INTERNATIONAL COLLABORATION IN ASSESSMENT OF RADIOLOGICAL IMPACTS ARISING FROM RELEASES TO THE BIOSPHERE AFTER DISPOSAL OF RADIOACTIVE WASTE INTO GEOLOGICAL REPOSITORIES

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Geological disposal is designed to provide safe containment of radioactive waste for very long times, with the containment provided by a combination of engineered and geological barriers. In the extreme long term, after many thousands of years or longer, residual amounts of long-lived radionulides such as Cl-36, but also radionuclides in the natural decay chains, may be released into the environment normally accessed and used by humans, termed here, the biosphere. It is necessary to ensure that any such releases meet radiation protection objectives through the development of a safety case, which will include assessment of radiation doses to humans. The design of such dose calculations over such long timeframes is not straightforward, because of the range of potentially relevant assumptions which could be made, concerning environmental change and changes in human behavior. These conceptual uncertainties are additional to those that more typically arise, for example, in the assessment of present day situations, but which also have to be addressed. The issue has therefore been subject to international cooperation for many years. This paper summarizes the evolution and results of that collaboration leading up to the present day, taking account of developments in international recommendations on radiation protection objectives and the more recent greater focus on preparation of site specific safety cases.

KEYWORDS : Dose assessment, Biosphere Modelling, Waste Repositories, International Cooperation

1. INTRODUCTION

Decisions on permitting, controlling and monitoring releases of radioactivity into the environment are made on the basis of a great many factors. Important among these is the prospective assessment of radionuclide behaviour in the environment, assessment of the associated migration and accumulation among and within specific environmental media, and assessment of the resulting environmental and human health impacts. Models and techniques to undertake such assessments have been developed over several decades based on knowledge of the ecosystems involved, as well as monitoring of previous radionuclide releases to the environment, laboratory experiments and other research.

In some cases, problems arise in obtaining good data for these assessments. Particular difficulties arise in the case of long-lived radionuclides, for present purposes, those with a half-life greater than 30 years. These difficulties arise partly because of the logistical issues of setting up relevantly long term monitoring and experimental programmes. Such efforts cannot directly address the long-term migration and accumulation processes which affect the long-term impacts. Furthermore, the ecosystems themselves will change over time, due to natural processes and the interference of mankind. Assumptions for human behaviour over periods as long as 30 years, or longer, are bound to be questionable.

These assessment issues are particularly difficult to address in the case of assessment of possible releases of radionuclides from solid radioactive waste repositories. The timescales for assessment in this case can extend over thousands of years, well beyond the normal lifetime of political boundaries and other institutions. Such difficulties were recognised at an early stage in the development of radioactive waste management solutions. This led to the idea of international cooperation to develop common solutions, where circumstances make this appropriate, for example the European collaborative project PAGIS, Performance Assessment of Geological Isolation Systems in the 1980s [1].

This paper summarizes the evolution and results of that collaboration leading up to the present day, taking account of developments in international recommendations on radiation protection objectives and the more recent greater focus on preparation of site specific safety cases.

2. INITIAL COLLABORATION EXPERIENCE AND LESSONS LEARNT

Within the PAGIS program, among other things, a number of alternative land-based disposal systems was considered, each focusing on different types of geological environment. However, given the very long time before any release to the accessible environment normally accessed by humans, or the biosphere as we call it here, it was considered appropriate to develop one biosphere assessment model for assessing doses to humans. This was prepared and reported in reference [2].

The model provided [2] described a simplistic representation of land and water bodies, the ways by which radionuclides might migrate and accumulate between such parts of the biosphere, and the ways in which humans might interact with that environment giving rise to radiation exposure. None of the model assumptions linked to the assessment was very detailed since such details were considered to be likely to be unjustifiable. The key assumption was that radionuclides would be released from the geosphere to the biosphere in contaminated groundwater discharges. A wide range of exposure pathways involving ingestion, inhalation and external irradiation was considered, so that all potentially significant pathways could be identified. It was recognized that environmental change could affect dose estimates. Changes that could be relevant could be separated into those occurring before the release to the biosphere occurs, and those which occur while release is on-going or after it is complete. The most important biosphere changes to consider were thought to be those which result in acute release of otherwise stable and non-bio-available accumulations of radionuclides, such as river bed sediments.

