub-divided into homogenous areas that have the same land use, soil type and elevation etc. to derive a spatial distribution of the overall water balance components. Cropland systems have more surface water run-off than forest areas, whereas there is higher evapotranspiration associated with forests than croplands. However, following water balance calculations, recharge rates are similar for both land uses. River network recharge and discharge are also calculated and are then used as input to the groundwater flow simulations: The calculated recharge rate and river level are used as input to the groundwater flow simulations.

For the groundwater flow simulations, three types of boundary conditions are applied based on the water balance analysis performed during the first step. For inland areas, downward flow occurs leading to groundwater recharge, whereas for surface water bodies there is upward flow and groundwater discharge. The presence of a well affects groundwater flow such that groundwater converges into the area near the well, affecting radionuclide transport. Such areas therefore need to be considered.

The source of radionuclides to the aquifer is the radionuclide release from the geosphere-biosphere interface, which is calculated from the geosphere assessment module with a simple stepwise function for the geosphere-biosphere interface. Radionuclide transport in an aquifer is calculated using an advection and diffusion equation that takes into account radioactive decay and sorption. Radionuclide migration follows the groundwater flow and discharge to surface water bodies. The majority of radionuclide discharge occurs to an upper river section, with some radionuclides being transported to the sea/shoreline area or to a lake. The effect of sorption has been tested for I-129 and Th-229 which have very different degrees of retention. Th-229 is being strongly retained due to a high Kd whereas I-129, which has a low Kd, reaches the surface of the aquifer more rapidly.

The radionuclide concentrations in groundwater reaching water bodies such as lakes/rivers can be calculated. On reaching a river, COMSOL simulates 1-dimensional radionuclide transport along the route of the river based on river discharge which is calculated by SWAT.

A process-level detailed biosphere assessment module has therefore been developed that allows radionuclide transport to be simulated in connection with a geosphere assessment module. By applying GIS data, the potential spatio-temporal variability of radionuclides in the biosphere can be evaluated. The next step will be to test the long-term assessment capabilities using future development data and to assess spatially distributed doses.

Discussion

The biosphere module presented is very interesting, particularly in how change over time is represented. It would be interesting to compare the approach with other types of model, including both more- and less-detailed approaches.

2.3 UPDATE ON SKB ACTIVITIES

Ulrik Kautsky (SKB) presented.

SKB is the organisation responsible for all radioactive waste in Sweden. This includes spent nuclear fuel from the nuclear power plants but also radioactive wastes arising from industry and hospital applications, and legacy wastes. The journey began around 50 years ago when SKB was a small company. In the years since, SKB has grown into a much larger organisation.

Different ways to manage radioactive wastes have been explored. For spent nuclear fuel, the decision was made to construct a repository at around 500 m depth with fuel being disposed of in copper canisters surrounded by bentonite clay. A similar disposal system is being developed by Posiva.

The siting process for the repository initially involved investigations throughout Sweden to identify promising areas from which two sites were selected for detailed site investigation. Forsmark was ultimately selected. In 2011, SKB applied to increase storage capacity, build an encapsulation plant for canister construction and to construct a spent nuclear fuel repository. Since this application, SKB has also applied to extend the operational repository for short-lived radioactive waste (SFR). A safety evaluation for a repository (SFL) for long-lived radioactive waste that would not be destined for either SFR or the spent fuel repository has also begun, and that work is likely to continue for some decades.

The spent nuclear fuel repository application was declared complete in 2015 and several hearings have taken place, including in the Environment Court and with the two local communities that will be affected. The Environment Court declared the application was acceptable to the Government in 2017 and a decision to increase storage capacity was granted in 2021. A positive Government decision on the application was made in 2022. The next step will be a new hearing with the Environment Court at which terms and conditions will be set. SSM, as the nuclear regulator, will also need to review a preliminary safety report for which approval is needed before construction can commence. SKB will therefore begin preparations for the next hearings that are due to take place later in 2022 and will also submit the preliminary safety report. The level of detail contained in the various assessments that have supported the process has increased with each stage. Similarly, engagement and cooperation with the international community has also increased.

In addition to progressing work related to the spent nuclear fuel repository, SKB is also updating their research and development plan that feeds indirectly into the safety assessment. The last iteration of the plan was submitted in 2019 and the next version is due in September 2022. The plan will be in Swedish, but an English version will be published at a later date.

2.4 NWMO STATUS UPDATE AND HUMAN RECEPTORS FOR POST-CLOSURE SAFETY ASSESSMENT

Antoine Boyer (NWMO) presented.

2.4.1 Status update

An Adaptive Phased Management (APM) approach is being implemented for the management of used nuclear fuel in Canada in the long-term, including a deep geological repository. The associated site selection process is progressing with two sites currently undergoing characterisation work with boreholes being drilled. The geology at one site is crystalline bedrock and the other is sedimentary. Site selection is planned for 2024, with the regulatory review process beginning soon afterwards. The submission of the project description is planned for 2024, which will trigger the federal impact assessment. The application for a licence to prepare the site will be submitted as well. For planning purposes, it is estimated that the approval of the impact assessment and licence to prepare site is granted in 2028, and a licence to construct would be granted in 2032. It is estimated that the design and construction would start around 2033.

Preliminary site-specific safety analyses are currently being prepared, and key results will be shared with the two communities associated with the two remaining sites. The analyses will draw upon data available at the end of 2021 from early site characterisation activities, current environmental conditions and the evolving design of the facility which is developing in light of constraints identified as a result of the characterisation works.

Work has been progressing on the development of various components of the current phase of post-closure assessment, including site geology models, iteration of the geosphere-biosphere interface, screening of contaminants, identifying potential receptors for each site, developing proposed safety assessment acceptance criteria and developing the assessment models. Future assessments will draw on site-specific features, events and processes (FEPs) and an updated assessment report will be produced for each site.

2.4.2 Human receptors for post-closure assessment

Human receptors for the post-closure assessment are being developed on a site-specific basis.

An integrated system model is being developed that encompasses the near-field, far-field and biosphere and will allow different failure scenarios to be evaluated. In order to demonstrate safety, doses will be compared against dose criteria and against natural background. This requires the biosphere model to account for different pathways for human exposure such as agricultural production, garden produce, well-water extraction etc. In order to conceptualise the different receptors, knowledge of the different lifestyles of local people and how they interact with the environment is important. Various pathways of exposure need to be considered, including food and water ingestion, immersion in water, inhalation etc.

Work on defining the habits of potential exposure groups has been ongoing since 2002. Initial focus was on a single lifestyle – that of the most exposed group. The most exposed group was the imaginary maximum and is based on conservative estimates. In 2005, a report was published titled ‘Alternative exposure groups, characteristics and data for the post-closure safety assessment of a deep geological repository’. This included consideration of both Indigenous peoples and local municipalities. The report was reviewed in 2012 by the Assembly of the First Nations and recommendations were made for pathways and data for parameterising lifestyles of Indigenous peoples. In 2013 a further NWMO report was published titled ‘Aboriginal Lifestyle Characterisation’ (NWMO TR-2014-13), which covered three lifestyles. The report was passed to the Assembly for the First Nations and further recommendations were again received, such as including natural products used in ceremonies.

Within the two siting regions, the NWMO is looking to support community acceptance and, therefore, in 2021, specific lifestyles were investigated, based on the recommendations from the Assembly of the First Nations. Data on food and nutrition were drawn from Indigenous owned data sets and a lifestyle questionnaire was developed to obtain information on water and food consumption habits and environmental interactions. Results from the questionnaire, combined with previous work on the topic, were used as input to the development of a new internal report in 2021 that includes six illustrative lifestyles for use in site-specific analyses. These lifestyles will be used this year for the first site-specific assessments. The lifestyles include imaginary maximum, Indigenous A and B, town resident, rural resident and hunter-gatherer groups.

For the Ignace Area (northern crystalline geology), the Indigenous A group represents an individual in a community, whereas Indigenous B is an individual living in a rural environment that represents the area of highest dose potential. The hunter-gatherer is also assumed to live and obtain all food and water from in this area. The rural resident lifestyle assumes meat from a hobby farm is consumed and that drinking water is abstracted from a well located above the repository. The town resident has a lifestyle representative of an individual living within the town and using the area near the repository for recreation. Two resident areas are considered – the original siting community (Ignace town) and Dryden which is located downstream. The imaginary maximum lifestyle was defined using bounding assumptions and data, assuming a self-sufficient farming individual located in the most contaminated area and drawing maximally on local groundwater for drinking. This lifestyle is intended to help address the inherent uncertainties associated with the long assessment timeframes.

For the South Bruce Area (sedimentary geology), similar local lifestyles have been defined. More towns are located around the area of greatest dose potential and have been included. The Indigenous A lifestyle represents an individual located downstream of the repository, inhabiting an area near Lake Huron. With the exception of the location and specific ingestion rates, the lifestyles are similar to those of the Ignace area.

Exposure pathway analysis involved eight exposure media (outdoor air, indoor air, soils, well water, surface water, aquatic sediments, autotrophs and heterotrophs) that together contained twenty different exposure pathways that were screened either in or out for each lifestyle. Each lifestyle was then defined quantitatively, based on a representative person in each case. Various references were used to derive these data. Many rates were drawn from the Canadian standard on the development of receptors for biosphere assessment in the nuclear realm. In most instances, the median rate was applied, but for the imaginary maximum the 95th percentile was applied. For some lifestyle-pathway combinations, the use of median rates was not appropriate, such as soil ingestion for Indigenous lifestyles, so data from alternative sources were applied.

Diet is a major factor in terms of exposure pathways, consisting of more than 50% of the associated data input to the biosphere model. The proportion of locally derived food varies considerably across the different lifestyles. In the case of the imaginary maximum and hunter-gatherer, 100% of food is obtained locally but their food groups only overlap in terms of fish consumption. In the case of the imaginary maximum, the largest proportion is associated with crops that are irrigated with well water, whereas for the hunter-gatherer the main food groups were wildlife, wild plants, and fish. For a town resident, the proportion of food from the local area was the lowest at 40% with most being associated with milk and egg consumption. For the Indigenous A and B groups, the proportion of locally derived foods was 60%. Local crops were important for these groups, along with wildlife rather than local livestock which were important for both town residents and rural lifestyles.

Work to refine the local lifestyles will continue through further engagement with local partners. The safety assessment will also be further progressed in an iterative manner consistent with the BIOMASS methodology with illustrative local lifestyles being updated with each iteration as further information and data become available from site characterisation activities, results of engagement, and feedback from external review groups.

Discussion

Forecasting future behaviours and socio-economic trends is difficult and the imaginary maximum group has been developed as a means of calculating bounding doses that can then be compared against doses that would arise based on current lifestyles. Such an approach helps to provide confidence that conclusions are robust, taking account of current lifestyles and uncertainties with possible future lifestyles.

Work undertaken by SKB on the contribution to dose from different diets found that diet had only a relatively small effect on the total dose. However, the radionuclides of importance to dose did vary with diet. Analysis of different diets can therefore help inform on the radionuclides that should be focussed upon in site characterisation and can be important in the narrative of which radionuclides matter for different lifestyles.

The use of groundwater extracted for agriculture from a well is very stylised with a large fraction of release from the geosphere being captured. The approach therefore maximises doses to anyone using the well.

2.5 A REVIEW OF THE LIKELY IMPACTS OF A GDF ON BIOTA IN THE SUBSURFACE

Kat Raines (NWS (GDF)) presented.

A technical note has been developed by NWS (GDF) that summarises existing knowledge on sub-surface biota, identifies knowledge gaps, considers how to move forward with supporting research programmes, and summarises understanding of how and when subsurface biota have been included in other programmes and how impacts have been assessed.

UK Government policy for the long-term management of higher activity radioactive waste is geological disposal, preceded by safe and secure interim storage. Geological disposal will isolate the radioactive waste from the surface environment with the design of the facility ensuring both natural and manmade barriers minimise the release of radioactivity. The siting process for the repository in ongoing with several communities being involved in the process.

As part of the siting process, subsurface macrofauna and microbial communities are to be considered and their sampling and surveying will be included in the site characterisation programme. Such biota have not been extensively studied either worldwide or in the UK.

Subsurface biota inhabit a harsh environment where both light and oxygen are limited but conditions are relatively stable over time, which enables adaptation. They can exist at different levels from just below the surface of the biosphere to considerable depth. The largest macrofauna tend to inhabit the vadose zone between the surface and the groundwater table and in cave systems. Below this there is the phreatic or saturated zone which is a dynamic and energetically rich source-sink zone that can support a lot of macrofauna. Within the lithosphere, a lack of resources such as space and nutrients limit the presence of macrofauna and microfauna therefore dominate and can be present to several hundred metres below the surface.

Groundwater food webs tend to be smaller and less complex than those of the surface environment since there is minimal primary production. As such, it is worth considering subsurface biota in terms of the ecosystem services. Subsurface biota maintain food web functionality (i.e. carbon flux) and provide bioremediation services to maintain aquifer functionality. They also create biofilms that feed into wider ecosystem services that they provide. There is also the potential to use subsurface biota as bioindicators of ecosystem health and water quality.

One particularly interesting group of subsurface biota are stygobites. Stygobites are a group of macrofauna with special adaptations that enable them to inhabit harsh environments. They are found only in subsurface environments where groundwater is present and provide a range of ecosystem services such as contributing to biogeochemical cycling and maintaining water quality. As a result of adaptations that include relatively slow metabolisms and long life spans, they have the potential to bioaccumulate which could pose interesting challenges for the GDF safety assessment.

