Transparency in the Selection of Biosphere Parameters for Geological Disposal Systems –11515

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ABSTRACT

Performance assessments require a large number of parameters, many of which are element specific. The data that support this modeling are limited or nonexistent and the selection of model parameters is challenging. The parameters chosen for one recent performance assessment are investigated and the sources of the original data are examined. Of the 538 parameters followed, 139 (26%) reference at least one peer-reviewed article, 210 (39%) reference an institutional publication, 140 (26%) have no reference, and 49 (9%) are justified or derived internally by the case study's authors. The need for transparency in this process and straightforward methods for making parameter choices are discussed.

INTRODUCTION

Modeling the transfer of radionuclides from the abiotic to the biotic environment is an essential component of performance assessments for geological disposal systems; it is only when migrating radionuclides reach animals and plants that they begin to assert a deleterious effect and pose a risk to people. Performance assessments rely on element specific parameters to describe how each nuclide will migrate out from a repository and behave in the biosphere. The fact that data are limited for many radionuclides has not constrained predictions of transfer across a wide range of species and environments where site or nuclide specific data are lacking. The fact that predictions may have been based on chemical surrogates, dissimilar species, or expert judgement often is lost in the fine print of appendices, and the uncertainty surrounding an estimate obscured. This work briefly reviews; standard methods of biosphere modeling, the data supporting that modeling, and the EPRI IMARC Performance Assessment of Yucca Mountain as a case study in how a lack of data has been coped with in the past. The paper closes with a discussion about dealing with a lack of appropriate data in a transparent manner.

BIOSPHERE MODELING

Recent years have seen the development of modeling efforts designed to predict the doses to future human communities that may result from long term geological disposal of radioactive wastes. The formal process of assessing the safety of a repository is known as performance assessment. This involves an extremely sophisticated modeling effort, Miller et al. [1] describe the process as having the following steps:

> "1) Construction of a conceptual model which describes the system and includes all of the important processes and their couplings;

2) Translation of the conceptual model into a mathematical model and coding in the form of a computer program;
3) Verification of the numerical 'correctness' of the code;
4) Validation of the code's 'applicability' to the repository system to assess its predictive capabilities."

Miller et al. [1] break down a performance assessment into a sequential chain of models, models of: canister corrosion, waste dissolution, near-field diffusive transport, far-field transport, release to the biosphere, and uptake by humans. This paper focuses on biosphere submodels, but many of the concerns raised here will likely be of concern in other submodels as well. As seen in Fig. 1, these models break down the doses resulting from each nuclide separately and many of the parameters used in the models are element specific as the chemical properties of different elements significantly affect their transport, both subsurface and in the biosphere.