The methodology and models in reference [2] included estimation of annual individual doses and collective doses, the latter, distributed in time and space.

Notwithstanding the availability of this generic model developed within the PAGIS program, the PAGIS report [1] included results for alternative regionally based models.

Collaboration on a global rather than European basis was initiated by the Swedish regulatory authority within a program called BIOMOVS, which ran from 1985 to 1990. The project allowed for inter-comparison of models to assess radiation doses arising due to long-term release of long-lived radionuclides in a variety of circumstances. This enabled the identification of potentially important processes, particularly those for which the then current information base was poor. These processes related to the biosphere systems as well as radio-ecological data on how radionuclides behave within those ecosystems, as reported in reference [3].

Typical of the BIOMOVS output was a report which compared models for the assessment of environmental contamination levels arising from long-term release of Th-230 and Ra-226 into a lake [4]. Site specific data for a real lake system and exposure assumptions were provided, so as to avoid arbitrary differences in results. Models applied to the scenario came from Sweden, USA, Belgium and UK, reflecting a range of different experience on the topic under study. The different models involved quite different conceptual interpretations of the scenario and gave quite different results. However, it was clear that the largest concentrations would arise as the lake dried out in long-term processes, making activity accumulated in lake bed sediment accessible, for example as farmable soil. It was also clear that models were not detailed enough to make use of the site specific information provided, which implied the need for more detailed understanding and interpretation related to long term processes affecting long term impacts.

The BIOMOVS project was followed up from by a second phase, BIOMOVS II, which ran from 1991 to 1996. It involved many organizations from around the world and included a special focus on the problem of defining biosphere systems relevant to performance assessment (PA) of radioactive waste repositories [5]. Among the key outputs in this context were very substantial quantitative model inter-comparison exercises made by expert groups from Switzerland, Netherlands, France, Belgium, Sweden, Canada, Spain and the UK [6]. Results extended to dose calculations for critical groups for important radionuclides, such as I-129, Np-237, U-238 and their radioactive progeny, and included investigations of uncertainties. At this stage, while a number of uncertainties were still considered worthwhile further consideration, some consensus was emerging on the basic structure for the models and processes.

Over the same period, further consideration was given to the need to consider site specific issues, bearing in mind that current site circumstances would be subject to change. The key question was whether a limited number of 'reference biospheres' could be sufficient for the analysis of safety of radioactive waste repositories. Such an approach would avoid the need to provide assumptions for human behavior and environmental changes, but arguably, would fail to address the problem in sufficient depth. Factors affecting the approach included not just site specific issues, but also the regulatory background within which the PAs were required to be made. Progress was made within BIOMOVS II by the production of an outline reference biosphere biospheres methodology and a list of potentially relevant features, events and processes (FEPs) [7].

The advantage of long-term monitoring data to support prospective modeling was not neglected, where suitable data were found to be available. A particular example in BIOMOVS II was the use of short and long term measurement data for the uptake of C-14 into fish following release into a Canadian shield lake. The assessment need here arose due to the relatively high assessed doses from fish consumption, based on an equilibrium distribution coefficient between C-14 in water and C-14 in fish. The data allowed the testing of the validity of this equilibrium assumption and for the consideration of dynamic uptake of C-14 into fish during their growth cycle. This models testing exercise demonstrated that dynamic models provided results more consistent with the field measurements. In addition, the release of C-14 from the lake surface to air was found to be an important process that had been neglected in some models [8]. This was typical of the advantages of this type of international cooperation. Use was then made in project specific applications, such as in the USA [9].

3. BIOMASS REFERENCE BIOSPHERES METHODOLOGY

By the time of the completion of BIOMOVS II, it was recognized that the issue of the need for more detailed assessment of the biosphere depended on many factors, such as whether the PA was being made at the early stage of repository development and site generic, intended only to support the further development of a disposal concept, or, at the other extreme, forming part of an application to operate a repository. At the same time, international recommendations and national regulatory guidance were being developed, e.g. reference [10], on the relevance of timeframes and different safety indicators, and reference [11], which modified the USA approach towards a greater focus on dose and risk assessment rather than containment requirements. In fact, it could be argued that different approaches were being taken in different countries, but it was not clear why.