There is no explicit protection for groundwater macrofauna provided by UK legislation. However, the Water Framework Directive requires the ecological health of groundwater-dependent systems to be protected and the Groundwater Directive encourages consideration of groundwater ecosystems in the management of groundwaters. In addition, the British cave shrimp (*Niphargus glenniei*) has been listed as a priority species in the UK Biodiversity Action Plan. More explicit protection of groundwater species is provided in other countries. For example, in western Australia explicit guidance for the protection and sampling of groundwater fauna has been developed to assist in environmental impact assessments and, in Switzerland, the Water protection Ordinance of 1998 requires groundwater biota to be maintained in a natural state reflecting low pollution levels. Whilst there are not specific regulations in place, the Environment Agency has indicated that protection of groundwater biota should be demonstrated.

There is only limited information on the distribution of stygobites in the UK. Most information has been gathered from caves so tends to be quite localised and biased toward accessible caves and thus cave dwelling species. Nonetheless, a lot can be learned in terms of controls on their distribution, such as how populations have been affected by past glaciation events (stygobites are generally absent from areas that were covered by the ice sheet during the last glaciation).

Microbes are ubiquitous and a lot of work is to be done in terms of characterising subsurface communities and developing understanding of how microbes could affect the GDF near-field. In higher strength rocks there is low permeability and microbes are likely to be confined to fractures. Consolidated rocks are less likely to contain microbes due to the small pore spaces in the rock matrix. Pore space is further reduced in clay. Nonetheless, the presence of microbes cannot be ruled out irrespective of the host rock.

A GDF could affect microbial communities by introducing new species, by changing geochemical conditions as a result of drilling mud, and by changing water flow. Concrete surfaces could also provide favourable conditions for biofilm formation. Whilst microbes are generally considered to be radioresistant, effects from higher dose rates in the near field cannot be ruled out and could lead to adaptation.

The siting process for a GDF is underway with three community partnerships in Cumbria in Northwest England and one working group at East Lindsey in the southeast having been formed and additional communities could also come forward. Cumbria is located above the previous glaciation line so subsurface groundwater macrofauna are unlikely to be present whereas East Lindsey is on the boundary and may provide an ideal habitat. Further desk-based risk assessments will be undertaken for subsurface macrofauna as the siting process progresses and consideration will be given to how and when to sample subsurface macrofauna and microbial communities during the siting process.

Discussion

There is no explicit guidance internationally on assessing dose rates to non-human biota in groundwater. In the UK there is also no explicit requirement to evaluate the potential impacts of exposure on subsurface biota, but there is an implicit requirement from the Environment Agency.

Before being drawn into impact assessments for geological disposal (or any other type of sub-surface development), a much greater degree of understanding will be needed concerning groundwater biota, especially with regards to distribution and vulnerability. Few studies have been undertaken to-date, although there is a report from SKB (TR-08-06).

Review of potential impacts would need to consider the slow metabolism of subsurface macrofauna and different lifecycles, which may affect uptake and retention of contaminants such that application of concentration ratios from similar reference organisms (e.g. crustaceans) may not be appropriate.

The bacterial community is known to be extremely important for groundwater chemistry. Biogeochemistry is an important component of assessment programmes, although focus to-date has been on its implications for performance and potential contaminant migration.

If impacts on non-human biota at depth are to be considered, more realistic models for the spatial distribution of pollutants in groundwater will be needed. Currently, groundwater tends to be thought of as a transport route to the biosphere rather than considered as an endpoint in its own right.

2.6 UPDATE ON RADIOACTIVE WASTE MANAGEMENT IN BELGIUM

Maryna Surkova (FANC) provided a brief update on activities relating to radioactive waste management in Belgium.

A decision has been made to move away from nuclear energy in Belgium. The current reactors will be shut down one at a time, with just two reactors remaining operational. Decommissioning projects will therefore be increasing and a draft Royal Decree on the national policy for intermediate- and high-level waste has now been given. The policy will include deep disposal. As the Decree is currently being drafted, the final decision will only be made after a public consultation process.

2.7 ELEMENT CONCENTRATIONS IN CROPS ARE MORE DEPENDENT ON PLANT SEPCIES THAN SOIL CONCENTRATIONS – THE CONCENTRATION RATIO CONCEPT REVISITED

Sari Peura (SKB) presented.

Cultivation experiments have been undertaken to look at concentration ratios for a range of different crops. A new safety analysis is on the horizon and the work is being undertaken to address site-specific data gaps for crops. Soil conditions at Forsmark are different to most other areas of the globe due to ongoing post-glacial land uplift and high calcite concentrations in soils that are likely to decline over time. Concentration ratios from other regions of the world are therefore unlikely to be applicable to the Forsmark site.

Of the IAEA crop categories appropriate to Sweden, site-specific data were available for cereals (wheat), tubers (potato) and cabbage as a reference vegetable to cover all other vegetable categories. Whether or not cabbage was an appropriate representative for all other vegetables was questioned. How concentration ratios for cabbage compared to those for other vegetables was therefore investigated. Data were limited but of the data that were available, concentration ratios were found to be similar between cabbage and carrot for many elements, but in the case of iron, the concentration ratio was thirty times higher in carrot. The use of cabbage as a representative vegetable could not therefore be concluded to be a conservative approach.

A project to derive more stable isotope concentration ratios for different crops and soils began two years ago at a study site located to the south of Forsmark. The site emerged from the sea around 3,000 years ago and therefore provides an analogue for future conditions at Forsmark. A lake at the site was previously drained to allow the site to be used for agriculture but has recently reflooded, collecting nutrients from the surrounding agricultural land.

Soil from three different sites close to the site were collected in 2020. The intention was to have three different soils with varying clay and organic content and for there to be three replicates of each. However, no soil had particularly high clay/organic content and so an additional nine plots were added in 2021. Not all results from the 2021 experiments have been analysed to date and so results presented focussed on the 2020 experiments.

In order to derive concentration ratios, concentrations in both crops and soils are needed. Four different methods were used for soil extractions. Aqua-regia is the harshest extraction method and will extract more than just the bioavailable fraction. A range of other methods were therefore also applied.

In the 2020 experiments, each plot was divided into two parts. One part was fertilised with an inorganic fertiliser in irrigation water. The other part remained unfertilised. A range of crops were grown in each plot that covered a wide range of crop categories (root vegetables, cereals, tubers, legumes). Pasture was also evaluated but sampling was from the surrounding area rather than the experimental plots.

Cultivation was successful and crops were collected, cleaned with tap water and dried prior to analysing for 72 different elements. The results were generally good, with many crops grouping, indicating that crops within groups have some common elemental signature. For example, barley and pea were very similar and both are high protein content crops. Parsley was a particular outlier, with a lot of variation being detected which may have resulted from soil contamination. Results for parsley were therefore excluded from further analysis.

Results were normalised according to carbon content and clear groupings were observed that followed the IAEA crop groupings. There were also two clear element groupings evident, with some elements being consistent across all crops and others for which there were large variations depending on the particular plant. For example, calcium concentrations were particularly high in kale compared to other crops. The variations in concentrations did not reflect differences in soil concentrations. Rather, plants appear to actively take up the elements that they need, hence concentrations of essential elements can be considerably higher in plants than soils. In the case of non-essential elements, concentrations can be lower in plants than soils for some elements and for others they are comparable. The reasons for differences in behaviour between non-essential elements need to be investigated further.

Results therefore suggest that rather than soil concentrations driving plant concentrations, the plant species is an important factor governing uptake. It may therefore be appropriate to revise the current concept of using plant groupings to a more individual crop approach or to review how different crops are grouped, increasing or decreasing the number of groupings depending on differences observed as further results become available.

Samples have been taken for different parts of plants but have not yet been analysed.

Discussion

Results are very different when elements are normalised against carbon. There are also plans to look at the results normalised against the clay content of soils.

Results indicate that soil contamination of crops can be a big issue. Therefore, in considering any regrouping of crops it will be important to consider that some crops are more susceptible to soil splash or to irrigation uptake. From the experimental plots, the crops affected by soil contamination were the root crops and leafy vegetables. The crops least affected were pea and barley. While all crops were washed well prior to analysis, it was difficult to remove all soil contamination.

Early work undertaken in BIOPROTA considered the contamination of crops from root uptake and from spray irrigation. Whether root uptake or spray contamination was important varies depending on how contamination reaches the soil and subsequent mobility. As such, spray irrigation can dominate in some instances, and it may be worth revisiting this early work.

To address the issue of soil contamination of crops, it may be possible to use a marker, such as titanium, to allow residual soil contamination on crops to be estimated and accounted for. Titanium has a very low bioavailability and high concentration in soil and hence could be a good indicator for soil contamination.

2.8 CIGÉO UPDATE – THE FRENCH DGR PROJECT FOR ILW AND HLW

Cigéo is the planned repository in France for the disposal of all high level waste (HLW) and long-lived intermediate level waste (ILW-LL) from current nuclear installations. The site of the facility was selected based on an opt-in approach with a location in the Meuse/Haute-Marne district in the north-east of France ultimately being selected in 1998. The site provides a geological barrier in the form of clay-rock at a depth of around 500 m. An underground research laboratory (URL) has been constructed at the site and there has been lots of communication and community involvement activities in the region.

Reversibility is required for at least a century. The facility will be gradually developed over time and be operational for around 120 years. There will be a pilot phase prior to the initial storage of waste.

Surface features of the facility will be comprised of two main zones; a shaft zone to support underground activities and a reception zone where waste control and preparation will occur. Underground, there will be five shafts, a transfer ramp and two disposal areas, one for ILW-LL and one for HLW. The facility will be able to accept around 85,000 m^3 of waste which will arrive to the reception zone via railway. The underground footprint will be around 15 km^2 whereas the overall surface footprint will be larger at around 25 km^2. The cost estimate for the facility is €25 billion.

Excavations will mean that a lot of mining debris (particularly clay) will be stored on the surface and work is currently ongoing to look into the environmental impacts associated with debris.

A step-by-step roadmap has been followed since the creation of Andra in 1991 and the inception of the HLW long-term management programme. The roadmap has involved decision milestones and has benefited from stable and predictable funding. The safety case has been developing gradually and is supported by the URL.

A new research and development (R&D) programme has been defined for the next 10 years. The programme is based around four axes and involves around 25 thematic areas. The majority of the research areas are devoted to the URL, such as sensor operations for gas emission measurements etc. The development of full-scale demonstrators also falls within the R&D programme and ongoing environmental research associated with the long-term monitoring of the area potentially impacted by industrial facilities, including an environmental specimen bank for retrospective analysis.

The licensing process for Cigéo was launched in August 2020. The first stage was a declaration of Public Convenience and Necessity which was sent to the Environmental Authority for review. The review has been completed, along with a public enquiry and a favourable opinion without reservations has been published. A Prime Ministerial decree is expected in 2022. The next stage in the licensing process is obtaining an authorisation for the construction of facilities in the non-nuclear zones of Cigéo; these will allow the modification of existing infrastructures and natural components of the site and an associated authorisation has been requested. The third stage is a request for construction of facilities in nuclear zones, which is expected to be submitted in mid-2022. Review of this application by ASN-IRSN is expected to take between 3 and 5 years and, if accepted, construction of the deep disposal facility can then begin.

The Cigéo project has reached a mature phase but a lot of work remains for the project to become reality. If the licensing process is favourable, then it is anticipated that initial construction activities could begin in 2025. A pilot phase will precede any radioactive waste disposals, the first of which are unlikely to occur within the next 15 years so there remains many years for further research to be undertaken.

Andra is currently undergoing reorganisation to ensure a smooth transition from the design and conceptual stages to construction and a more operational phase. The reorganisation is in line with legislation since, in France, construction activities fall within the scope of a nuclear licensed installation, and there will be a requirement to demonstrate an appropriate organisation to support this new status and associated activities. As part of the reorganisation, the R&D division has merged with the engineering division to create a new scientific and technical division, which includes a new environment and surface water department.

Discussion

Following the reorganisation, radioecology research will continue into the behaviour of key radionuclides, including selenium, iodine and chlorine, but, overall, there will be a more coordinated interdisciplinary approach to research that takes a more global view of the different impact assessment studies associated with the construction and operation of Cigéo. Construction activities are expected to have a large impact in the region which is why much of the R&D programme for the next 10 years is focussed on impact assessment studies. Following construction, there will also be a review by the national authorities who will challenge on topics that will likely require further research to address them.

The integration of departments that is occurring through the reorganisation will help ensure continuity in safety assessments, such as consistency in assumptions between operational and post-closure phases and assumptions used to justify the end of the period of authorisation. It is important to consider not just how to start a project, but also how to justify ending a programme.

2.9 PROPOSED NON-RADIOLOGICAL ACCEPTANCE CRITERIA

Chantal Medri (NWMO) presented.

A report on proposed non-radiological acceptance criteria relevant to deep geological disposal of spent nuclear fuel (NWMO-TR-2021-21)[a] was published at the end of 2021. The criteria are for the post-closure assessment and so are based on chronic exposure data for non-radioactive potentially hazardous contaminants associated with the spent nuclear fuel. The criteria are to be used to assess impacts to both humans and non-human biota and are expressed as concentrations in five environmental media (soil, sediment, air, surface water and groundwater).

