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Biosphere modelling for the assessment of radioactive waste repositories; the development of a common basis by the BIOMOVS II reference biospheres working group

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Abstract

Performance criteria for radioactive waste repositories are often expressed in terms of dose or risk. The characteristics of biosphere modelling for performance assessment are that: (a) potential release occurs in the distant future, (b) reliable predictions of human behaviour at the time of release are impracticable, and (c) the biosphere is not considered to be a barrier as the geosphere and the engineered barriers. For these and other reasons, differences have arisen in the approaches to biosphere modelling for repository dose and risk assessment. The BIOMOVS II Reference Biospheres Working Group has developed (a) a recommended methodology for biosphere model development, (b) a structured list of features, events and processes (FEPs) which the model should describe, and (c) an illustrative example of the recommended methodology. The Working Group has successfully tested the Interaction Matrix (or Rock Engineering Systems, RES) approach for developing conceptual models. The BIOMOVS II Working Groups on Reference Biospheres and Complementary Studies have laid the basis for considerable harmonisation in approaches to biosphere modelling of long term radionuclide releases. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Performance criteria for radioactive waste repositories are often expressed in terms of dose or risk. If other criteria are used, they may well have been derived from dose or risk criteria. Some sort of biosphere modelling is therefore usually required to assess radionuclide migration and accumulation in the human environment, and to assess the associated radiation exposure. Different views are held, however, both on the scope of processes to be included and on the level of detail required in biosphere models.

The characteristics of biosphere modelling for performance assessment of solid radioactive waste disposal are that (a) potential release and exposure occur in the distant future, (b) reliable predictions of human behaviour at the time of the release are impracticable and (c) the biosphere is not considered to be a barrier as the geosphere and the engineered barriers and cannot be optimised. For these and other reasons, differences have arisen in the past in the approaches to biosphere modelling in different countries and projects.

Given the uncertainties associated with biosphere modelling, it has been suggested that a desirable approach might be to adopt 'reference biosphere models'. These models could then be used to derive conversion factors, expressed as the radiological dose or risk associated with unit release rates of radionuclides. These release rates to the biosphere would be provided by geosphere modelling within the performance assessment. A Working Group on Reference Biospheres was set up within the BIOMOVS II programme to address these issues.

Participants in the Reference Biosphere Working Group are experts in the field of biosphere modelling and data collection working for the implementator as well as the regulator.

The Reference Biospheres Working Group considered that the concept of 'reference biosphere models' would be difficult to achieve, because of the different types of waste, sites and assessment purposes. The Working Group did not find it practical to try in the early stages of its work, to develop just one or a limited number of reference biospheres. It decided rather to develop and test a 'reference biospheres methodology' for analysing radionuclide behaviour in the biosphere and associated radiological exposure pathways. It limited the scope of work to assessment of the long-term implications for deep geological disposal. Nevertheless, it considered that many of the basic principles would also apply to other areas of biosphere assessment for solid radioactive waste disposal. The objective was to define a systematic generic approach for developing a biosphere model. This would include the documentation of an 'audit trail' and would show that a biosphere model is fit for its intended purpose. The Working Group expected that this approach would also reduce the unresolved differences between different models and so harmonise biosphere modelling.

The BIOMOVS II Reference Biospheres Working Group, therefore, defined its aims as to develop (BIOMOVS II, 1994):

- a recommended methodology for biosphere model development, which is consistent for different types of radioactive waste and disposal concepts (Section 2 of this paper),

- a structured list of generic Features, Events and Processes (FEPs), which can be used to guide the development of conceptual biosphere models for specific assessments by indicating which FEPs should be included (Section 3 of this paper),
- an example illustrating the application of the methodology (section 4 of this paper), which uses the test case of the Complementary Studies Working Group (BIOMOVS II, 1996b).

This paper summarises the results of the extensive discussions of these items in the Working Group. The interim and final reports of the BIOMOVS II Reference Biospheres Working Group (BIOMOVS II, 1994; BIOMOVS II, 1996a) provide more details.