Bearing this in mind, the International Atomic Energy Agency set up a project within Theme 1 of the BIOMASS program with the objective of developing the concept of 'Reference Biospheres' into a practical system for application to the assessment of the long-term safety of repositories for radioactive waste [12]. The project ran from 1996 until 2001, and attracted a great deal of interest, with participation and material inputs provided by 68 experts from 43 organisations and 17 countries from North and South America, Europe, Asia and Africa.

Because of the complex nature of the project, work was divided into various activities which were reported upon at workshops and the output was published as working material so that it could be reviewed in the interim and used in specific applications, such as in reference [13] from Japan. An advantage of this approach was that the interim applications provided feedback regarding the practical usefulness of the work.

The final version of the methodology is summarised in Figure 1 and each step in Figure 2. The success of the methodology lies in the systematic approach to addressing the assessment issues. Not all issues have the same significance for all PAs. For example, some assessments are not required to consider environmental change, whereas others are. The BIOMASS reference biosphere methodology, however, provides a common basis for any assessment team to consider each issue in a practical sequence. In order to help the user understand how the methodology can be applied, a set of examples was provided, ranging from the very simple to complex consideration of how groundwater interacts with the biosphere via a geosphere-biosphere interface and then radionuclide migration and accumulation in a valley comprising a series of ecosystems. Dose results were presented for each example for a set of radionuclides relevant to waste disposal: Tc-99, I-129, Nb-94 and Np-237. This set conveniently provided a range of chemical and radiation properties which illustrate the significance of different FEPs and exposure pathways in each case. A wide range of additional illustrative variant calculations was also provided, which showed the significance of different assumptions about exposure group assumptions and different data assumptions. In addition, a protocol was suggested for determining suitable data assumptions given a range of sources and potentially relevant references.

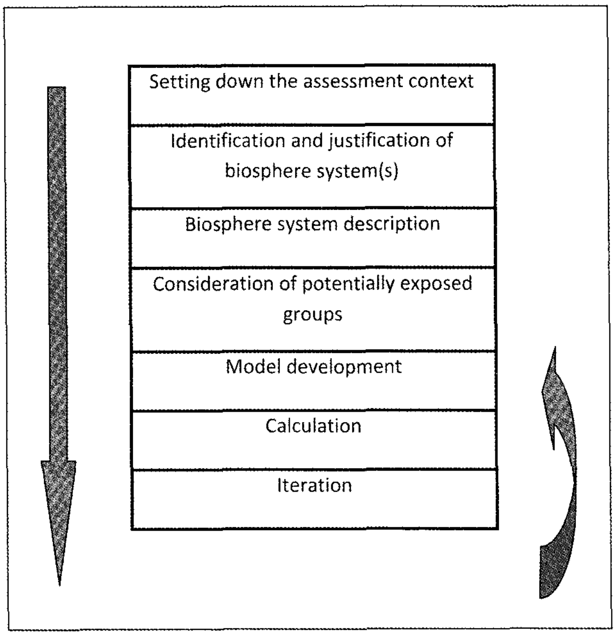

Fig. 1. Summary Representation of the BIOMASS Reference Biospheres Methodology

1. SETTING DOWN THE ASSESSMENT CONTEXT

- Set out what is to be done and why
- Set out the initial premises
- Set out context components (parts) e.g. purposes, endpoints etc, and suggest some alternatives
- Make a clear record of the purposes for the calculation.

The assessment context will help to establish the appropriate level of documentation to provide the necessary traceability and transparency.

OUTPUT: The underlying premises of the calculation (what is being calculated and why) are stated explicitly.

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2. IDENTIFICATION AND JUSTIFICATION OF BIOSPHERE SYSTEM(S)

- Review the assessment context.
- Using the series I tables (Volume II, Annex A), select the principal components of interest and then the principal component types for an initial biosphere system, and justify the selection (repeat if more than one system).
- Use the three step process to consider the need for biosphere change (details in Volume II, Section 3.1). Repeat step in previous bullet point as required.