Development of the preliminary acceptance criteria has progressed over several years. In 2013, a generic safety assessment for a hypothetical site in crystalline/sedimentary rock was published (NWMO-TR-2012-16 / NWMO-TR-2013-07). This was followed in 2015 with a first independent report on the development of non-radiological interim acceptance criteria (NWMO-TR-2015-03). However, there were data gaps for many elements and so efforts were made between 2017 and 2019 to address these gaps through literature searches and the use of chemotoxicological data to derive missing criteria; results of these efforts were published in 2019 as NWMO-TR-2017-05. The most recent report (NWMO-TR-2021-21) replaces the previous work and includes details of the methodology applied to further address data gaps.

A tiered methodology was applied that considered a hierarchy of reference sources that were ranked according to suitability for the Canadian context. The tiers were worked through successively in order to select criteria. Any remaining gaps were then addressed through the application of surrogate approaches to ensure acceptance criteria were available for all elements in all five environmental media.

The first step in the methodology was, therefore, to create a document hierarchy. The primary references were guidelines from Canadian Council of Ministers of the Environment (CCME), followed by Federal and Ontario provincial guidelines and standards. The third tier of references were guidelines and standards from other jurisdictions or criteria derived using toxicity data.

CCME guidelines are available for the protection of:

- aquatic life (surface water);
- agricultural water uses (groundwater and surface water);
- environmental and human health (soil); and
- aquatic life (sediment).

All preliminary criteria were assumed to be protective of both people and non-human biota. Several federal and Ontario provincial secondary references were also available covering a range of environmental media. Tertiary references included a number of international publications that were intended to support screening assessments and it was necessary to be aware of the applicability of the criteria for the intended purpose. The tertiary references also included the 2019 report on supplementary non-radiological interim acceptance criteria (NWMO-TR-2017-05) since this included

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[a] Available from Reports | The Nuclear Waste Management Organization (NWMO)

criteria that had been derived from toxicity data. All references used were published by reputable organisations and were readily obtainable.

The second step in the methodology involved the selection of criteria. For each tier, the minimum benchmark was selected by comparing benchmarks from each reference of each tier. Different species (e.g. Cr-III versus Cr-IV) and different compounds (e.g. methyl mercury versus elemental mercury) were also compared. In general, the lowest benchmark was selected. However, less restrictive criteria could be selected where justifiable. For example, the minimum value may not have been applicable to post-closure conditions or the conditions to which the benchmark applies may not be appropriate (e.g. it may have been linked to specific environmental parameters such as pH or water hardness). Alternatively, the intended use of a benchmark may have aligned well with its use as an acceptance criterion.

The third step in the methodology was then to address remaining data gaps through the use of surrogates. Surrogate approaches included the following.

- Use of surface water criteria, which were more abundant, to derive groundwater criteria. A dilution factor of 10 was applied for substances that were known to be non-toxic to humans. No dilution factor was applied if a substance was suspected to be toxic.
- Soil and sediment criteria were applied interchangeably.
- Acute air benchmarks were applied in the absence of chronic benchmarks.
- Chemical analogues were applied to fill any remaining data gaps. Chemical analogues were considered to be elements falling within similar groups or columns of the periodic table.

In addition to acceptance criteria, screening criteria were also derived and developed using a similar approach but with minimum benchmarks always being accepted. The method involved screening the fuel element inventory against the minimum environmental criteria to derive the volume needed to meet the criteria. The elements requiring no more than 0.1% of media volumes to meet the criteria were screened in. In total, the following 17 elements were screened in: Ag, Ba, Cd, Cr, Cs, Hg, La, Mo, Nd, Pb, Pd, Rb, Rh, Ru, Sn, U, Zr**Error! Reference source not found.**.

The resulting acceptance criteria are colour coded to clearly identify the source of the data, based on the four tiers (primary, secondary and tertiary references and surrogate approaches) and the source of all criteria are clearly documented. The benchmark type, protective endpoint (e.g. biota group protected) and the compound or species the benchmark relates to are all detailed. The particular surrogate approach applied is also documented, as appropriate.

Discussion

The approach adopted by NWMO provides a quick and relatively simple method by which the safety of modelled environmental concentrations can be tested. These could periodically be updated based on advances in international approaches and developing science.

The use of a single benchmark for an element to protect all biota, including people, can be of concern and this is why the minimum value across all available data is selected. Nonetheless, differences in effects between different species are recognised.

The use of acute data for air concentrations can be questionable since acute toxicity can often be substantially different from chronic toxicity in terms of the sorts of effects observed and there should therefore be some scrutiny of the data on whether the effects are applicable. The NWMO approach was to ensure data were available for all elements. If issues arise in terms of benchmarks being exceeded in assessments, then there would be greater scrutiny of benchmarks and their applicability. An iterative approach is therefore applied. There is generally less concern about air acceptance criteria for post-closure assessment of geological disposal since water concentrations are of typically of greater interest in this context.

2.10 OVERVIEW OF NWS'S 'NON-RADS' INTEGRATED PROJECT: DEVELOPMENT OF SAFETY CASE CLAIMS, ARGUMENTS AND EVIDENCE IN CONSIDERATION OF NON-RADIOLOGICAL POLLUTANTS

Andy Cooke (NWS) presented.

Nuclear Waste Services (NWS) is the successor organisation to Radioactive Waste Management (RWM) in the UK and is continuing a programme of work to identify and quantify non-radiological pollutants (non-rads) that may be associated with Geological Disposal Facility (GDF), and to undertake assessments of potential related risks to human health and the environment. The materials destined for disposal at the GDF that may pose a non-radioactive hazardous risk include not only those associated with the radioactive waste itself, but also GDF materials such as containers and backfill. A wide net is therefore being cast when considering potential hazardous substances, examples of which include lead, mercury and organic compounds.

A number of projects have been undertaken over several decades toward the goal of understanding and quantifying the potential impacts of non-rads in a GDF. Recently, a non-rads integrated project team (IPT) has been established with the aim of drawing together all the previous work, identifying gaps and addressing those gaps in order to enable assessments to be undertaken to demonstrate that the GDF provides adequate protection against non-rads. A whole life-cycle approach is being taken to the GDF that includes transport and operations as well as the post-closure phase.

Several regulatory issues have been identified of which three are ongoing:

- developing a full understanding of the nature and consequences of non-rads in the inventory for disposal that are hazardous to human health or non-human biota, or are considered hazardous substances or non-hazardous pollutants in terms of groundwater pollution and use this to assess quantitatively their impacts;
- developing appropriate criteria for assessing the non-radioactive component of radioactive waste in the disposability assessment process in order to gain confidence that waste will meet future waste acceptance criteria for hazardous substances and non-hazardous pollutants; and
- continuing to engage with the Environment Agency to agree an approach for demonstrating that the requirement to prevent the entry of hazardous substances to groundwater can be met in a generic context, and the transferability of this approach to a future site-specific situation.

The three remaining regulatory issues have led to five strategic goals being developed for the IPT:

- Goal 1: Regulatory requirements.
- Goal 2: Inventory.
- Goal 3: Safety case methodologies.
- Goal 4: Disposability Assessment.

- Goal 5: Waste Package and GDF Design Specifications.

The IPT has a four-year duration, completing in 2025, and has the overall aim of developing the safety case Claims, Arguments and Evidence (CAE) for non-rads related to the UK Radioactive Waste Inventory (RWI) and the GDF, based on consideration of each of the goals.

Goal 1: Regulatory requirements

All regulatory requirements are being considered, including waste transport, operations and post-closure, surface water and groundwater protection and overall safety. A regulatory framework document is being developed that sets out the regulatory framework and specific requirements, whether they be generic or quantitative in nature. The objective is to set out all the requirements from which a regulatory action plan can be developed. Any uncertainties in the regulatory framework will be addressed with interaction with the regulator throughout the duration of the project.

Goal 2: Inventory

Goal 2 is comprised of 4 tasks:

- Task 1 is to develop and maintain lists of contaminants for transport and operations as well as post-closure. Screening methods are being developed in order to produce priority lists for the different phases of the GDF that can then provide focus for other tasks within the IPT. Lists will be continuously reviewed as more information becomes available throughout the duration of the project.
- Task 2 involves the review of the non-radioactive inventory method and information. This involves reviewing the non-rads and precursor materials in wastes, packages, infill materials and GDF infrastructure and undertaking an in-depth study to identify contaminants of concern in each material.
- Task 3 involves material composition studies and aims to address the presence of non-rad contaminants within wastes, packaging, backfill and infrastructure associated with the GDF and, for each material, to identify contaminants of concern.
- Task 4 is then to develop the RWI and inventory for geological disposal (IGD) for non-rads by integrating data from the previous tasks into the 2022 RWI and produce a 2022 IGD that will be updated further in 2025.

Goal 3: Safety case methodologies

The aim of goal 3 is to develop requirements for safety assessments (environmental safety case, post-closure safety assessment etc.), including claims, arguments, and evidence (CAE) for non-rads and identifying data gaps with the requirements and CAE being subject to periodic review. Claims can be broken down into sub-claims and each is supported by arguments that sit between the claims and evidence. An approach to transport, operations and post-closure assessments will also be developed and implemented in relevant software and illustrative calculations performed. An analysis will also be undertaken with a focussed literature review being performed to address data gaps and identify where experimental work is needed to address residual key knowledge gaps.

Also within goal 3 is an objective to develop an experimental programme to develop better understanding of the behaviour of hazardous organic species in conditions representative of the near field in order to provide arguments that increase confidence in the input parameters for organic species in non-rad assessment models. Ten substances have been proposed initially, based on key substances of concerns and data gaps, and a detailed experimental programme for these is being finalised, with a focus on behaviours such as solubility, degradation products etc.

Goal 4: Disposability assessment

The disposability assessment goal aims to develop advice for waste packagers on the non-rads that should be considered when compiling submissions for disposability assessments and the qualitative information needed for assessments. Updated procedures for disposability assessments to accommodate non-rads will also be produced and trialled with further updates to procedures being made as necessary.

Goal 5: Waste package and GDF design specifications

Goal 5 is being run in parallel with another IPT on backfill that is looking at different formulations for backfill and, together, these will develop contamination inventories for each formulation. The non-rads IPT will consider the implications of the different backfill choices. This will feed into updated waste package and design specifications and the development of generic and site-specific waste acceptance criteria and support the siting process.

Discussion

The initial experimental programme will be focussed on the mobility of contaminants to support arguments as to whether they could be transported from a GDF. Work on assessing the potential impacts of the contaminants in the biosphere, including on non-human biota, will also be progressed. This will be supported by research conducted separately from the IPT, including PhD research programmes.

2.11 THE RADONORM PROJECT: MANAGING RISKS FROM RADON AND NORM

Laureline Février (IRSN) and Jordi Vives i Batlle (SCK·CEN) presented.

RadoNorm is a project focused on radon and NORM that began in 2020 and will continue until the end of August 2025. The project involves 56 partners from 20 European Member States plus Norway and Switzerland. There are 7 work packages in addition to overall coordination of the work programme:

- WP2: Measuring and/or modelling of exposure for humans and the environment
- WP3: Dosimetry
- WP4: Assessment of radiation induced biological effects as well as risks to humans and the environment
- WP5: Innovative mitigation techniques and strategies aiming at dose reduction
- WP6: Social and economic aspects including communication
- WP7: Education and training
- WP8: Dissemination of information and re-use of knowledge

The presentation focussed on WP2 – Exposure, which is being coordinated by IRSN.

The overall general objective of WP2 is to provide a better characterisation of the exposure of the population (public and workers) and biota to radon and other naturally occurring radionuclides (NOR). The main scientific objectives are then to:

- develop missing measurement methods and protocols to assess both radon and thoron derived dose;
- fill gaps of scientific knowledge on factors and processes that impact radon and NOR transfer and dispersion at various places indoor and outdoor (workplaces, environment, etc …) and for different spatial scales; and
- develop new models and/or improve existing ones for quantifying the transfer of radon and NOR, focusing on relevant exposure pathways and spatial and temporal scales.

Eight tasks have been developed within WP2, four of which are focussed on radon and four on NOR. Five tasks were highlighted during the presentation.

Task 2.5: Overview of NORM sites and exposure scenarios and their characteristics in Europe
Task 2.5 has the objectives of providing a systematic overview of NORM exposure sites across Europe; to comprehensively characterise the most important exposure scenarios with respect to NORM but also other hazards; and to investigate conditions and processes at NORM sites that influence effects and risks and, consequently, to consider necessary steps towards the development of integrated decision-making procedures. A methodology has been developed, along with necessary tools, to collect information on the NORM sites. The method involves a four-tier system for collecting information from a range of NORM sites, including industry, legacy and high natural background areas. A NORM survey was distributed to collect information from national, regional and local regulators, NORM industry operators and operators in the field of waste management.

Task 2.6: Identifying biological and chemical parameters controlling the transfer of NOR to plants to derive more robust transfer factors
The key objectives of Task 2.6 are to develop understanding of the impact of bacteria, fungi and earthworms on NOR transfer to plants and to refine transfer factors. Both laboratory and field studies are being undertaken, focussing on the transfer of uranium, thorium and radium under different conditions. The influence of factors such as soil acidity and light availability are being studied.