2. Methodology for the development of biosphere models

The methodology recommended by the Reference Biospheres Working Group consists of several steps (see also Fig. 1). The Reference Biospheres Working Group discussed the following steps 1–3 in detail, because they are relatively new in biosphere modelling. The further steps which are standard components are summarised in point 4.

Step 1. A case-specific FEP list is developed (see details in BIOMOVS II, 1996a) starting from a generic FEP list such as the *international FEP list* (*italics* refer to items in Fig. 1) in Table 1, by marking non-relevant FEPs and giving detailed comments to the relevant FEPs. This needs to take account of the *assessment context*, consisting of (a) the assessment purpose and target audience, (b) the endpoints to be assessed (including regulations and the definition of critical groups), (c) the description of the repository system, (d) the site context and (e) the nature of the release.

Step 2. The *basic system* representative of long-term conditions including the characterisation of the process system domain, climate conditions, assumptions for human actions (society) and identification of the biosphere systems.

Step 3. *Conceptual models* or textual descriptions of the biosphere system are constructed. This involves an *initial screening* of the FEP list against *the basic system description* and the *assessment context*, and the *identification of relationships between FEPs*. For this step several methods can be applied such as (a) influence diagrams (Chapman et al., 1995), (b) the rock engineering system (RES) approach (Eng et al., 1994; Hudson, 1992; Smith et al., 1996a) which involves the development of an interaction matrix (this approach was tested by the Working Group), (c) directed diagrams (UK-NIREX, 1995), or (d) a reverse method, which compares existing models with the assessment-specific FEP list obtained after the *initial screening* (see above in this paragraph). The result is a *relational FEP list* indicating the relationships between the FEPs. These FEPs and their relationships are categorised according to priority, taking into account (a) the known influence of the FEP or the interaction on the result, if known from previous experience or expert opinion (well known important FEPs have high priority, well known unimportant FEPs low) and (b) the state of knowledge about the FEP or the interaction (unknown FEPs have high priority). FEPs with high priority should be included in the models. FEPs with low priority

