
Biosphere Modeling for Solid Radioactive Waste Disposal - International Perspective Based on IAEA Sponsored BIOMASS, EMRAS and EMRAS II Programs

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Outline

• Introduction
• Reference biosphere methodology for development of assessment biospheres
• Example reference biospheres
• Sources of uncertainty
• Model validation
• Overview of IAEA-sponsored international biosphere modeling programs
Geosphere and Biosphere Components of PA

• Performance assessment (PA) – evaluation of how well the repository’s engineered and natural barrier systems are projected to perform in their capacity to retain or retard the migration of radionuclides to the accessible environment through the specified period following disposal.

• In most assessments, performance is evaluated in terms of the radiological dose to a defined human receptor or to a population.

• Because the exposure is projected to occur in the future, the evaluation of the doses involves combining the analyses of the performance of the natural and engineered barriers with the stylized exposure scenario involving a future population.
Biosphere Model Role in PA

- Biosphere model - Representation of the human exposure scenario, including the environmental transport pathways and human exposure pathways.
- Converts radionuclide releases from the geosphere to dose or risk to individuals or populations.
- Provides the means of measuring repository performance and comparing it to the performance standards established by the regulator.
- Prospective assessment – to demonstrate that the releases will result in doses or risks that are less than regulatory limits; analyses of this type typically use many conservative assumptions.
Biosphere Model Role in PA (continued)
Assessing Impact of Radionuclide Releases

• The public exposure and environmental impact of releases of radionuclides from nuclear facilities are typically assessed with the use of models.
• Different levels of model complexity from relatively simple, generic, screening models to very complex, site-specific models of the biosphere systems.
• The formal methodology for development of assessment biospheres was introduced in the BIOMOVS project, further refined by BIOMASS project, and is now continued in EMRAS II project.
Formal Methodology for Developing Biosphere Models

• Formal biosphere methodology provides a step-by-step roadmap for developing an assessment biosphere (biosphere model) that is relevant and appropriate for a given assessment context.

• Mistake made by many modelers - Underlying premises of a biosphere assessment taken for granted at early stage of model development leading to failure to prove model appropriateness/sufficiency later on, or to provide an “audit trail”.

• Using a formal methodology ensures logical and defensible construction of assessment biospheres, and that assessment biospheres are appropriate for their intended purpose.

• The methodology includes practical examples of reference biosphere.

Reference Biospheres Methodology

Defining the assessment context

Identification and justification of biosphere systems

Biosphere system description

Consideration of potentially exposed groups

Model development

Development of biosphere models for radioactive waste disposal assessment is an iterative process. After performing calculations, the next model iteration is done.
Defining Assessment Context

• The “assessment context” answers fundamental questions about the performance assessment, namely: (a) what are you trying to assess/calculate, and (b) why are you trying to assess it/calculate it?

• The overall assessment context defines the role and the form of the biosphere component.

• Purpose of the assessment
  • Demonstrate compliance with regulatory requirements
  • Contribute to confidence of the public/policy makers/scientific community
  • Guide research priorities
  • Guide site selection
  • System optimization
Defining Assessment Context (continued)

- Assessment endpoint (what is the final outcome)
  - Individual risk/dose
  - Collective risk/dose
  - Distribution/concentration of repository radionuclide in the environment
  - Dose to non-human biota
- Fluxes into or through part of the biosphere
- Site context
  - Has the site been selected (site specific assessment), or is the assessment generic, i.e., could be applied to any site?
  - Spatial extent, surface topography, current climate, soil types, fauna, flora, surface water bodies, near-surface aquifers
Defining Assessment Context (continued)

- **Assessment timeframe**
  - From closure to 100 years
  - From 100 to 10,000 years
  - From 10,000 to 1,000,000 years
  - Beyond 1,000,000 years

- **Representation of changes in the biosphere, e.g., climate change, site evolution, societal changes.**

- **Societal assumptions**
  - Intensive or extensive farming and use of modern technology
  - Simple technology associated with subsistence farming
Defining Assessment Context (continued)

• Assessment philosophy – defines the approach to the treatment of irreducible uncertainties through basic assessment assumptions and modeling choices.
  • Cautious (conservative assumptions, assessment focused on very few individuals who receive the highest doses)
  • Equitable (risk from radioactive waste disposal regulated to the same level as other risks that the society currently tolerates; exposure groups defined on a wider, less pessimistic basis)