One laboratory experiment conducted to date focussed on Ra-226 is using rye grass and a radium contaminated soil from a site in Belgium within a soil microcosm to look at the factors influencing transfer. The pH of soil was found to have an impact on transfer, but the presence of earthworms had no effect on the Ra-226 concentration in soils or grass. Experiments on the influence of bacterial diversity on Ra-226 transfer are planned.

A field study has also been undertaken at a former uranium mining site in France. Two plant species were focussed on and the transfer of uranium and thorium quantified. Uranium was found to impact physiological parameters such as chlorophyll and nitrogen balance index in one species of plant but no impact on photosynthetic parameters such as electron transport rate were observed. Further studies on bacterial diversity of rhizospheric soil are planned.

In order to link environmental availability to phytoavailability, the availability of uranium and thorium in soils from the French field site is being studied using four successive batch extraction methods applied to different soil layers, whereas quantification of phytoavailability will be performed by a RHIZOtest bioassay.

Alternative approaches for modelling plant NOR concentrations are also being investigated with a constant plant concentration model being applied to see whether it can explain the occurrence of natural concentrations of NOR in plants. The model is being applied to Finnish data sets.

Task 2.7: Identifying geochemical and biological parameters controlling the mobility of NOR in soils

The objectives of Task 2.7 are to:

- elucidate the effect of NORM speciation, including changes induced by microbial processes, on NORM mobility in the environment;
- identify key soil properties that govern the mobility of NOR in soils;
- consider dynamics of sorption-desorption reactions on soils; and,
- develop models to predict Kd values from site-specific information and laboratory experiments.

The effect of microorganisms on NOR mobility in uranium mine waters is being investigated to develop understanding of the relationship between water chemistry and microbial processes on uranium immobilisation and, from this, to possibly generate a microbial Kd. Batch sorption-desorption experiments to quantify Kd values for radium and uranium for both short- and long-term scenarios are also underway using a wide range of different soils. The effect of soil aging and contamination speciation on uranium desorption in soils is also being studied.

In terms of modelling, two approaches are being developed. A “smart-Kd” approach is being applied to the site in France, drawing on lability and speciation studies, to look at site-specific Kd modelling. The other approach involves the application of a statistical-mathematical approach to predict Kd for NOR in relevant scenarios.

Task 2.8: Updating approaches for modelling long-term prediction of NOR transfer in the environment

The objectives of Task 2.8 are to undertake a critical review of exposure pathways considered in radioecology models for dose assessments for people and non-human biota at NORM sites and provide guidance on the application of the most suitable models by taking account of improved understanding of biological and geochemical processes. Several scenarios are being focussed on, including the management of NORM residues in the context of conventional waste disposal and sludge from sewer depuration systems of liquid effluents used as fertiliser in agriculture. For the scenarios, the objectives are to provide information on good practice and guidance on how to approach and carry out dose assessments for the different exposure pathways of relevance. Leaching of NOR and the groundwater exposure pathway is also a scenario of interest with different modelling approaches being reviewed.

Task 2.2: Transport of radon in the environment

Task 2.2 has the objective of improving understanding of environmental transport processes and factors contributing to variability in outdoor radon, thoron and decay product concentrations and exposures. Various factors and processes will be considered, including:

- soil emanation and exhalation, taking account of spatial and temporal variations;
- atmospheric transport;
- deposition of radon and thoron decay products on plants and trees and subsequent transfer to litter;
- environmental factors including soil parameters, humidity, wind, temperature, precipitation, plants and animals; and
- calculation of radiation doses to humans and biota exposures.

Radon and thoron cycling by vegetation, including the role of trees, is being investigated in field studies at a Fen complex in Norway. The goal is to assess the pathways of deposition and transfer from soil to biota and litter and to characterise uncertainty related to heterogeneous distributions.

Integrated soil-vegetation-aerosol modelling falls within Task 2.2. Radon is not only an issue in houses, but also in the outdoor environment. The role of trees in the radon cycle is being investigated, including how much radon progeny can be intercepted by trees and translocated, returning to the soil via litterfall and how much radon is emitted by trees from internally incorporated Ra-226. The advanced forest SVAT model ECOFOR (presented during the 2020 BIOPROTA annual meeting[b]) has been combined with a model of radon aerosols in outdoor air. This makes it possible to look at deposition fractions to leaves and gas exchange with stomata and to consider the impact of radon and its progeny (Po-218, Pb-214, Bi-214, Po-214) on trees and the surface fauna and flora living in the litter layer.

The ECOFOR model has been simplified for this application to include only one soil layer and dynamic processes are represented by transfer rates that are derived from the original ECOFOR model. Model integration has been completed and dose coefficients from ERICA have been incorporated to allow biota dose assessment to be performed. The model is currently being verified and some parameter extractions are still required. The model will then be applied to a Belgian NORM site and guidance will be developed for its application to other environments and there will be discussion around radon dose interpretation.

Initial dose rates show marked differences between surface, external and internal exposure with internal dose rates abruptly changing between day and night. Results indicate that trees can reduce the equilibrium factor and increase the unattached fraction of radon decay product clusters in air.

Work on parameterising and validating the model will be continued and simulations will be run to look at the relative importance of different pathways. General recommendations on the application of the model will also be developed and work on biota dose rates associated with radon and its progeny will contribute to continued discussion around biota dose rates above benchmarks in areas subject to high natural background due to radon (e.g. where radium-rich soils occur).

Discussion

Radon issues were identified with respect to biota dose assessments involving Ra-226 in soils during recent updates that were made to the ERICA assessment tool for calculating dose rates to non-human biota. Output from the RadoNorm project should provide useful input to further developments on this topic. Output from the project could also provide useful data and knowledge on the behaviour of radionuclides associated with NORM that could help inform on the way we model these radionuclides in assessments associated with radioactive waste disposal.

2.12 CLIMATE CHANGE IMPACTS AND ADAPTATION FOR LEGACY AND WASTE DISPOSAL SITES

Mike Thorne (Mike Thorne and Associates) presented.

A synthesis report ‘Regulatory considerations of climate change impacts and adaptation for waste deposit, landfill and land contamination’ has recently been produced. The report covers policy-level issues and extends lessons learned from radioactive waste disposal to landfills, general land

[b] Annual meeting report available from BIOPROTA | Annual meeting reports

contamination and also the reuse of waste material (e.g. in construction). The project involved consultation with a wide range of organisations including the Environment Agency (England), but also devolved agencies (National Resources Wales and Scottish Environment Protection Agency), and research organisations such as British Geological Survey.

The report aims to provide a baseline of knowledge to inform assessments, contribute to the Environment Agency's Nuclear Decommissioning and Clean-up programme and climate change work under Water Quality, Groundwater and Land Contamination, and assist decision making that addresses timescales of around 1000 years after present. The report also provides an assessment of climate models and their outputs, environmental change and response, and uncertainties. Coastal change is a particular focus of the report, with the aim of moving toward a systematic approach throughout the UK, where practicable. The scope includes waste recovery on land, landfill sites, contaminated land and near surface disposal, but does not include deep disposal.

Many aspects of the report will be familiar to the radioactive waste disposal community, such as the use of Features, Events and Processes (FEP) lists and interaction matrices and the treatment of uncertainties. These are, however, new to those working at landfill sites etc.

Some key points arising from the report are, as follows.

- Much of the work undertaken in the UK with respect to climate modelling has focussed on UKCP09 datasets rather than the more recent UKCP18 projections, although work is ongoing to bring available tools in line with UKCP18. However, the inconsistent use of climate emissions scenarios may be leading to inconsistent decision making between sites.

- Most current approaches advocate consideration of both "long-term" (up to 2100 AD) and shorter-term climate changes/impacts, with the focus of assessments to be on 'reasonable' or plausible future changes and/or on those changes identified as requiring most urgent action. Again, the inconsistent use of climate assumptions could lead to inconsistent decision making between sites.

- In order to address these issues, a clear statement of regulatory expectation is needed along with direction on appropriate data resources to enable uptake and consistency, with a view to ensuring long-term resilience and protect the environment.

Facility related timelines include the post-closure phase. However, most focus is on the first few hundred years after present, extending out to 1000 years, but further extension of timescales, even for surface facilities is not ruled out.

The project had a broad brief and included several case studies, including on-site disposal and recovery of radioactive and non-radioactive waste, historical coastal landfill, and coastal non-hazardous and radioactive waste landfill. Much focus was on coastal processes and existing coastal erosion models were reviewed, particularly with respect to the soft rock cliffs of Britain, although hard rock cliffs were also considered. Models were scored according to the range of characteristics they addressed.

Good flood modelling tools are available, but coastal erosion is not so well addressed with only a limited set of models being available. Maps of future erosion are available that address the next 100 years or so, but the basis of these maps is poorly documented which undermines their quality and reliability.

Overall, the report identifies 34 areas requiring consideration, with each area discussed in terms of problem characteristics, potential action, importance and ease with which it can be addressed. Some actions can be grouped and could be delivered together through guidance documents, particularly those relating to decision making policy/philosophy. Others relate to the tools needed to perform assessments. The report therefore aims to provide the necessary direction in terms of guidance/code of practice that is required to inform operators of expectations on what should be addressed and the datasets that could be helpful in constructing environmental impact assessments, as well as identifying priority research areas such as the development of integrated flooding and erosion models for shoreline management plans.

It is understood that the Environment Agency plans to produce a summary paper on the way forward.

2.13 THE BIOSPHERE ANALYSIS IN THE PSAR FOR SFR

Peter Saetre (SKB) presented.

SFR is SKB's existing repository for short-lived radioactive waste. A preliminary safety assessment report (PSAR) has been developed to demonstrate that the SFR and its proposed extension is radiologically safe for people and the environment. The biosphere synthesis report (TR-23-06) is close to finalisation and will soon be published. The biosphere assessment broadly follows the BIOMASS methodology, and a lot of focus is given to the management of uncertainties.

The repository is located under the sea with radionuclides being released primarily to biosphere object (sub-catchment) 157_2 which is located to the north of the repository. The release area is governed by the configuration of the bedrock. Biosphere object 157_2 is currently under the Baltic Sea but will become terrestrial over time due to continued post-glacial land uplift.

Potential exposure groups receive the highest doses from the repository when radionuclides are released to wetlands or to lakes that then transition to wetlands prior to being drained for agricultural use. A number of calculation cases have been worked through. The calculation cases are focused around landscape uncertainties, with different cases being configured around alternative future landscapes and radionuclide transfer pathways. The use of multiple calculation cases to address uncertainties allows a robust safety case to be made.

The radionuclide transport model (BioTEx) considers release to a natural ecosystem with radionuclide transport and accumulation with a simpler model then being applied to calculate exposure of people in the future by taking radionuclide concentrations in a mire which is then cultivated. The model has been developed from that applied in previous assessments. New data on chlorine in mires has recently been published (SKB report R-21-04), which includes updated concentration ratios for plants, as well as new data on the fractionation of chlorine in soils between organic and inorganic forms; the new data have been incorporated within the model. Both the new and older version of the model have been compared to illustrate how changes affect model output. There is increased discretisation of the lower regolith in the most recent version of the model, which leads to the retention and decay of some radionuclides thus preventing their release to the surface.

In the base case, releases occur to object 157_2 which has both terrestrial and aquatic components over time. Terrestrial components arise at 3000 AD and the object is fully emerged from the sea at 4000 AD. Releases occurring in the first 1000 years are diluted in the sea and exposure of potential exposure groups during this time is minimal. Over time, however, exposures increase as terrestrial components arise and mires are drained for agricultural use. The main radionuclides contributing to dose are Mo-93, C-14 and Ca-41.

The fate of radionuclides has been investigated. Mo-93 in mire ecosystems accumulates in the regolith. As much Mo-93 decays as accumulates. What happens to the Mo-93 when the mire is drained and then cultivated over a period of 50 years has been considered. The majority of the Mo-93 is retained in an inorganic form in agricultural soil with uptake to cereals being the main exposure pathway.

The effect of data uncertainties has been studied. The mean of 1000 simulations was compared against a deterministic simulation using best estimates; the results illustrate that risk dilution is not an issue. C-14 and Mo-93 were the key radionuclides contributing to dose for most of the simulation but Ca-41 and Ni-59 were important in some instances. Uncertainties around the release location were also investigated in a calculation case that used sub-horizontal fractures to look at the distribution of release across three biosphere objects. A slightly more complex model was needed to cover the scenario. Results showed a spatial distribution across all three objects with object 157_2 receiving 60% of the radionuclides. Doses in object 157_2 therefore decreased compared to the base case. Groundwater dilution as a result of sub-horizontal fractures can also reduce dose.

There are uncertainties as to whether streams will form and so one calculation case considers the implications of a stream. The stream transports radionuclides to the next landscape object leading to accumulation in a down-stream mire. Doses associated with the down-stream object remain below those of object 157_2.

A sensitivity analysis was performed around the different object properties to look at the importance of variability on individual parameters for four radionuclides. The area of the object was important for all radionuclides with dose increasing with reduced object size. This is, however, counteracted by the opposite effect on the proportion of the release that reaches a smaller area. Properties associated with the release area, therefore, had only a limited effect on calculated dose. Uncertainties in the properties of the biosphere object and pathways in the landscape had only a limited effect on calculated dose (< a factor of 2). Based on the various analyses undertaken, the base case was concluded to be sound and calculated doses are robust with respect to uncertainties associated with the future landscape.