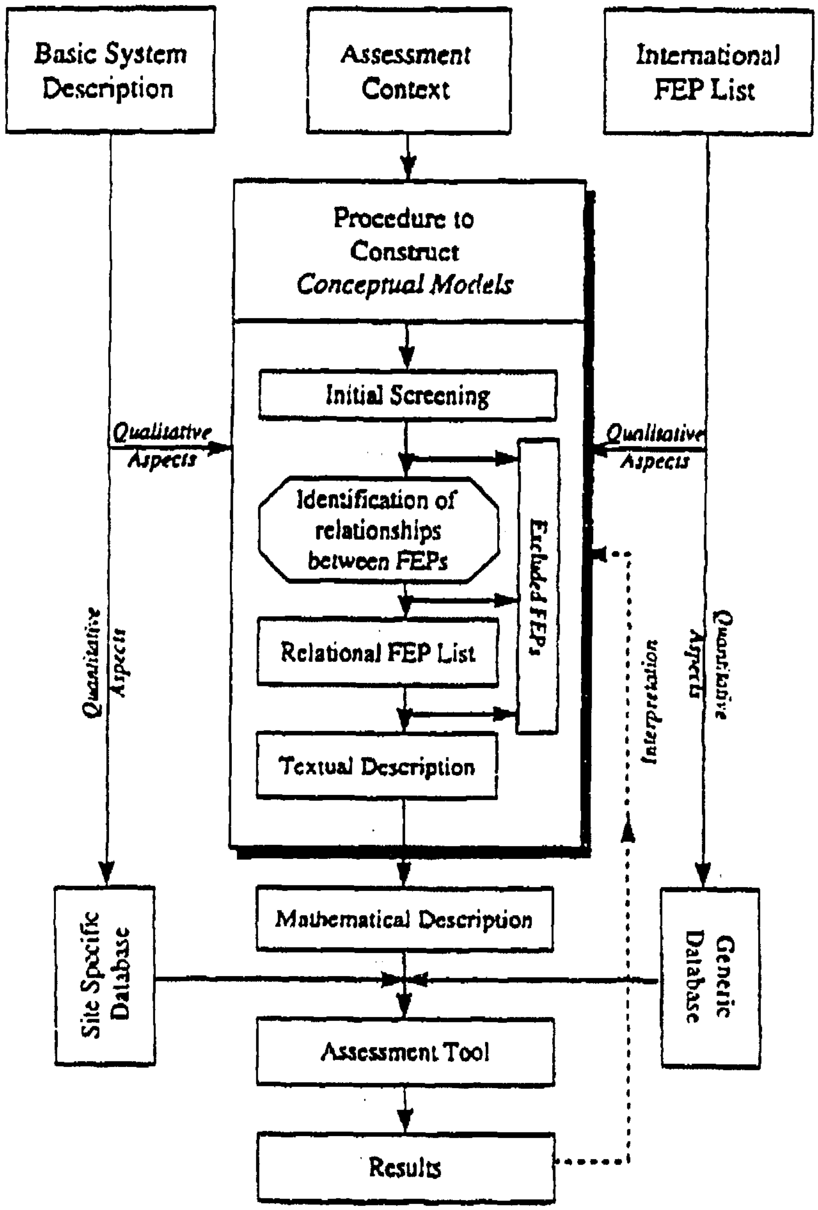

Fig. 1. Illustration of the *Reference Biospheres* methodology. One phase in an iterative process is shown. In practice, the procedure for defining the conceptual model includes the results of previous calculations based on existing mathematical representations and assessment tools (mathematical model plus appropriate database). The development of conceptual models was performed within the Reference Biospheres Working Group, while the implementation of mathematical models for an inland biosphere in a temperate climate is addressed in the Complementary Studies Working Group.

might be left out. The result is an assessment-specific *relational FEP list* of included FEPs and a list of *excluded FEPs* with the reasons for exclusion. *The relational FEP list* forms the basis for the *textual description* or the conceptual model.

Step 4. The *textual description* is developed into the *mathematical description.* A *site-specific database* is defined based on the *basic system description* and a *generic database* is defined consistent with the *international FEP list.* The *assessment tool*, generally a computer code, is developed and finally, calculations produce *results*, which have to be interpreted relative to the *assessment context.*

The methodology described here is applied in several iterations involving one, several or all steps.

The following two subsections of Section 2 discuss the steps that were particularly important in the study as the Working Group discussions showed.

2.1. Critical group definition

ICRP has developed the critical group concept for normal routine releases. In a habit and diet survey of the exposed population, the most exposed groups have to be identified (ICRP, 1977, 1985a, 1991). For solid radioactive waste disposal, because potential releases may occur far in the future, habits and diet cannot be surveyed and the exposed population is hypothetical (ICRP, 1985b). Therefore, the principles have to be adapted. The approaches used in previous assessments as well as regulatory guidance were reviewed (Appendix A2 of BIOMOVS II (1996a) reports the results). The review showed that assumptions vary significantly and harmonisation seems desirable. A new international exercise, Theme 1 in BIOMASS, continues the work initiated here (BIOMASS, 1996). The critical group could be defined as a subsistence agricultural community and, so far, many assessments have implicitly or explicitly used this definition. However, situations can be imagined where other critical group definitions would be required, for example in a tundra climate.

A release into the biosphere will result in a distribution of doses or risks within the exposed populations, with a small number of persons being exposed to relatively high levels and a large number exposed to lower levels. Important are the degree of conservatism and the level of protection required by the authorities. Details of the treatment of FEPs in the calculations depend significantly on the critical group assumptions, for example the size of the modelled biosphere and diet.

2.2. Conceptual model development (procedure to construct conceptual models, see Fig. 1)

Various methods for the identification of relationships between FEPs and the subsequent development of conceptual models or textual descriptions have been tested in national programmes. Examples are the 'influence diagrams' approach (Chapman et al., 1995), the 'rock engineering system (RES)' or 'interaction matrix' approach (Eng et al., 1994; Hudson, 1992; Pinedo et al., 1996; Smith et al., 1996a; Vieno et al., 1994) and 'directed diagrams' (UK-NIREX, 1995). In most assessments published so far, a reverse method has been applied in which the list of relevant FEPs is mapped against previously developed conceptual and mathematical models.