OUTPUT: Biosphere system, or a series of biosphere systems, identified by the principal component types e.g. climate type, topography category etc.

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3. BIOSPHERE SYSTEM DESCRIPTION

- Step 1. Use the series II tables (Volume II, Annex A) to identify which characteristics of the principal component types are relevant or not (i.e. "in" or "out"). In addition, the human activities Table HIIb (Volume II, Annex A) is used to identify potential exposure pathways.
- Step 2. Establish interrelationships between the principal component types of the biosphere system. (Depending on the assessment context this step may not be necessary). Where appropriate use an interaction matrix.
- Step 3. Produce a word picture of the biosphere system. Check for consistency within the biosphere system by carrying out calculations of, for example, water balance. This will require appropriate use of the data protocol.

OUTPUT 1: A word picture, which provides a qualitative and, where appropriate, quantitative description of the biosphere system.

OUTPUT 2: A description of potential exposure pathways.

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4. CONSIDERATION OF POTENTIALLY EXPOSED GROUPS

- Step 1. Review exposure modes and routes.
- Step 2. Identify relevant human activities.
- Step 3. Combine human activities and exposure modes to identify those that are most likely highest doses.

OUTPUT: List of candidate critical groups and/or other groups of interest

The next two steps can follow step 4 of stage E, model development.

- Step 4. Establish data requirements for quantifying hypothetical critical group habits.
- Step 5. Review data availability and select appropriate data making use of the data protocol.

OUTPUT: Fully characterised exposure groups.

5. MODEL DEVELOPMENT

- Step 1. Identify conceptual model objects i.e. distinct environmental media potentially influencing dose to the candidate critical groups. These media should become evident from screening of Table HIIb (Volume II, Annex A) and the previous formulation of the system description.
- Step 2. Construct the conceptual model by considering the interactions between the conceptual model objects. An interaction matrix has been shown to be useful.
- Step 3. Ensure that no potentially important FEPs are omitted from the conceptual model.
- Step 4. Identify data sources. Define the mathematical model taking account of available data sources and scientific understanding. Derive relevant parameter values according to the data protocol.
- Step 5. Incorporate the exposure group information.

OUTPUT: Assessment model.

6. CALCULATION

- Calculate concentrations of radionuclides in environmental media.
- Where necessary, carry out calculation of doses to the previously described group(s).
- **Iteration as necessary of previous steps**

OUTPUT: Doses or concentrations as required by the assessment context.

Fig. 2. Description of the Steps in the BIOMASS Reference Biospheres Methodology

The methodology has been used in its various aspects in a wide range of PAs, for example in France [14] and the UK [15], and so one can see the advantage being taken of the internationally developed methodology.

4. CLIMATE CHANGE

One aspect of the BIOMASS reference biosphere methodology which was not fully demonstrated was the quantitative consideration of climate change. Important questions include: what change will occur, when, and how will it affect biosphere systems in a particular region, as opposed to globally. The European Commission therefore set up a project to consider the climate change issue called BIOLCIM. The final deliverable [16], completed in 2004, set out the development and application of a methodology for taking climate-driven environmental change into account in PAs. In particular, various downscaling methods were developed to allow climate model output to be incorporated into PA models. It was also concluded that environmental change is not driven solely by alterations in climate.

This point has been taken up in reference [17]. Here it was noted that in biosphere modelling it is generally assumed that ecosystems are in equilibrium in response to the modelled stationary climate conditions. Consideration of transition phases between stationary climates, however, could be of importance, as they might result in higher releases, e.g. due to an accumulation and then acute release of radionuclides below an ice shield during a glaciation event. For some sites, these issues are strongly linked to other broader geo-physical change, for example, sea level change at coastally located sites under investigation in Sweden [18] and Finland [19].

5. BIOPROTA AND RECENT DEVELOPMENTS IN INTERNATIONAL COOPERATION

In the last decade, an increasing number of solid waste repository projects have switched from site generic to site specific investigation. This has meant that the generic applicability of the BIOMASS reference biospheres methodology is increasingly tested, as site investigation data come available, for example, as in Sweden and Finland mentioned above, but also at Yucca Mountain in the USA [20].