Discussion

In the stochastic assessment, all model parameters were varied with the exception of those describing the landscape. This included all parameters relating to transport, accumulation and uptake and all were treated independently (correlations were not taken into account). The most important parameters were Kd and concentration ratios. Human exposure pathway parameters were not varied as these are treated conservatively.

2.14 FIRST RESULTS FROM THE NAT-LAB-14C PROJECT – USING GEOTHERMAL FIELDS TO INVESTIGATE TRANSFER OF C-14 FROM BELOW GROUND SOURCES INTO FOREST VEGETATION

Ari Ikonen (EnviroCase) presented on behalf of University of Eastern Finland (UEF).

UEF has been studying C-14 dynamics in the biosphere; however, there are practical difficulties associated with research of carbon cycling. Carbon is ubiquitous, so little information is available on the source of carbon if total carbon is analysed. Furthermore, C-14 labelling techniques can be difficult. Two approaches have therefore been studied by UEF. One has been to use the C-14 signature in an old, depleted peat in Finland and measure the signature in biota directly living on the substrate. The other, more recent, approach employed has been to use the C-13 signature in volcanic areas of Iceland.

Results using C-14 peat signature method were variable with between 0% and 60% of carbon in biota being attributable to uptake from the soil[c]. A parallel project also looked at C-14 transfer from sediments into the aquatic food web to consider how model assumptions could be adjusted to improve radioecological modelling through a critical review of modelling assumptions. The current focus of research (the NAT-LAB-14C project) is in the use of volcanic geothermal fields to investigate the transfer of deep geological carbon sources into terrestrial food webs. The hypothesis is that magma intrusion into the near-surface environment can result in contaminants being released to the biosphere, and that that magma has a distinct C-13 signature that can then be measured as it is incorporated into the food web. A terrestrial area is being investigated that is comprised of forest, grassland (some of which is used for pasture) and wetland areas. Soil gas, soil solution, plant roots and above ground plants are being sampled. The non-invasive sampling of cattle and sheep (hair) was planned but did not happen due to issues being encountered with the sampling campaign. Further sampling may, therefore, be required.

Results are to be reported in a master's thesis that is currently under formal review[d] and will also be published in a series of conference papers. An increasing trend in soil gas C-13 concentrations has been observed relative to increasing thermal input, but the trend is not statistically significant. More scrutiny of the data is required to determine the level of confidence that can be placed on the results.

The efflux of CO_2 from soil has also been measured. Where volcanic input is absent, the majority of CO_2 efflux is from fresh biological origin and only 8% is geothermal. This trend is reversed in plots with a greater volcanic influence.

For carbon in plants, a higher degree of carbon from past biological circulation has been observed, but a notable geothermal portion was also detected. The plant species present in the different plots varied, so comparison of results across different species in different plots makes interpretation of results more difficult. Therefore, whilst interesting patterns of carbon uptake have been observed, more study is required to further interpret the data.

The results available to date show an observable volcanic signature that varies with sampling site and the extent of geothermal input. The fraction of soil-derived carbon in plants can be quantified in most cases, varying between 5% and 15%, but some further analysis is required. Different plants have different carbon uptake strategies and there is some trend between the type of plant and the contribution of soil-derived carbon. Knowledge of plant physiology is therefore relevant to understanding carbon uptake.

Work is continuing to complete reporting of the results from the field monitoring conducted to date and it is hoped that further sampling can take place to address gaps if further funding is made available. Modelling exercises were also planned but with some data missing from the sampling campaign there is a need to postpone modelling until further sampling has been completed. Ultimately it is hoped that the work undertaken will help develop a landscape view of C-14 behaviour that combines both terrestrial and aquatic systems.

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[c] See Majlesi et al., 2019 (https://doi.org/10.1021/acs.est.8b06089); Majlesi et al., 2020 (https://doi.org/10.1016/j.jenvrad.2020.106450).

[d] Jyllilä, P. 2022. Potential transfer of 14C from deep geological deposits following release into forest vegetation. M.Sc. thesis in review. Department of Environmental and Biological Sciences, University of Eastern Finland.

Discussion

The results presented represent the first sampling year at the site and it is hoped that further monitoring can be undertaken. There is also interest in expanding the scope and in collaborating internationally. The sampling site is part of a monitoring network relating to climate change and could form a useful source of data for future model-data comparisons.

3. ONGOING BIOPROTA WORK PROGRAMMES

3.1 CARBON-14 PROJECT UPDATE

Mike Thorne presented on behalf of the project Technical Support Team (TST).

The current BIOPROTA C-14 project began in 2021 and is comprised of 4 tasks:

- Task 1: Literature review
- Task 2: Development of conceptual models
    - Task 2.1: Terrestrial agricultural, wetland, forest and freshwater ecosystems
    - Task 2.2: Estuarine, coastal and offshore marine systems
- Task 3: Development of mathematical models
- Task 4: Preparation of a final report

A substantial technical note was produced as the deliverable for Task 1 in 2021 that then fed into Task 2 – the development of conceptual models. The conceptual models were reported in a further technical note and presented to project sponsors and participants during an online project workshop in March 2022 and, aside from some tidying up, the task is largely complete. The project is currently focussed on Task 3, thinking about what can be done with respect to the development of mathematical models within the constraints of the available project resources.

The literature review focussed on secondary rather than primary literature. A lot of carbon modelling work is focussed on the global carbon cycle in the context of climate modelling. This takes account of the long-term organic and inorganic pools of carbon, including within the Earth's mantle and crust and considers the carbon balances throughout the system, the size of carbon pools and the impact on these from the use of fossil fuels. This is useful for climate modelling but is not so useful when considering C-14 releases from radioactive waste disposal facilities into local environments. For this purpose, it is useful to consider different levels of modelling, starting with broad characteristics and to then break those down into types of environments and to spatially represent the different components within those environments. For example, it is useful for terrestrial environments to be considered in terms of surface-water catchments and the forest, agricultural land, wetland and river components within the catchment. Each component can then be further broken down into various features that can then be used to construct interaction matrices. The different levels are illustrated in Figure 2. Similar representations can be derived for different systems. The approach aids thinking around the structural elements of a system and also the imports from outside the system, including transfers across boundaries such as riparian zones, and how to calculate impacts at the end, by developing linkages to the different components within a system that people and biota rely upon. Interaction matrices then need to be developed to include all these different aspects.

Interaction matrices have been developed for agricultural land, forest, wetland, river, estuarine and coastal systems. The interaction matrices focussed on interactions leading to fluxes of carbon between components of the environment as input to the next stage, which involves decomposing the matrices for mathematical modelling.

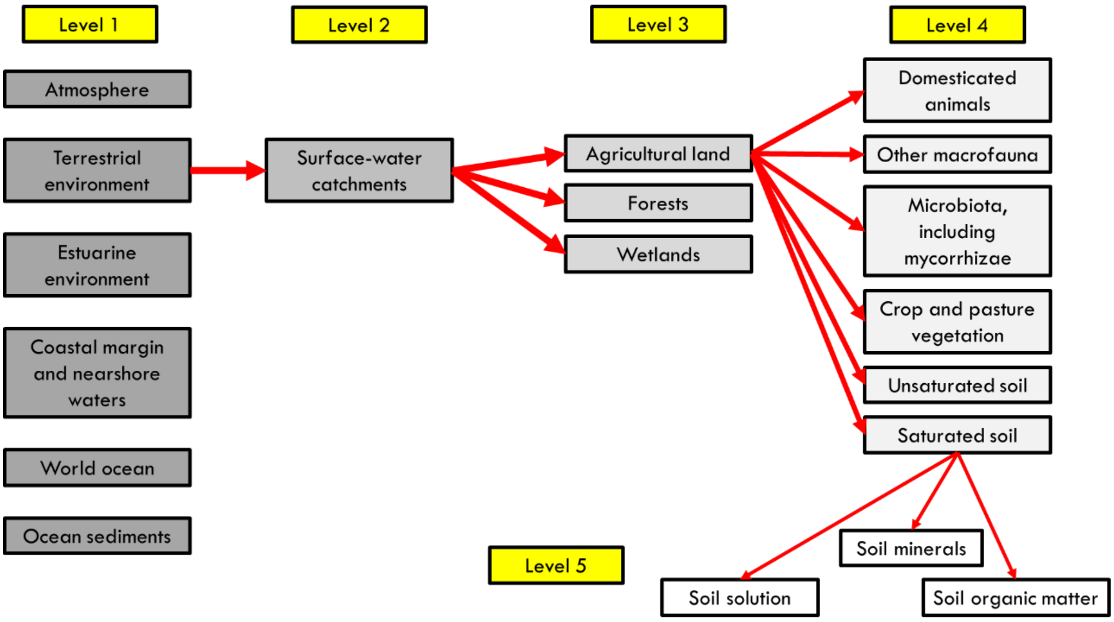

Figure 2. System disaggregation scheme illustrating pools and flows as input to the construction of interaction matrices.

The source term for the interaction matrices is the geosphere. In the interaction matrix for agricultural land, the next lead diagonal element is 'surface water drainage network'. The whole of the agricultural land matrix lies underneath that of the surface water drainage network so this diagonal element is a place holder to reference out to another interaction matrix. There are too many interactions between lead diagonal elements to be able to define in detail and so a colour-coding approach has been applied in the conceptual modelling task to visualise the system and highlight types of processes, with a key to the colour coding being provided. The approach helps to visualise functional distinctions when developing a mathematical model from the conceptual framework of the interaction matrix.

For lead diagonal element components of the system, the processes linking each component to other lead diagonal elements are also tabulated. It is important to recognise that, in some instances, internal processes occur within a component. For example, in the table for the capillary fringe, interactions within the capillary fringe are detailed (advection and dispersion). Some further unpacking of these diagonal elements may therefore be required to develop a set of conceptual models in order to move further toward the development of a mathematical model of the system.

In the case of rivers, different segments can be considered that are then joined together such that there is an upstream source that transitions through the segment of interest to itself become a source to the downstream segment. Lakes can be considered within the river continuum and the above-stream atmosphere can be considered as both a source and a sink. This helps build a picture of where the interactions lie throughout the surface water drainage system.

The interaction matrices developed for the different systems have slightly different conventions used to identify key processes. For example, in estuarine and coastal waters, intermittent and continual processes are specifically identified in recognition of the intermittent influence of tidal processes on these systems. An example for coastal waters is provided in Figure 3.

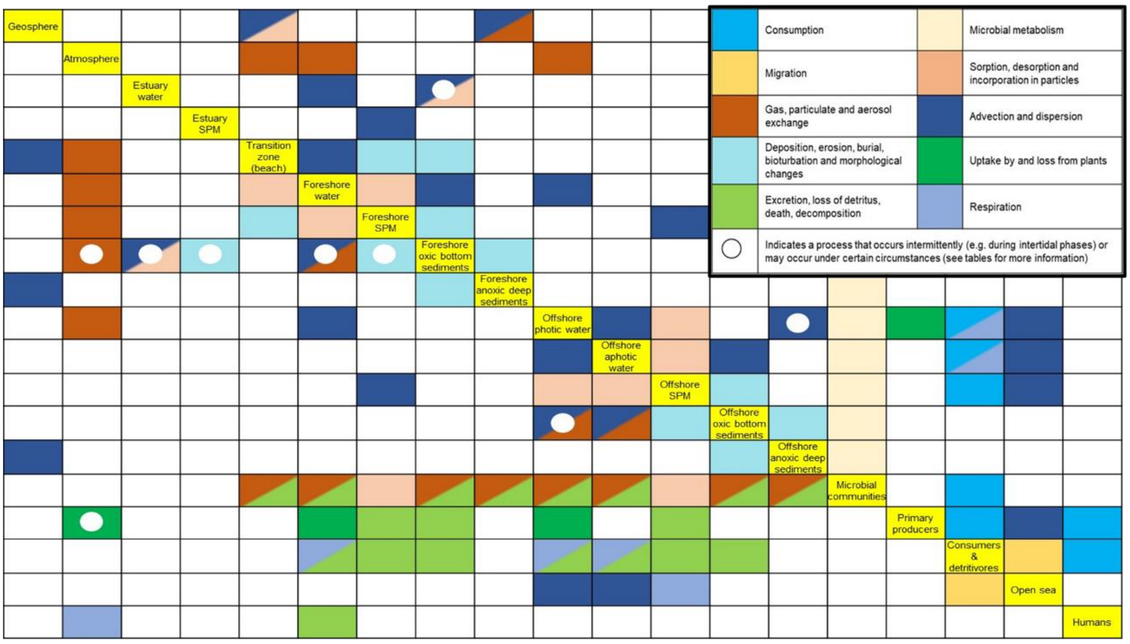

Figure 3. Interaction matrix for coastal waters.

In order to develop the interaction matrices, a list of principal components for each system was initially defined and tables were then developed to set out explicitly the processes resulting in carbon fluxes between the principal components. An interaction matrix was then developed by setting out each principal component as a lead diagonal element and colour coding the processes linking each component. The matrices can then be examined to identify connected regions that could be treated as sub-models that may be loosely coupled to other sub-models. Transfers between environments can be addressed by having the same principal components in each matrix to act as a bridge between source and sink. The matrices have been thought of in terms of fluxes which allows them to be combined relatively simply when building an overall model.