The BIOMOVS II Reference Biospheres Working Group has tested the RES approach and concluded that it can provide a clear overview of the interactions between processes and features to be included in the conceptual model (Fig. 2).

SOURCE TERM		1.2 Contamination	1.3 Contamination	1.4 Contamination	1.5 Contamination	1.6	1.7 No (No gaseous release)	1.8 Yes (Special local release)	1.9	1.10 B.C. (No mediation of the release)	1.11 Yes (Possibly)
PERMANENT SAT. ZONE	2.1		2.3 Flow water + solute (discharge)	2.4 Flow water + solute (discharge)	2.5 Water transport	2.6 Via irrigation Capillary rise	2.7 No	2.8 Irrigation due to human activities	2.9 Drinking water due to human activities	2.1 Use of water	2.11 Ingestion and other water uses
SURFACE WATER	3.1	3.2 Recharge		3.4 Sedimentat. Erosion Diffusion Advection	3.5 Recharge (through river bank)	3.6 Flooding Diffusion Sedimentat. Erosion Irrigation	3.7 Aerosols formation Degassing Evaporation Suspension	3.8 Uptake Irrigation	3.9 Uptake	3.10 Water supply	3.11 Uptake External immersion
SEDIMENT	4.1	4.2 Water + solutes	4.3 Sediment Resuspension		4.5 Conversion Recharge at river bank	4.6 Conversion Dredging	4.7 Aerosols formation Degassing Evaporation	4.8 Uptake External contamination	4.9 Uptake External contamination	4.10	4.11 External and direct contamination
VARIABLE SAT. ZONE	5.1	5.2 Percolation Solid transport	5.3 Exfiltration Discharge Transport of eroded material	5.4 Bank collapse		5.6 Gas Capillary transfer Soil formation	5.7	5.8 Deep root species uptake	5.9 Burrowing species	5.10 Builders land use	5.11 External (digging)
SURFACE SOIL	6.1	6.2	6.3 Erosion Run-off	6.4 Conversion Bank collapse	6.5 Infiltration		6.7 Suspension Evaporation Gas transfer Resuspension	6.8 Uptake Rain splash	6.9 Soil contamination	6.10 Land uses Materials resource	6.11 Direct exposure
ATMOSPHERE	7.1	7.2 No	7.3 Precipitation Deposition	7.4 Wind erosion Rainfall (if dry)	7.5	7.6 Deposition Precipitation Wind erosion		7.8 Deposition Precipitation Snow Rain	7.9 Inhalation Deposition	7.10 Minimal on weather depending	7.11 Inhalation External immersion
FLORA	8.1 Not or very small	8.2 Only for special plants	8.3 Contamination (by leaves)	8.4 Bioturbation Death	8.5 Deep rooting	8.6 Organic Bioturbat. Fertilisation Washout Water upt.	8.7 Exhalation Transpirat. Burning Red, wind speed		8.9	8.10 Viability (Diet and Boundary Conditions)	8.11 Ingestion External
FAUNA	9.1	9.2	9.3 Contamination	9.4 Bioturbation	9.5 Burrowing	9.6 Excretion Bioturbation Burrowing Erosion	9.7 Exhalation	9.8 Consumpt. Fertilising Direct contamination		9.10 Depending on boundary conditions	9.11 Ingestion External
HUMAN ACTIVITIES	10.1 Intrusion (not considered)	10.2 Water extraction Pollution Recharge Treatment	10.3 Water recharge, extraction Pollution Civil eng.	10.4 Dredging Removal	10.5 Pollution Civil engineering (Deep plowing)	10.6 Agriculture Pollution Forestry Construct. Irrigation	10.7 Pollution Filtration Ventilation	10.8 Recycling Storage Burning Making furniture	10.9 Farming Storage Hunting		10.11 Depending on boundary conditions
DOSE TO CRITICAL GROUP	11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9	11.10	

Fig. 2. The Reference Biospheres interaction matrix developed for the Illustration described in Section 4.