In fact the generic approach and preliminary assessments help to define the necessary biosphere aspects of site characterization work necessary to support a site specific PA. The process of identifying priorities has been investigated and developed, for example, in Japan as reported in reference [21]. The project of geological disposal is in the stage of site selection in Japan. In JAEA's case, the existing biosphere parameter values for the generic assessment were mostly collected from related technical reports on safety assessment of radioactive waste disposal and environmental radioactivity research in Europe and the United States, as reported in reference [13]. The data of some biosphere parameters need to be revised for site-specific assessment in Japan, because they might be inappropriate for use of the assessments in Japan, due to the differences of climate condition, vegetation, etc. On the other hand, it is difficult to acquire all of biosphere parameters at the repository site because several hundreds of parameters have to be dealt with in one calculation case of the biosphere assessment. Therefore, the methodology for identification of the priority of the parameters was developed for the effective data acquisition of biosphere parameters at the site. This methodology was developed based on the BIOMASS data protocol [12]. Figure 3 shows the flow diagram for setting biosphere parameters for site-specific assessment starting with an existing generic dataset, which was constructed referring to the previous reports, such as [12,22]. Suitability of the existing biosphere dataset for generic assessment can be evaluated using this flow diagram, and the significant biosphere parameters that should be acquired at any specific proposed repository site have been selected by sensitivity analysis, taking account of the importance of the parameters for the assessment and the feasibility of data acquisition. This priority list can be useful for effective data acquisition at the site. Based on this priority list, the biosphere database for the significant element-specific parameters (e.g. distribution coefficients on soil, soil-to-plant transfer factors) for generic assessment has been updated to include domestic data throughout Japan collected by NIRS (National Institute of Radiological Sciences). Accordingly, the approach takes advantage of international activities in developing the site specific application, but then addresses the local situation.

As the estimates of radionuclide release into the biosphere produced by the rest of the PA tend to become more precise, and the biosphere systems tend to be more fully characterized, then the number of major biosphere uncertainties tends to be reduced: only relatively few radionuclides dominate the peak estimates of radiation