• Definition of the source term and the geosphere-biosphere interface
  • Well
  • Water body (e.g., lake, river)
  • Below-surface soil
  • Volcanic eruption (considered for Yucca Mountain)
  • Release rates
Identification and Justification of Biosphere Systems

• Review assessment context
• Select principal components of interest and principal component types of the initial biosphere
  Examples of principal components and component types:
  • Climate and atmosphere (at a minimum define climate state, e.g., arid, temperate, boreal)
  • Near-surface lithostratigraphy – Rocks and their types, e.g., sedimentary rocks; soils and their types, e.g., sierozems
  • Topography, e.g., inland, upland, plain, fluvial erosion
  • Water bodies, e.g., natural, e.g., lakes; artificial, e.g., reservoirs; subsurface water bodies
  • Biota – ecosystem classification, e.g., terrestrial ecosystems
  • Human activities (human community types based on socioeconomic and environmental control considerations)
• Consider the need for biosphere change
Identification and Justification of Biosphere Systems (continued)

Decision tree for use in the identification and justification of biosphere systems
Biosphere System Description

Provide practical and self-consistent stylized description of biosphere system such that the principal components of the biosphere system components are represented in the assessment model and are broadly coherent.

Step 1 – Selection of relevant characteristics of identified principal components of biosphere system.
Step 2 – Establish interrelations between the types of biosphere system principal components.
Step 3 – Provide a basic qualitative description of the biosphere system.

Systematic consideration of potentially relevant FEPs is used to confirm validity of system description.
Consideration of Potentially Exposed Groups

- Assumptions regarding the behavior of human communities are fundamental to the evaluation of radiological exposure as well as the definition of future biosphere systems.
- The concept of critical group – originally introduced to address the problem of setting quantitative limits on present day and near future releases of radionuclides.
- Critical group as a subset of the population that because of their location, diet, life style, work, physiological factors receives higher exposures than the other members of the exposed population.
- More than one critical group may be initially considered; the most exposed of the candidate groups becomes the critical group used in the assessment.
Biosphere Model Development

Conceptual Model

• Development of conceptual model by taking into account the range of FEPs.
• International list of FEPs
• The starting point is a description of the biosphere system in which exposures could take place
  • Identify the biosphere system principal component types that will be modeled as separate conceptual model objects (media) in the representation of radionuclide transport, e.g., atmosphere, soil, crops, farm animals
  • Devise a conceptual model of radionuclide transport between these objects (the use of interaction matrices is helpful in clarifying the interactions between the objects)
  • Ensure that all relevant FEPs are adequately addressed (provide a coherent justification for screening FEPs in the conceptual model)
Simplified interaction matrix representation of a conceptual model in a biosphere system based on an agricultural well

<table>
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<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SOURCE (groundwater)</td>
<td>Irrigation</td>
<td>Evaporation</td>
<td>Irrigation interception</td>
<td>Ingestion of water</td>
<td>Bio-accumulation (water use in fisheries)</td>
<td>Drinking water ingestion</td>
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<tr>
<td>2</td>
<td>Leaching</td>
<td>SURFACE SOIL</td>
<td>Particle resuspension, gas release, soil erosion</td>
<td>Root uptake</td>
<td>Soil ingestion</td>
<td>—</td>
<td>Soil ingestion, external exposure</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>Dust deposition</td>
<td>AIR</td>
<td>Dust deposition, photosynthesis</td>
<td>—</td>
<td>—</td>
<td>Inhalation of particulates, gases, and aerosols</td>
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<tr>
<td>4</td>
<td>—</td>
<td>Weathering, harvest removal</td>
<td>—</td>
<td>PLANTS (crops)</td>
<td>Ingestion of feed</td>
<td>—</td>
<td>Crop ingestion</td>
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<tr>
<td>5</td>
<td>—</td>
<td>Fertilization</td>
<td>—</td>
<td>—</td>
<td>ANIMALS (animal products)</td>
<td>—</td>
<td>Animal product ingestion</td>
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<tr>
<td>6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>FISH</td>
<td>Fish ingestion</td>
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<td>7</td>
<td>—</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>HUMAN (receptor)</td>
</tr>
</tbody>
</table>
Mathematical Model

• Mathematical representation of environmental transport processes (i.e., how radionuclide migrate through the environment and accumulate in the environmental media) and of the consequent human exposure pathways.