A comparison of the FEP list and the matrix of interactions between the most important aspects produced by the RES approach lead to identification of missing elements in each. This process provides confidence in the completeness of the conceptual model, given that absolute completeness can never be proven. A further step in the RES approach is the categorisation of the FEPs and their interactions. This categorisation should take into account the importance for the results and the state of knowledge concerning a FEP or an interaction. FEPs with significant effect on the result and FEPs with an insufficient state of knowledge should get a high priority in the categorisation. This categorisation will often be based on experience, for example from previous assessments, or on expert opinion. The interactions or relationships identified by the RES approach form a *relational FEP list*. The relationships identified in the *relational FEP list* form the textual basis (*textual description* or *conceptual model*) of the equations to be included in the *mathematical description*. Due to time limitations, the Reference Biospheres Working Group could not investigate these relationships.

3. The international biosphere list of features, events and processes

Table 1 shows the structure and the key FEPs of the International Biosphere FEP list developed by the Reference Biospheres Working Group. The Working Group constructed this list (a) for groundwater release from a deep repository at an inland site and (b) in view of the requirement to calculate the annual dose to a representative member of a critical group (representing the *Assessment Context* for the illustration, see Section 4). For other releases, other sites and other Assessment Contexts the FEP list may have to be extended, for example for coastal sites.

This FEP list should provide a comprehensive framework which can be used (a) as a starting point to develop project-specific FEP lists or (b) as a list against which to check the completeness of project-specific FEP lists. Most FEP lists published so far do not systematically contain features such as an *assessment context* and *basic system description*. When comparing models, these features have been shown to contribute significantly to differences between models. An example is the implicit assumptions about the person for whom doses are calculated (critical group definition) and the degree of required conservatism. Therefore, the Working Group has added *assessment context* and *basic system description* at the beginning of the FEP list.

The approach for constructing the International Biosphere FEP list is consistent with the approach of the 'NEA Working Group on development of a data base of features, events and processes relevant to the assessment of post-closure safety of radioactive waste repositories' (NEA, 1998).

4. *An illustration of application of the methodology*

The Reference Biospheres Working Group defined the *assessment context* for illustration of the methodology as one in which the endpoint of interest is the dose to an individual of a critical group. Releases to groundwater from geological disposal at

Table 1
Structure of the International Biosphere FEP list

1	FEATURES
1.1	**assessment context**
1.1.1	assessment purpose
1.1.2	assessment endpoints
1.1.3	repository type
1.1.4	site context
1.2	**source term**
1.2.1	geosphere/biosphere interface
1.2.2	release mechanism
1.2.3	source term characteristics
1.3	**basic system description**
1.3.1	general climate description
1.3.2	general biosphere system description
1.3.3	general human society description
2	EVENTS AND PROCESSES
2.1	**natural events and processes**
2.1.1	environmental evolution
2.1.1.1	environmental dynamics
2.1.1.2	climate-driven changes
2.1.2	radionuclide transport
2.1.2.1	atmospheric transport processes
2.1.2.2	surface water aqueous transport processes
2.1.2.3	porous media aqueous transport processes
2.1.2.4	transport processes between surface waters and porous media
2.1.2.5	solid phase transport
2.1.2.6	dual flow systems
2.1.2.7	transport mediated by flora and fauna
2.1.3	processes affecting radionuclide concentrations
2.1.3.1	chemical reactions
2.1.3.2	physical processes
2.1.4	radionuclide metabolism
2.1.4.1	crops and natural, semi-natural flora
2.1.4.2	livestock and natural, semi-natural fauna
2.2	**events and processes related to human activity**
2.2.1	chemical changes by human action
2.2.2	physical changes by human action
2.2.3	recycling of materials and mixing by human action
2.2.4	radionuclide transport mediated by human action
2.3	**events and processes related to human exposure**
2.3.1	human habits
2.3.1.1	resource usage
2.3.1.2	storage of products
2.3.1.3	air, water and food processing
2.3.1.4	location and shielding factors
2.3.1.5	diet
2.3.2	external exposure processes
2.3.3	internal exposure processes

an inland valley site form the main component (source term) of the *basic system description*. The illustration is based on the Complementary Studies case (BIOMOVS II, 1996b). The climate is as at present (*basic system description*). The society in which the dose or risk to an average individual of the critical group is to be calculated is a subsistence community in a mountain valley. Such a community makes significant use of natural (e.g. forests) and semi-natural environments (e.g. alpine meadows). However, the databases for such environments are not yet complete (mainly Cs data are available) and have not yet been evaluated for radioactive waste disposal. Therefore, only agricultural environments could be included at this stage.