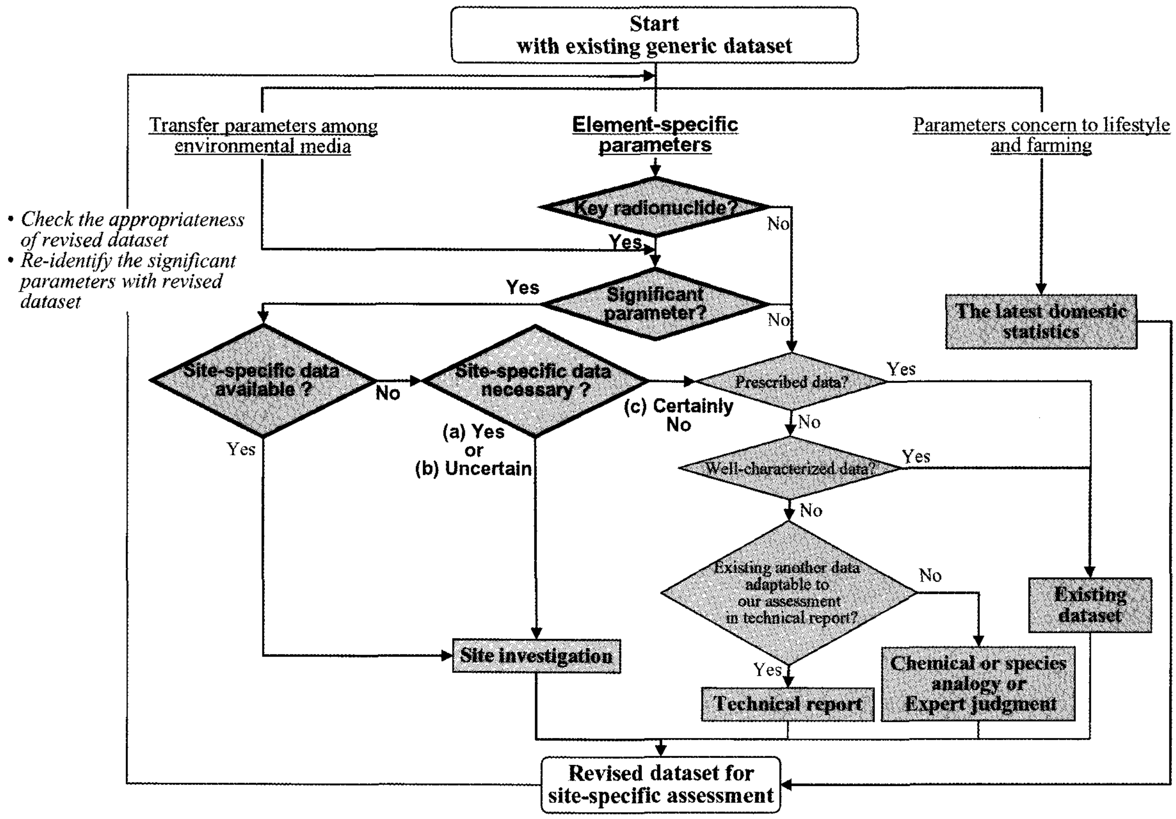

Fig. 3. Flow Diagram for Setting Biosphere Parameters for Site-specific Assessment Starting with an Existing Generic Dataset

doses and only the processes relevant to their migration and accumulation.

To help the international community address these issues in an effective and efficient matter, the BIOPROTA international collaboration project was set up in 2002. Membership includes a wide range of radioactive waste management organizations, including operators, regulators and their technical support organizations. It specific objectives were, and remain:

- To provide a scientific forum for exchange of information to support resolution of key issues in biosphere aspects of assessments of the long-term impact of contaminant releases associated with radioactive waste and contaminated land management.
- To make available the best sources of information to justify modelling assumptions made within long-term radiological assessments. Particular emphasis is placed on key data required for the assessment of long-lived radionuclide migration and accumulation in the biosphere, and the associated radiological impact, following discharge or release to the surface environment.
- The project is driven by assessment needs identified from previous and on-going assessment projects. Where common needs are identified within different assessment projects in different countries, a common effort can be applied to finding solutions.

The results of BIOPROTA range from suggestions on what parameter values to select in particular assessment situations, e.g. to advice on the more generic types of information which should be taken into account when making modelling assumptions. Reports and workshop proceedings, on issues such as dilution and dispersion at the geosphere-biosphere interface, application of dose assessment methods for non-human biota to the case of repository PAs, and site characterisation, are all made available at www.bioprota.com, so as to facilitate access and further cooperation.

In the earlier stages of the BIOPROTA program, updated consideration was given to modelling of key exposure pathways for key release modes [23-25], to ensure that the best information was being made mutually available on relevant processes and how to represent them. Most recently, the program focus has been on critical radionuclides, such as Cl-36 [26] and Se-79 [27]. For this work, experts have been included on selenium and chlorine in the environment, as well as the more general experts in ecology and radiological assessment. Similar work is in progress on C-14 and U-238 series radionuclides, as well as on the uncertainties in non-human biota assessments within repository PAs and on the enhancement of a specialised database for radionuclide specific data.

The above work is designed to support national programs directly, such as work on-going in Japan on Construction of domestic biosphere database and revision of the biosphere parameter set.

The importance of international cooperation in this interesting area is reflected in the BIOPROTA membership and the number and scope of the projects developed and carried out within the program. At the outset, it was recognised that there are radioecological and other data and information issues which are common to specific assessments required in many countries. The mutual support within a commonly focused project was intended to make more efficient use of skills and resources, and provide a transparent and traceable basis for the choices of parameter values as well as for the wider interpretation of information used in assessments. The aim remains the same. The challenges evolve as PAs focus increasingly on decisions on development and operation of new repositories at real sites. Ideally one seeks to maintain coherence across international best practice, e.g. by following the methodology set out in Figure 2, while applying that approach with proper account given to the specific assessment context of a particular repository.

To this end attention is drawn to scope for enhancing cooperation, for example through Radiation Safety and Radioactive Waste Management (RS&RWM) project within the Forum for Nuclear Cooperation in Asia., thereby adding to the important contributions from Korea and Japan. In addition, it is noted that the IAEA has recently set up a Waste Working Group within its EMRAS II program, thus providing a further mechanism to support stakeholder engagement in this area.

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