The project is currently focussed on Task 3, with work starting on developing illustrative examples of systems that link the different components of the system from which an illustrative mathematical representation can be developed. Initial work on this task has considered an agricultural system comprising pasture and croplands combined in a single system with upstream and downstream surface water drainage components (Figure 4). This illustrative catchment with an embedded stream channel, riparian zone and areas of pasture and arable land is proposed as an initial basis for exploring some of the key areas of interest for C-14 modelling, such as uptake into biota, transport and loss across the vadose zone, and the interplay between terrestrial and aquatic carbon pools.

In order to get a handle on the hydrological system, simple relationships between the different areas within the illustrative catchment have been drafted to show exchanges. The next step was then to consider the hydrology in each of the different land use areas, which links to the interaction matrices developed for each environment. The main components and sub-components of each system have been identified based on the catchment illustrated in Figure 4 including consideration of the lateral flows, allowing the spatial understanding of the interplay between components to be represented.

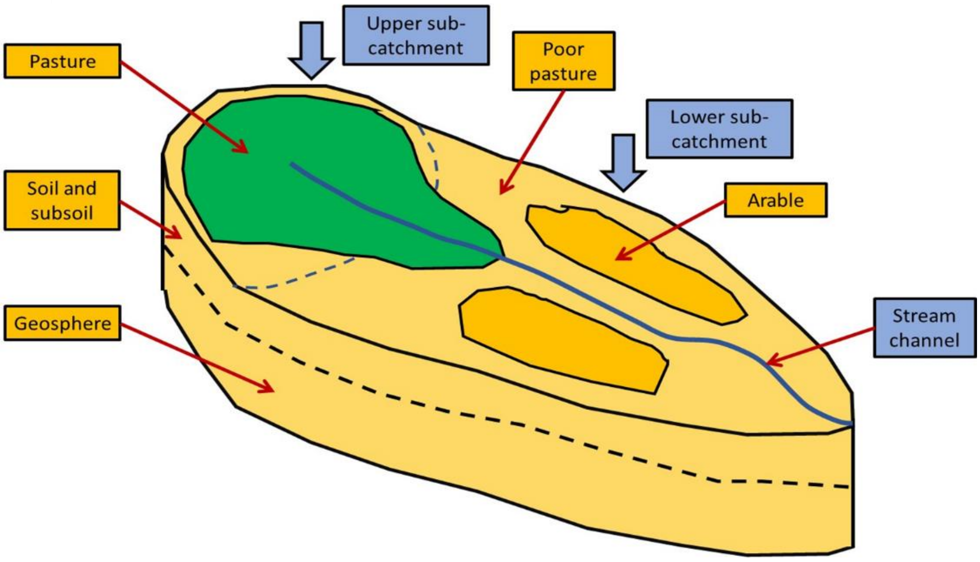

Figure 4. Illustrative catchment for initial C-14 modelling.

A number of simplifying assumptions have been made. For example, it is assumed that the carbon content of plants can be treated as a single pool (i.e. roots, foliage etc. can be aggregated) and, since the focus is on an agricultural system, soil can be treated as well-oxygenated to depth so that the capillary fringe and deeper anoxic soil can be excluded. Similarly, within the stream, only superficial oxic deposited sediments are considered, since deeper oxic and anoxic sediments are more relevant to lakes. Stream macrobenthos and microbial community are also aggregated.

The primary carbon exchanges between the different components and within the components have been identified. The fluxes between components are illustrated in Figure 5.

The final project report will be a compilation of the technical notes on the literature review and conceptual model developed with the output from the mathematical modelling task. An appendix on C-14 dose coefficients is also being developed as detailed below.

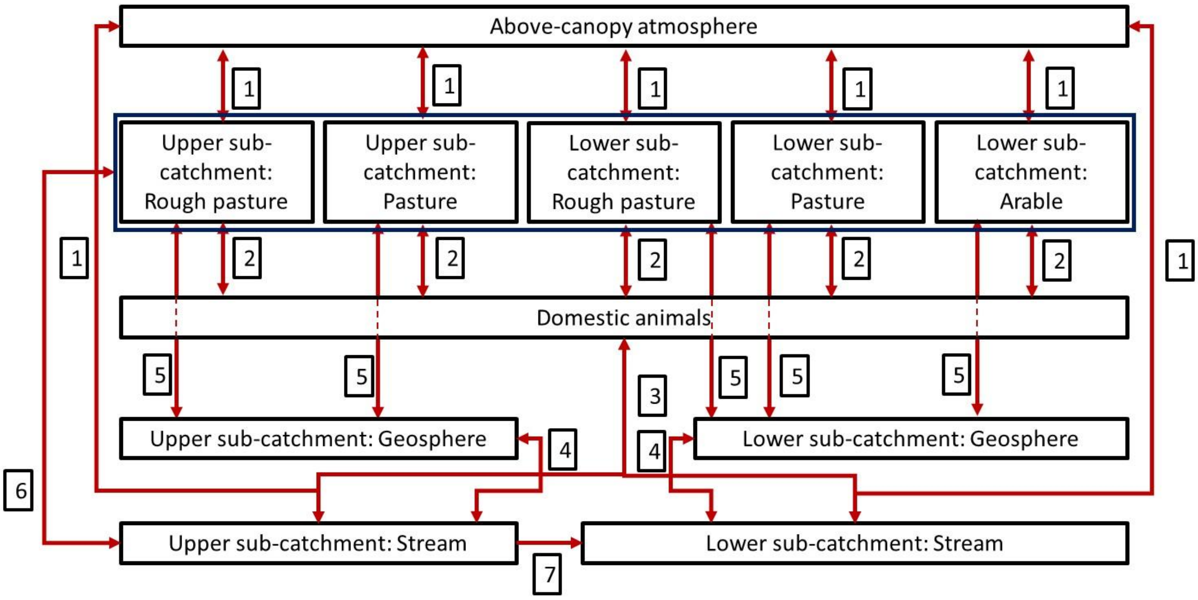

Figure 5. ***Main Fluxes between Components (1 = gas exchange with the sub-canopy atmosphere and the surfaces of open water bodies; 2 = food consumption and excretion; 3 = drinking water consumption and excretion; 4 = water exchange between the geosphere and the stream; 5 = water exchange between the soil and the geosphere; 6 = water exchange between the soil and the stream; 7 = downstream flow; consumption of plants and animals by humans are not shown, nor are internal exchanges within plant-soil systems or within a stream segment).***

3.2 CARBON-14 DOSE COEFFICIENTS

Graham Smith (TST) presented.

An addendum to the C-14 report has been proposed to provide some guidance around the selection of C-14 dose coefficients for a specific site and is in the process of being developed.

Within site-specific assessments consideration is given to the selection of appropriate model parameters that are related to the conditions at a particular site, such as soil properties, but discussion around the selection of appropriate dose coefficients for a specific site is usually neglected.

There is therefore merit in reviewing generic assumptions that support default ICRP values for dose coefficients in general. In recent years, there has been discussion around the selection of appropriate dose coefficients in assessments for C-14 and Cl-36[e], recognising that doses are affected by uptake, that different forms of radionuclides affect uptake and that uptake can also be affected by diet. For example, chlorine concentrations are homeostatically controlled, so salt consumption has a direct effect

[e] See Harrison and Leggett, “Appropriate selection of dose coefficients in radiological assessments: C-14 and Cl-36: response to the letter of G Smith and M Thorne.” J. Radiol. Prot. 36 (2016) 388–390 doi:10.1088/0952-4746/36/2/388.

on the Cl-36 dose coefficient. The ICRP dose coefficients assume that people eat the quantity of salt required in a diet rather than the amount that people actually consume, which can result in the Cl-36 dose being over-estimated. Where consumption habits in assessments are based on habit surveys for a specific area, the use of alternative dose coefficients can be justified.

Carbon-14 is often the dominant source of exposure for people from nuclear power plant operations and radioactive waste disposal, with ingestion of food and drinking water being the primary exposure pathways. It was noted in 2016 that the ICRP were updating dose coefficients for the ingestion of C-14 that would see a reduction of around 30% from the current value, and that a dose coefficient specific to ingestion as dissolved bicarbonate would be around 2.5% of the current value[e]. To date, these revised dose coefficients have not been published.

Discussion of the points raised will be included in an appendix to the final report for the current BIOPROTA C-14 project, to provide an additional reference to that provided by past correspondence in the Journal of Radiological Protection[e].

4. POTENTIAL TOPICS FOR FUTURE COLLABORATION ACTIVITIES

One of the key objectives of the BIOPROTA forum is to provide a platform where topics of common interest to member organisations can be identified and discussed and, where appropriate, taken forward as topics for discussion during focussed workshops or as projects aimed at addressing knowledge/data gaps and improving confidence in assessment approaches and models. An online questionnaire was distributed prior to the annual meeting to gauge interest among member organisations in topics for potential further collaboration. The results of the questionnaire were presented during the meeting and the highest scoring topics were selected for discussion during a break-out session. The session aimed to facilitate discussion amongst meeting participants on the leading topics for potential collaborative activities with feedback from each group helping to inform the development of the forward BIOPROTA work programme. To support discussions, previous work undertaken within BIOPROTA linked to the leading topics was briefly presented. The following sections provide an overview of the questionnaire responses, presentations on related previous work programmes, and a summary of feedback from each break-out discussion group.

4.1 QUESTIONNAIRE RESULTS

BIOPROTA member organisations all have a common interest in biosphere assessment, but overall interests can vary. Where areas of interest overlap, there is potential to organise collaborative work programmes such as projects and/or topical workshops. Several topics of potential interest for collaborative workshops and/or projects have been identified during previous annual workshops and a questionnaire was developed around these topics and shared with member organisations in March 2022. Nine potential topics of interest were included in the questionnaire. Fifteen organisations responded and results are summarised, according to the number of organisations identifying the topic as a priority, in Table 1.

Table 1. Summary of questionnaire responses on topics of potential common interest.

Topic	Interest	Priority
Updated comparison of biosphere modelling	9	6
Biosphere modelling for C-14	8	5
Experience of biosphere characterisation	6	3
Proportionality in assessing radioactive and hazardous waste	6	3
Experience stakeholder interest/engagement in biosphere	4	3
Modelling and data for sorption and plant uptake	9	2
Screening contaminants for quantitative assessment	7	2
Objectives for biota dose assessment	4	1
Application of BIOMASS to legacy sites etc.	2	1

A brief background to each of the potential topics was provided to inform discussions (topics underlined were selected for discussion during the break-out session).

- **<u>Biosphere modelling</u>**. Each member organisation has a biosphere modelling approach or the capacity to review modelling that has been undertaken. Various modelling approaches and/or aspects of models have been compared in the past through previous BIOPROTA projects and workshops, including comparisons of exposure pathways and modelling transfers across the geosphere-biosphere interface, but there is continuing potential for further workshops to provide an opportunity to present new and updated models and discuss reasoning behind model choices. Modelling for special radionuclides (i.e. those with particular behaviours that require special attention such as Cl-36, Se-79 and C-14) and the use of detailed models in support of assessment studies could also be topics for a biosphere modelling workshop. Biosphere modelling is therefore a broad topic. As such, the topic was taken forward to the break-out session in order to try and identify the main interest areas.

- **Biosphere modelling for C-14**. Carbon-14 requires careful consideration in assessments and remains a priority radionuclide for several organisations. A workshop to share the output from the current C-14 project following its completion and to discuss ongoing model developments and assessments would be useful to inform the development of a next-step plan for further modelling of C-14 in the biosphere. A final project meeting is already planned as part of the ongoing C-14 project that will provide an opportunity to discuss any follow-on work, including potential for a formal broader workshop.

- **Biosphere characterisation**. Over the last few decades, several programmes have moved from site-generic to site-specific assessments and there is potential to hold a workshop to share experience of biosphere characterisation, including planning, and how information gained through characterisation programmes has been used in assessments. A previous BIOPROTA study on site characterisation was published in 2006 and could provide some input. This topic was taken forward for discussion during the break-out session to help refine ideas around the scope and timing of a potential workshop.

- **Proportionality in assessing radioactive and hazardous waste**. Two workshops and a project have been undertaken previously in BIOPROTA on this topic and there is the potential for a further workshop to summarise previous work and consider further collaboration around proportionality and consistency in assessments, such as the potential for hazard indices and other techniques to support a proportionate and graded approach to risk management. This topic was taken forward to the break-out session to help refine ideas around a potential workshop.

- **Stakeholder engagement.** The biosphere assessment is the part of a safety case on which many stakeholders have views and areas of interest and stakeholder engagement is therefore an important topic for assessments. There is the potential to hold a workshop to discuss experience gained in stakeholder engagement and societal expectations with respect to biosphere assessments and the types of engagement used and lessons learned. This would be a new topic for BIOPROTA and a good topic for a workshop that was narrow enough as to not require further discussion in a break-out session.

- **Modelling and data for sorption and plant uptake.** Sorption and concentration ratios to calculate plant uptake from soils are key data for biosphere assessments. There has been discussion in the past around how to obtain data and the applicability of data in models, particularly with respect to whether data for plant uptake are representative of the bioavailable fraction. Different extraction techniques can be applied to extract elements from soil, plant and water samples that are then used to derive the necessary assessment parameters and the different techniques have implications of assessment models and results. A workshop has therefore been proposed on the topic with the potential for this to be followed with a technical project. The topic was therefore taken forward for further discussion to help refine the focus.