• Modeling tool does not need to be specific to biosphere assessment (e.g., GoldSim)

• Mathematical representation of many processes does not have to be explicit (i.e., the models does not need to be mechanistic); rather, it can be based on an empirical model of effects observed at a system level.

• All mathematical models require data but the number of model input parameters and the underlying data increases steeply as the models become more complex.

• Development of mathematical models should include consideration of the extent and form of available data.
Illustration of Reference Biospheres

BIOMASS Methodology

Example Reference Biospheres

- Example biospheres were developed by applying reference biosphere methodology to the assumed assessment context
  - Practical examples that demonstrate how biosphere models for long term assessment (assessment biospheres) can be developed
  - Can be used as a starting point to guide the development of the assessment biospheres for a given assessment context
  - Using example biosphere provides some assurance that over the very long term a reasonable level of caution has been adopted to determine system performance
  - Have been used to investigate the implications of adopting different assumptions in the biosphere model development
Example Reference Biospheres (cont.)

- Example (generic) reference biosphere may be used as “standard measuring instruments”, however it is expected that the assessment biospheres used in long-term performance assessment will include an appropriate mix of site-specific and generic elements.

- Example reference biosphere are a valuable tool, but should be used with caution in conditions which may conflict with the components of the assessment context that were used to develop the example biosphere.
BIOMASS developed several Example Reference Biospheres (ERB) to consider a range of potential issues of interest in the context of solid radioactive waste disposal for a variety of hypothetical assessment contexts.

- Drinking water well ERB
- Agricultural well ERB
- Natural release of contaminated groundwater to the surface environment ERB
Sources of Uncertainty – Model Uncertainty

- The choice of a model to represent a given process
  - Adequacy of the conceptual model
  - Approximations and assumptions made during development of mathematical model
  - Quality and appropriateness of the input data
  - Uncertainty in parameter values

Comparison of model predictions with measurements for the vertical distribution of Cs-137 in the soil

Sources of Uncertainty – Parameter Uncertainty

- Measurement errors
- Genuine stochastic nature of some parameters
- Difference between field and laboratory data
- Parameter dependence on factors that were not controlled during measurements or estimations
- Large spatial and temporal variation in parameter value
- Lack of observational data for a parameter
- Failure to account for correlations between parameters
- Use of values obtained under conditions different from those set by the assessment context
- Use of parameters outside their range of applicability
- Inappropriate use of generic values
- Errors made by the modeler, who may not be familiar with the determination of parameter values
The Biospheric Model Validation Study - Phase II (BIOMOVS II) was an international cooperative program that tested the accuracy of predictions of environmental assessment models. The efforts to quantify the confidence that can be placed in model predictions are usually concentrated on a statistical propagation of the influence of parameter uncertainties on the calculation results. Other sources of uncertainty are more difficult to quantify and frequently not even recognized. Model performance depends critically, not only on the formulation and parameter values of the model itself, but also on the experience and assumptions made by the user.
Effect of user interpretation of uncertainty estimates was investigated by BIOMOVS II (Technical Report No. 7). Up to 10 modeling teams were using terrestrial food chain models using three codes for three scenarios.

For any set of predictions, the variation in best estimates was greater than one order of magnitude.

Choice of parameter values contributed most to user-induced uncertainty; scenario interpretation was the second source of uncertainty.

The 95% confidence intervals about the predictions calculated from parameter distribution did not always overlap the observations.
Uncertainty and Validation (continued)

- Effect of model complexity on Uncertainty Estimates was investigated by BIOMOVS II (Technical Report No. 16).
- Models of varying complexity have been applied to the problem of downward transport of radionuclides in soils.
- Seven modeling team participated using 13 different models ranging in complexity from analytical solutions of a 2-box model using annual average data to numerical models coupling hydrology and transport using data varying on a daily basis.
- The complex models are often impractical to use in safety assessments for modeling biosphere transport; instead simpler model, e.g., box models are preferred. Predictions in many cases are similar, e.g., evolution of radionuclide concentration in the root zone. However, on other cases, the differences of many orders of magnitude can appear, e.g., prediction of the flux to the groundwater of radionuclides transported through the soil column.
Data Selection: Generic vs. Site-Specific Values

- Site-specific information about physico-chemical forms of the radionuclides, their environmental speciation and transport, and the biokinetic behavior may substantially improve the reliability of radiological assessments.
- The lack of data and experience of assessors, as well as the financial and technical limitations very often lead to the application of generic models and general parameter values.
- In the absence of site-specific information it is sometimes difficult to decide on the value that a parameter should have.
• You are not alone!