The Reference Biospheres Working Group has applied the methodology from the beginning to the construction of a *relational FEP list*. The Complementary Studies Working Groups started with the *textual description*, checked that the FEPs identified by the Reference Biospheres Working Group were included and proceeded with the methodology, finally producing results, doses to individual members of the defined critical group. The step from *relational FEP list* to *textual description* was only superficially investigated.

The exercise of defining the example illustration identified several points. When describing a generic system, it is difficult to simplify and to justify the simplification. Simplification is only justified if it either does not significantly effect the result or produces a more conservative result. In an early stage the Reference Biospheres Working Group tried to delete unimportant FEPs from the generic FEP list, but no such FEPs could be identified. Useful screening is possible given a particular assessment context and a FEP management procedure such as the Interaction Matrix.

The systematic application of the suggested methodology did make the definition of the example illustration straightforward and easy, although the result was not a simple model. This was possible due to the careful definition of the *basic system description* and the *assessment context* and, in particular, of the critical group. Analysing existing databases for the assessment of radioactive waste disposal showed that the requirements to be fulfilled by these data bases have not been sufficiently well defined; particularly important are (a) the potentially large number of relevant radionuclides or elements, (b) the long time scales for which the data should be applicable, (c) the fact that effective data are often required, for example by averaging recurring events (e.g. once-in-a-century flood) into processes and (d) the uncertainties, variabilities and averages relating to the temporal and spatial scale which are relevant for the assessment. Although the definition of the critical group as a self-sustaining agricultural community should include the use of natural and semi-natural environments, no relevant reviewed databases exist.

5. Summary and suggestions for future work

Conclusions (for details see BIOMOVS II, 1996a, b) from the study are

The methodology and the FEP list developed by the Reference Biospheres Working Group form a possible common approach to biosphere modelling, which should help to harmonise the approaches used in the different organisations.

The discussions showed that the same words often have a different meaning and that different words the same meaning for different persons. This is particularly pronounced in a more philosophical exercise such as the description of a methodology for assessments. Astonishingly, it was much easier to construct a biosphere model by applying the proposed methodology, than to define and document the principles. The authors apologise for any remaining confusion in terminology in this paper.

The formulation of simple, defensible models is not an easy task and in particular, the definition of generic biospheres is not straightforward. However, using the methodology (a) an audit trail can be documented, which facilitates the detailed scrutinising of all steps in a specific assessment and (b) differences in modelling will be reduced, or, if they still exist, will be better explained.

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BIOMOVS II and, in particular, the Working Groups on Complementary Studies and Reference Biospheres have laid the basis for harmonisation in the approaches for biosphere modelling. Smith et al. (1996b) have applied and demonstrated the viability of the Reference Biospheres methodology. Many of the tasks of the Reference Biospheres Working Group could be delegated to participants and results discussed in plenary. This demonstrated that international cooperation can be much more efficient than multiple individual efforts.

The Working Groups suggested the following further studies:

- Refinement of the steps in the methodology concerning (a) the definition of hypothetical critical groups and (b) the definition of criteria for databases to be used as input in assessments.
- Implementation of the methodology used to derive Reference Biosphere descriptions additional to the one of the example, including the derivation and testing of databases.
- Augmentation of the methodology to incorporate specific issues, for example the effects of transitions between climates, the effects of landscape evolution, and to evaluate the importance of different exposure pathways.

Theme 1 of the new international exercise BIOMASS (BIOMASS, 1996) has taken up these suggestions.

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