- **Screening of contaminants.** Screening of contaminants for explicit treatment is an important step in safety assessments and there is the potential to hold a workshop to explore the different approaches that have been employed, share experience, and discuss potential for greater consistency and good practice/lessons learned. The topic was considered narrow enough as to not warrant discussion in a break-out session.

- **Objectives for biota dose assessments.** Non-human biota dose assessments are becoming more routine, so it is useful to ensure approaches employed are up-to-date and consistent around endpoints modelled and criteria applied. Previous work in BIOPROTA looked at spatial scales of assessments for non-human biota relative to those employed in human dose assessments and there is potential to try and draw together guidance around how to represent populations of biota spatially in assessments to ensure assessment approaches are consistent with protection objectives and benchmarks. The topic is not currently of high priority to many organisations so was not taken forward to the discussion session but could be revisited in the future.

- **Wider application of BIOMASS methodology.** There is the potential to explore the wider application of the BIOMASS methodology to legacy sites, in situ disposal and radioactively contaminated land following the completion of the recent project to review and enhance the original methodology. This was not a priority topic based on questionnaire response so was not discussed further but could be revisited in the future if interest in the topic increased.

Of the 9 overall topics of potential interest, 4 were therefore taken forward for discussion during the break-out session with 2 further potential workshop topics being considered sufficiently narrow as to not require more detailed discussion at this stage. Next steps regarding C-14 will be discussed during a final project meeting.

4.2 OVERVIEW OF PREVIOUS WORK PROGRAMMES LINKED TO THE MAIN TOPICS OF INTEREST

Previous work programmes relating to the main topics of interest as detailed above were briefly presented to inform discussions.

4.2.1 Biosphere modelling approaches and ‘special’ radionuclides

Russell Walke presented.

BIOPROTA provides a platform for sharing of knowledge and experience on topics of common interest. The forum has been running for over 20 years and, during that time, a wide range of projects have been undertaken and workshops held, resulting in 26 technical project and 23 topic workshop reports, all of which are available from the forum website[f]. Early studies were focussed on modelling biosphere processes of common interest, including spray irrigation, inhalation exposures and radionuclide accumulation in soils. Each project aimed to share experience and understanding of the processes but also to consider for any one radionuclide if there was a dominant exposure pathway. Such analysis can then help focus on data needed for the exposure pathways of importance.

The spray irrigation project was aimed at investigating the significance of differing approaches and assumptions in modelling. Seven different models are described that varied in whether they used a leaf area index and storage capacity approach or an interception fraction approach. The models were

[f] https://www.bioprota.org/publications/

compared using a test calculation. Results were all within around a factor of 10 which built confidence in the models. The most important factors were the amount and frequency of irrigation, weathering and translocation.

The inhalation exposure project focussed on the calculation of doses arising as a result of the inhalation of particles resuspended from soil, which is a potentially important pathway for particle-reactive elements like actinides. Nine models are described and compared against a test calculation. Results spanned two orders of magnitude which was largely due to differences in assumptions for human behaviour since dust levels vary considerably with different activities. There were also differences around whether or not particle enrichment was taken into account and occupancy factors.

The project on modelling accumulation in soils considered accumulation over the long term in response to a continuous source term. Eight models were compared and applied to a prescribed agricultural scenario. Some models included seasonality which reduced concentrations whereas others used annual averages. Whether or not cropping was taken into account also affected results and there were some differences in irrigation rate assumptions. Nonetheless, there was reasonable agreement between the models.

There has been a sequence of projects within BIOPROTA on the geosphere-biosphere interface. An initial study was published in 2005. A workshop was then held in 2011 which was followed by a detailed project from 2013 to 2014, with a subsequent workshop in 2015. The 2014 project report provides a substantive investigation of issues, considering different geospheres and the implications of redox conditions on radionuclide mobility. Both irrigation and groundwater discharge pathways are considered, along with the implications of climate change. A range of different modelling approaches are available that range from detailed research models to more abstract assessment models and key aspects to be considered in modelling the geosphere-biosphere interface are identified.

Most recently, a BIOMASS methodology enhancement project has been completed. The BIOMASS methodology provides a workflow for biosphere assessments that has been widely applied and referenced in assessment projects. The methodology helps build confidence that no important processes are missed in assessments and provides for consistency in approach. Enhancement of the BIOMASS methodology was undertaken by Working Group 6 of the IAEA MODARIA II programme and was supported by a parallel BIOPROTA project to provide much of the necessary technical effort. The enhancement project recognised the importance of the workflow over detailed prescription in the methodology and gives greater emphasis to site understanding, integration with the overall safety assessment and safety case, the need for iteration and integration, as well as providing updated guidance on undertaking biosphere assessments. The report is currently with the IAEA publications department but a paper summarising the methodology has been published in the Journal of Radiological Protection.

A series of radionuclide-specific studies have also been undertaken within BIOPROTA, focussing on radionuclides of greatest interest across assessment programmes and that have particular characteristics that merit special consideration, such as redox behaviour. The studies have included both topical workshops and technical projects. The radionuclides that have been focussed upon include Cl-36, Se-79, Ra-226 and the U-238 decay series, in addition to C-14 for which a project is currently ongoing.

Work on Cl-36 began in 2006 with a workshop that was then followed with a phase I and phase II technical project. Phase I considered contamination of soil and uptake into crops, with phase II then taking the assessment through to dose and looking at uncertainties and variability. Ten models with varying degrees of complexity were applied in the phase I project. Specific activity models gave higher results than more complex models. The spread in results was reduced for coastal sites due to higher background chlorine concentrations. The phase II project had six models applied and results were within a factor of 15. The need to account for both stable chlorine and site-specific soil to plant uptake was identified. The need for general studies on foliar uptake and speciation in milk were also identified.

Studies on Se-79 also comprised of an initial workshop followed by a two-phase technical project. The phase I project involved a review of Se-79 behaviour and FEP analysis. The importance of speciation as it affects mobility was identified and volatilisation was identified as a potentially important loss mechanism. The phase II project then involved a model intercomparison exercise. The importance of redox conditions in determining bioavailability was noted and conventional models, that do not take into account redox conditions, tended to over-estimate uptake.

Work on the U-238 decay series began with a workshop focussed on Ra-226 in 2010, which was followed by a U-238 series project from 2010-2012 that developed a generic conceptual model as well as model comparison exercises to which both conventional and redox-sensitive models were applied with results typically being within 1 order of magnitude. Results indicated that assumptions around secular equilibrium were not always correct, with ratios between radionuclides in the decay series varying throughout the system. Radon, Pb-210 and Po-210 were identified as being particularly important to dose assessments as a result of the Ra-226 and it was noted that there are several gaps in understanding. The U-238 series project concluded that there was potential for site-specific sorption and a need to consider how natural background is accounted for in assessments.

4.2.2 Radioactive and hazardous waste disposal assessments

Graham Smith presented.

Environmental impact and human health assessments are used to support decisions on the management and disposal of radioactive and hazardous waste, but there are significant challenges faced in designing assessments for the co-disposal of radionuclides and other hazardous substances. For example, there has been separate development of the science, management strategies and regulations and there are a wide range of protection endpoints, ecosystems and timeframes of interest.

BIOPROTA began working on this topic in 2013. Two workshops were initially held and were then followed by a technical project that considered issues affecting the assessment of impacts of co-disposal in more detail.

The first workshop was focussed on the scientific basis for long-term radiological and hazardous waste disposal assessments and key differences and issues were identified. There are different management strategies and timeframes that apply. For example, radioactive waste is typically isolated and contained whereas the strategy for hazardous waste tends to be controlled release. It should be noted, however, that the IAEA definition of containment is 'Methods or physical structures designed to prevent or *control* the *release* and the *dispersion* of *radioactive substances*.[g]"; in essence, it includes leaking in a controlled manner. This is perhaps not how the average stakeholder would understand containment'. There are also differences around the endpoints of interest and the criteria associated with those endpoints. How assessment against criteria is done also differs. Key challenges faced include how to identify and address synergistic effects and how to take account of the effect that the presence of some chemicals

[g] IAEA Safety Glossary. Terminology Used in Nuclear Safety and Radiation Protection. 2018 Edition

can have on the behaviour of others. Key messages arising from the workshop were that a more integrated approach to criteria along with common assessment methods would promote proportionate radioactive and hazardous waste management and that, ideally, assessments should apply a common risk management basis with common assessment endpoints and timeframes. Development and use of common language to explain results etc. would help avoid confusion, errors and mistrust. Overall, the need for a holistic approach to assessments that takes account of all hazards from the outset was identified in moving forward to allow proportionate application of resources in line with hazards and risks.

The second workshop looked more closely at how safety and environmental impact assessments are done for the disposal of radioactive waste and hazardous waste. Again, separate development of the science, management strategies and regulations has led to differences in how assessments are undertaken. Recommendations arising out of the workshop included that radionuclides and hazardous materials should, ideally, be assessed on a common risk management basis, with consistent assumptions and criteria applied to evaluate risk and, where necessary, differences are justified and transparent, with a holistic approach being taken for any given site, facility or waste that encompasses all hazards.

The technical project, that reported in 2017, had the objective of providing information to support the development of a consensus on how to address the issues identified in the previous workshops that would support the application of more coherent and consistent assessment methods. In addition to identifying factors to consider in the design of assessments, the report includes appendices providing illustrations of how impacts of chemicals can be assessed alongside radiological impacts and gives consideration to the assessment of synergistic effects. Key findings include that non-radioactive materials in radioactive waste have been under-researched and that it is difficult to fit mixed hazardous wastes into current management schemes and regulatory regimes. It was also noted that non-radioactive hazards associated with radioactive wastes may dominate. In conventional landfill, hazard declines due to leaching/biodegradation, whereas waste conditioning of radioactive wastes reduces leaching potential. A key difference noted with respect to protection of the environment was that, whilst similar methods are applied to derive protection criteria for environmental protection, the criteria for chemicals tend to be applied as limits whereas for radiation they are screening values or benchmarks. Recommendations arising from the project were that the focus of assessments should be on risk rather than dose and to consider application of typical standards for hazardous waste to the management and assessment of radioactive waste. Clear and consistent protection objectives and assessment methods are needed, and the non-radioactive inventory associated with radioactive waste should be characterised with the same rigour as the radioactive inventory to ensure wastes are managed appropriately, taking account of all risks.

In terms of next steps, the technical report identified the need for coherence and proportionality in criteria and recommended that the scope for a methodology to support decisions around whether wastes should be managed as hazardous waste with some radiological protection additions or as radioactive wastes with some hazardous waste components be investigated. It is recognised that this will not be an easy task (there has been little progress since the 1990’s) so focussing on a few contaminants could help. Decommissioning wastes tend to have relatively few contaminants present and there are data that could support assessment so this could be a good starting point.

It is recognised that there are other international programmes focussing on similar topics and the suggestions is, therefore, that the next step for BIOPROTA could be to hold a workshop to draw together the latest knowledge and understanding and to develop a forward programme of activities.

4.3 COLLABORATIVE TOPIC DISCUSSION GROUP FEEDBACK

Four break-out discussion groups were organised to discuss particular areas of interest to take forward to future workshops or projects, to identify any constraints such as necessary timescales (e.g. deadlines in programmes) and to discuss practicalities of organising/hosting workshops and/or supporting projects with funds/technical efforts. The four discussion groups, as identified above, were:

- Biosphere modelling;
- Biosphere characterisation;
- Proportionality in assessing radioactive and hazardous waste; and,
- Modelling and data for sorption and plant uptake.

Feedback from each discussion group is summarised below. Other topics, including stakeholder engagement and contaminant screening were not discussed but would be good topics for workshops so will be considered in terms of planning the future work programme either as stand-alone workshops or as topical sessions during annual meetings.

4.3.1 Biosphere modelling

Models are applied for different purposes. Some are developed more as assessment models whereas others may be more research orientated models. It would be useful to create a list of models used within the BIOPROTA community and what they are intended for. Members can then decide themselves if there are other models they would like to compare their own against. It is suggested that a list be developed in MS Excel, detailing the model, who is developing it, its intended purpose, any challenges associated with the application of the model including uncertainties/weaknesses, platform in which it is developed etc. Supporting models such as hydrogeology and/or geochemistry modelling could also be captured. The list could be used to help motivate discussion.

A list of models for routine releases was generated by MODARIA II Working Group 3 and this could provide a useful template. There could also be an opportunity to work with others outside BIOPROTA through the IAEA MEREIA programme.

There is also interest in matching models with available data. For example, those developing models would be very interested in available site data. It was noted that NWMO are interested in using natural tracers from site characterisation studies to help validate models and it would be useful to consider model validation and confidence building when listing and discussing models.

Whether a sequential or snapshot approach is applied in modelling is a further topic of interest. If a sequential approach is taken then how transitions are represented needs to be considered, including how hydrogeology is treated; there will always be constraints to hydrogeological modelling in an evolving system. If a snapshot approach is taken, interpolation between individual snapshots is needed and this can be challenging. The issue relates to modelling of the geosphere-biosphere interface, ensuring overall consistency in the modelling approach and conservation of radioactivity between different climate states.

In the most recent safety assessment undertaken by Posiva, constant boundary conditions were assumed, even during glacial periods. Surface evolution modelling was then handled in a stylised way. The SKB approach has been to model sequentially, as this helps demonstrate system understanding. The interface with the deeper hydrological modelling can be challenging, since the two separate modelling groups tend to work independently. However, modelling the two systems together can be difficult due to complex mathematical problems such as the coupling of heat transport equations into groundwater flow equations, that need to be solved.