• Several international programs were initiated to develop and improve capabilities to predict transport of radionuclides in the environment, including model development and validation, data selection, process modeling, sources of uncertainty, etc.

• VAMP, Validation of Model Predictions, 1988-1996

• BIOMOVS and BIOMOVS II (sponsored by the Swedish Radiation Protection Institute)

• BIOMASS, BIOsphere Modelling and ASSessment, 1996-2001

• EMRAS, Environmental Modeling for Radiation Safety, 2003 to 2007

• EMRAS II – ongoing (2009 – 2011)
VAMP

- VAMP, Validation of Model Predictions, 1988-1996 – Validation of environmental transport model predictions in terrestrial, aquatic and urban environments
- Several VAMP publications are available either on-line or may be ordered from the IAEA's Publications Section
BIOMASS

- BIOMASS. BIOsphere Modelling and ASsessment, 1996-2001
- Developing and improving capabilities to predict the transport of radionuclides in the environment
- Theme 1: Radioactive Waste Disposal – the objective was to develop the concept of a reference biosphere for application to the assessment of the long-term safety of radioactive waste repositories
- Theme 2: Environmental Releases – increasing the confidence in methods and model used for radiological assessment in the context of dose reconstruction and remediation activities
- Theme 3: Biosphere Processes – improving capabilities for modeling radionuclide transport in parts of biosphere identified as being of radiological significance
- BIOMASS publications are available at IAEA web site.
EMRAS

• EMRAS, Environmental Modeling for Radiation Safety, 2003 to 2007
• Continued some of the work of previous international programs in the field of radioecological modeling.
• Focused on areas where uncertainties remain in the predictive capability of environmental models, notably in relation to the consequences of releases of radionuclides to particular types of environment (e.g. urban and aquatic environments) restoration of sites with radioactive residues and impact of environmental radioactivity on non-human species.
International Programs sponsored by IAEA

EMRAS (continued)

• Theme 1: Radioactive Release Assessment
  • The revision of the IAEA handbook of parameter values for the prediction of environmental transfer of radionuclides (TRS-472; IAEA-TECDOC-1616).
  • Model testing related to countermeasures applied to the intake of $^{131}$I from the Chernobyl accident.
  • Testing of models for tritium and $^{14}$C from routine and accidental releases.
  • Testing of models for predicting the behavior of radionuclides in fresh water systems and coastal areas.

• Theme 2: Remediation Assessment
  • Testing of models for the remediation of the urban environment; and
  • Modeling the transfer of radionuclides from naturally occurring radioactive material (NORM).

• Theme 3: Assessment Related to Protection of the Environment
  • The review of data and testing of models for predicting the transfer of radionuclides to non-human biological species.

EMRAS II

- Continues the work on the improvement and testing of environmental assessment models (BIOMOVS, BIOMOVS II, VAMP, BIOMASS and EMRAS)
- The general aim of the EMRAS II Program is to improve capabilities in the field of environmental radiation dose assessment by means of acquisition of improved data for model testing, comparison, reaching consensus on modeling philosophies, approaches and parameter values, development of improved methods and exchange of information.
  - Working Group 1: Reference and Graded Approaches for Assessing the Impact of Radioactive Discharges
  - Working Group 2: Reference Approaches for Assessing the Radiation Doses to Biota
  - Working Group 3: Assessment after Emergency Situations
  - Working Group 4: Integrated Assessment

Summary

• Assessment biosphere is a component of performance assessment model that converts radionuclide releases from the geosphere to dose or risk to individuals or populations.

• Internationally-developed methodology can be used to develop assessment biosphere used in performance assessment.

• Although an example reference biosphere can be used as a starting point, for the long-term assessment a site-specific biosphere should be used.

• Choices made during model development with regard to conceptual and mathematical models, and input data may result in very large differences in model predictions.