Two distinct topics were therefore discussed:

- understanding the different models being used in different programmes, the challenges faced and where data come from for potential model validation studies; and
- sequential versus non-sequential modelling and associated challenges in both generic and site-specific applications.

There would be potential to share experience on both topics. In taking these topics forward, thought needs to be given as to how best to elicit information on models and the topics / issues identified. There would be opportunity to further discuss the topic to refine ideas for collaboration in a separate online meeting should that be useful.

A further topic that could be of interest would be to share progress and developments in climate modelling. This could include work by SKB and Posiva on updating longer-term climate modelling, but also shorter-term modelling developments that have been progressing. Climate modelling is a rapidly developing area. For example, the work undertaken in the IAEA MODARIA programme was focussed on the 2013 IPCC report but there is now a 2021 IPCC report. There will be a lot of lessons learned, model results and implications for looking at longer timeframes and the underlying information continues to change rapidly. Coastal erosion and shoreline development work is also progressing. This could therefore become an ongoing theme to keep member organisations informed of work in different programmes with topical sessions being held from time to time.

4.3.2 Biosphere characterisation

It would be useful to hold a workshop to share experience around lessons learned in biosphere characterisation studies and several topics were identified:

- lessons learned on planning and executing programmes;
- development of site conceptual models based on data and links to models;
- technologies that can be applied in site characterisation studies, such as remote sensing;
- project phases and how they line up with characterisation studies;
- archiving samples; and,
- lessons learned in the characterisation of analogue sites and incorporation in site conceptual models.

In terms of timelines for holding a workshop, it would be useful to consider within the next year rather than longer term. NWMO are undertaking site characterisation work to support site selection so such a timescale would be useful in supporting the development of their forward programme. Depending on the location of the workshop, there could be an opportunity to include a field trip to give some perspective on how to undertake biosphere characterisation work.

It was noted that NWS is about to publish a report on site characterisation that addresses many of the points raised and a link will be provided once available.

A good range of topics were identified in discussions and would be sufficient for a few days of workshop. The different project phases of characterisation from site selection through to monitoring during the operational phase could be considered. A workshop scope will be defined with the intention of scheduling in 2023. Andra was suggested as a potential host for the workshop due to the possibility of visiting sampling archives and the ongoing site characterisation/monitoring programme. A field visit to Andra facilities was organised previously, but the programme has progressed and there are a number of new BIOPROTA participants since that time.

4.3.3 Proportionality in assessing radioactive and hazardous waste

There was general agreement amongst discussion group participants on the importance of the issues raised from previous work (see Section 4.2.2). Proportionality in assessments is important in enabling risk-based decisions to be made and to focus efforts on those risks that are not tolerable. There are technical tools and experience available within the radioactive waste management community that allow transfer and exposures to be evaluated, but the criteria and endpoints that are then applied are not proportionate. As such, decisions based on assessments risk not being proportionate so any actions taken with respect to the different hazards present may not be equivalent. This may result in engineering efforts etc. being focussed on protection from radioactive hazards when chemical hazards might actually dominate risks. There tends to be less capacity / resources for assessments within the chemical hazardous waste field and assessments tend to be done to the same level of detail. There can also be separate regulators / policies applied across the different hazard sectors and there can be resistance to change. The lack of coordinated policy and consistency are barriers to achieving proportionality and optimisation.

To address the issues, one approach could be to demonstrate at an international level that technical tools exist that allow migration and exposures from non-radioactive contaminants to be evaluated and to share experience on the selection and application of criteria for non-radioactive contaminants and on the key non-radioactive contaminants associated with radioactive waste, including particular issues such as radioactively contaminated asbestos. There is also the potential to develop a common toxicity index. Initially, the focus should be on humans and key radionuclides and chemical hazards. There are radiotoxicity indices for radionuclides and ranking tools for non-radioactive contaminants already exist, although they tend to be applied separately.

A common index could initially be used for screening contaminants on a common basis, with further development then looking at identifying common endpoints. Some case studies are available that could provide example assessments.

A topical workshop could be organised as a starting point to share experience around non-radioactive assessment capabilities, key contaminants and endpoints and to discuss issues around the development of a common index. The workshop should be fully documented with next step recommendations made with respect to the development of a common index for screening. The workshop should be inclusive with regulators, operators, technical support organisations and researchers present and could potentially be organised in cooperation with the Nuclear Energy Agency, but with BIOPROTA sponsoring organisations having control over publication.

A common index would be valuable in communicating with stakeholders, providing a means of placing chemical and radioactive risks in context. The difficulties in establishing a common index shouldn't be underestimated, however, as so many different endpoints are in play when it comes to chemical contaminants (toxicity, endocrine disruption etc.). It is suggested, therefore, that a qualitative approach to screening different hazards be considered in the first instance rather than a quantitative approach, concentrating on a combined situation where radioactive waste disposal leads to the co-disposal of toxic substances. For the toxic substances, there would be a need to classify as to whether they are hazardous or non-hazardous contaminants, and a wide range of data are already available that could be further built upon.

In the UK, there has been a shift in policy with the introduction of the Groundwater Daughter Directive from assessing human toxicity to working toward compliance demonstration in terms of concentrations at points in the system such as soils or groundwater. There is also interest in toxicity to non-human species. It might be useful as part of work on the topic to iron-out the regulatory drivers so that work is focussed.

It was therefore recommended that, in the first instance, a workshop be organised to discuss the different issues concerning potential development of a common hazard index and to propose and agree a possible way forward.

4.3.4 Modelling and data for sorption and plant uptake

Sorption and plant uptake parameters are important for many radiological assessments, but there tend to be large uncertainty bounds on them. It would be useful, therefore, to explore whether it is possible to reduce uncertainties or improve the way in which transport within soils and uptake into plants is represented in assessments. This would be a good topic for a workshop to share knowledge and improve understanding.

From an assessment perspective, it would be interesting to see how data are collected, such as the extrapolation techniques applied to recover elements, and to consider the kinetics and whether equilibrium is reached. There would then be a better understanding of the uncertainties and applicability of data when applying those data within assessments. There is a tendency in assessments to apply recommended parameters in models without recognising the imperfect procedures and practices that are necessarily involved in the derivation of these parameters, so discussion during a workshop would help in gaining a better understanding. From a data analysis perspective, greater understanding of the application of data in assessments would help those responsible for deriving data to understand the challenges associated with modelling. There has been discussion of data and quality assurance within the IAEA EMRAS and MODARIA programmes and it would be useful to try and tap into this experience.

One of the key challenges associated with data are that different extraction techniques for soils have implications for calculated Kd's and concentration ratios. Some extraction techniques will be quite reasonable with respect to bioavailability of an element in soil, whereas others will be aggressive and have high recovery rates. As such, the extraction technique applied will determine whether results over- or under-estimate retention and/or availability for transfer. A further issue is that concentration ratios can change over time. For example, data from Chernobyl have shown that bioavailability of caesium has reduced over time, as a result of the long-term kinetics. This has resulted in a reduction in concentration ratios over time. The context within which data are applied should therefore be considered.

It is suggested that a workshop be held over 2 to 3 days to share understanding around extraction methods, calculation of assessment parameters, their application in assessment models and the scope for improving data/models (e.g. through the use of correction factors to account for the different extraction techniques). Others from outside the BIOPROTA community with experience in this field could also be invited (e.g. Steve Sheppard who has considered the challenges and how to address them in the past).

4.4 NEXT STEPS FOR THE FORWARD PROGRAMME

All the topics discussed have potential for moving forward and the Technical Secretariat will work to help coordinate further discussion and the development of proposals that will then be shared with member organisations to invite participation, hosting of workshops, and shared funding to support them moving forward. It is proposed that planning meetings be organised on each topic for November (action). Prior to November, requests to register interest in topics will be sent to inform on the level of interest and prioritise the development of proposals.

Those topics that were not discussed also have potential to move forward but may be more suited to shorter discussions in the first instance as topical sessions during the next annual meeting.

5. FORUM ARRANGEMENTS FOR 2023

5.1 FEEDBACK FROM THE 2022 SPONSORING COMMITTEE MEETING

Alex Diener (BfS and BIOPROTA chair) presented feedback from a Sponsoring Committee meeting that took place during the course of the annual meeting. Key points, including actions agreed in discussion of the feedback are summarised below.

- **BIOPROTA objectives and scope**. The objectives and scope of BIOPROTA, including policy for membership, are set out in the Forum Arrangements document that is issued annually. No changes to the scope of the document were proposed.

- **Membership status**. Two member organisations from Czech Republic were lost in 2021. BGE in Germany had been identified as a potential new member, but BIOPROTA membership is not currently a focus for them. Nonetheless, Alex Diener will continue to engage on the topic periodically. FORTUM in Finland and European Spallation Source were identified as two organisations that could be interested in membership and should be contacted (action on the Technical Secretariat).

- **Ongoing projects**. The C-14 project is continuing and has benefited from additional funding from SKB and SSM. A further C-14 project following completion of the current work will be included in the list of future project proposals.

- **Future meeting arrangements**. The web-hosted annual meetings have resulted in strong participation and there is therefore interest in exploring the potential for hybrid meetings in the future. One option would be to hold face-to-face meetings during the morning with a hybrid arrangement for the afternoon. It was noted, however, that there can be a lot of issues in hosting hybrid meetings and there is a lot of pressure on the meeting chairperson to ensure everyone is engaged (both those attending in person and online). Sound issues can also be a problem. Alternatively, arrangements could be made to record workshops to make available online for those unable to attend in person. If recordings were to be made, these would need to be available for restricted timeframes to avoid misuse. It may be possible to share to members with password protection. Others that have shared content in such ways (e.g. DSA (ICRER) and SRP) will be contacted to help identify whether this could be a useful way forward.

- **Potential topical workshops in forward programme**. It may be beneficial to combine topical workshops to reduce travel requirements. The suggestion to hold web-hosted meetings in autumn 2022 to help further develop ideas and proposals was agreed on (action above).

- **Forum administration matters**. A report numbering system is still to be implemented (action on the Technical Secretariat). The website has recently been updated, and there is the potential to move some material (e.g. annual meeting reports) into a restricted password-controlled area in the future, if this is of interest. To avoid issues with holding personal information, an annual password could be issued to members. It was also noted that a restricted area could hold information on the different members to improve networking. Alternatively, an introduction session could be reintroduced to meetings once face-to-face meetings start again. An online poll will be arranged to gauge interest in creating a restricted area on the website (action on the Technical Secretariat). This will also consider whether the restricted area should share information area on members and/or contain the annual meeting reports.

5.2 FORUM ARRANGEMENTS FOR 2023

Kat Raines (NWS) has been confirmed as the new chairperson of BIOPROTA. Many thanks go to Alex Diener (BfS) for good collaboration in his role as chairperson since 2018.

Several potential offers were made to host the next annual meeting. These include NWS (England) and Andra (France). No decision was made and there will be follow-up with each organisation to discuss possibilities.

APPENDIX A. 2022 MEETING PARTICIPANTS

Participant	Organisation	Country
Yves Thiry	Andra	France
Špela Mechora	ARAO	Slovenia
Alexander Diener	BfS	Germany
Jelena Popic	DSA	Norway
Naeem Ul Syed	DSA	Norway
Yngvild Sauge	DSA	Norway
Philipp Schädle	ENSI	Switzerland
Ari Ikonen	EnviroCase/UEF	Finland
Dan Schultheisz	EPA	USA
David Stuenkel	EPA	USA
Jay Santillan	EPA	USA
Mike Boyd	EPA	USA
Caroline Roelandt	FANC	Belgium
Mayrna Surkova	FANC	Belgium
Graham Smith	GMS Abingdon	UK
Laureline Février	IRSN	France
Rodolphe Gilbin	IRSN	France
Kyoko Ichikawa	JANUS	Japan
Tomomi Ito	JANUS	Japan
Yukiko Fukaya	JANUS	Japan
Jongtae Jeong	KAERI	Korea
Minjeong Kim	KAERI	Korea
Mike Thorne	Mike Thorne & Associates	UK
Priska Hunkeler	Nagra	Switzerland
Deborah Oughton	NMBU	Norway
Yukiko Kusano	NUMO	Japan
Antoine Boyer	NWMO	Canada
Chantal Medri	NWMO	Canada
Mihaela Ion	NWMO	Canada
Andrew Cooke	NWS (GDF)	UK
Kat Raines	NWS (GDF)	UK
Ray Kowe	NWS (GDF)	UK
James Ridehalgh	NWS (LLWR)	UK
Sam Stead	NWS (LLWR)	UK
Lauri Parviainen	Posiva	Finland
Jordi Vives I Battle	SCK·CEN	Belgium
Talal Al Mahayni	SCK·CEN	Belgium
Olle Hjerne	SKB	Sweden
Peter Saetre	SKB	Sweden
Sari Peuri	SKB	Sweden
Ulrik Kautsky	SKB	Sweden

Anki Hägg	SSM	Sweden
Karolina Stark	SSM	Sweden
Maria Norden	SSM	Sweden
Karen Smith	Technical Secretariat (RadEcol Consulting)	UK
Russell Walke	Technical Secretariat (Quintessa)	UK
Laura Limer	Teams administrator (Quintessa)	UK