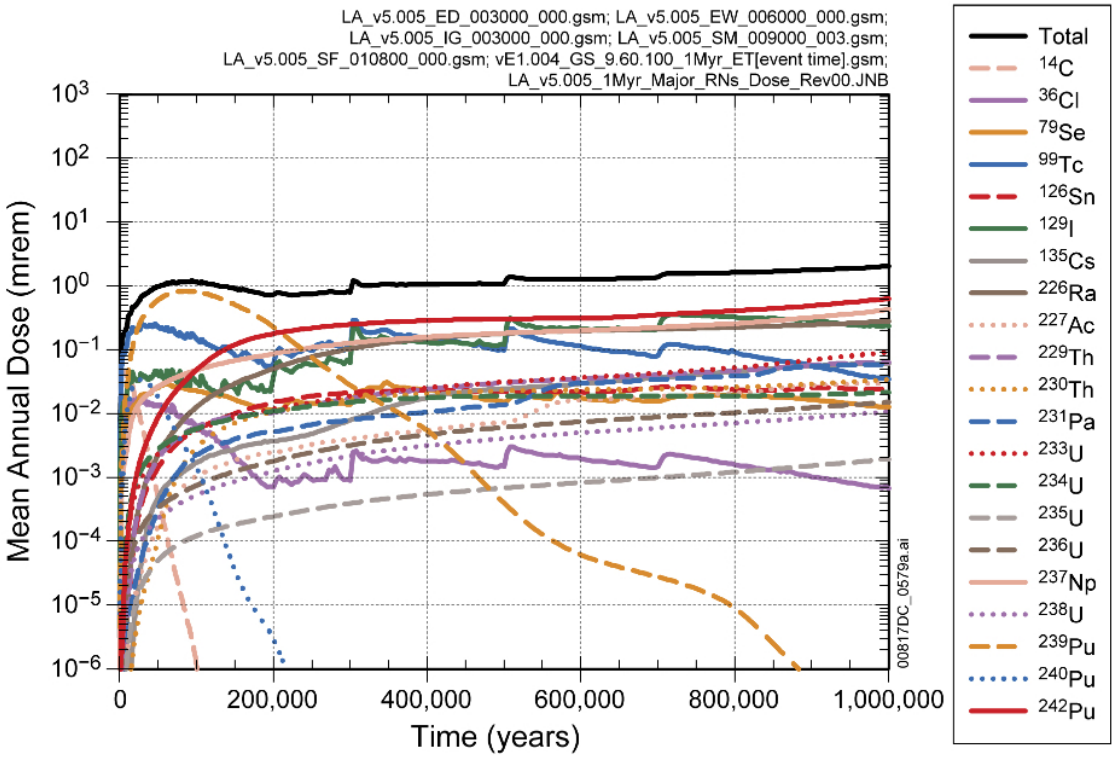


Fig. 1. Predicted Mean Annual Dose from the OCRWM's Total System Performance Assessment of Yucca Mountain [2].

Biosphere models are most often based on empirical concentration ratios and transfer factors, which predict radionuclide levels in biota based on their levels in the environment or the animal's diet. Concentration ratios refer to the ratio of a radionuclide's concentration in soil and plant. Transfer factors relate radionuclide concentrations in an animal's diet with the concentration in food products produced from the animal.

Some of the major features of the biosphere model used in one specific case, the EPRI IMARC model [3], are discussed below. This model is used to calculate concentrations of radionuclides in crops and animal products. These are widely adopted methods; the ERB2A model from the IAEA's BIOMASS program uses substantially identical equations [4].

Conventional models take foliar interception, (the interception by leaves of contaminated irrigation water) into account with a term that follows the concentration factor term. The concentration in the plant is the sum of contributions from root uptake and uptake as a result of interception.

$$C_{\text{crop}} = C_{\text{root uptake}} + C_{\text{foliar interception}} \quad \text{(Eq. 1)}$$

Where:

- C_{plant} is the radionuclide concentration in the crop, Bq kg^{-1},
- C_{root} is the radionuclide concentration in the plant attributable to root uptake, Bq kg^{-1},
- $C_{intercept}$ is the radionuclide concentration attributable to intercepted activity, Bq kg^{-1}.

$$C_{\text{root uptake}} = \frac{(F_{\text{p2}} CF_{\text{crop}} + F_{\text{p1}} S_{\text{crop}}) C_{\text{soil}}}{(1-\theta_{\text{t}})\rho} \quad \text{(Eq. 2)}$$

Where:

- CF_{crop} is the concentration ratio from root uptake for the crop, Bq kg^{-1} (fresh weight of crop) / Bq kg^{-1} (dry weight of soil),
- S_{crop} is the soil contamination on the crop, kg (dry weight soil) kg^{-1} (fresh weight of crop),
- θ_t is the total porosity of the cultivated soil compartment,
- ρ is the grain density of the cultivated soil compartment, kg m^{-3},
- F_{p1} is the fraction of external soil contamination on the edible part of the crop retained after food processing,
- F_{p2} is the fraction of the internal contamination associated with the edible part of the plant at harvest that is retained after food processing.

$$C_{\text{interception}} = I_{\text{crop}} V_{\text{irr}} C_{\text{water}} \left(\frac{(1-F_{\text{abs}}) e^{-WT} F_{\text{p3}}}{Y} + \frac{F_{\text{abs}} F_{\text{p2}} F_{\text{transloc}}}{Y} \right) \quad \text{(Eq. 3)}$$

Where:

- I_{crop} is the fraction of radionuclide in irrigation water that is initially deposited on standing biomass,
- V_{irr} is the rate of irrigation water applied to the soil, $m^3m^{-2}y^{-1}$,
- C_w is the radionuclide concentration in the well water, mol m^{-3},
- F_{abs} is the fraction of intercepted radionuclide initially deposited onto the plant surface that is absorbed from external surfaces into plant tissues,
- W is the removal rate of radionuclides deposited on plant surface by irrigation by weathering processes, y^{-1},
- T is the interval between irrigation and harvest, y,
- F_{p3} is the fraction of external contamination from interception that is retained on the edible part of the crop after food processing,
- $F_{transloc}$ is the fraction of absorbed activity that is translocated to the edible portion of the plant by the time of harvest,
- Y is the wet weight biomass of the crop, kg m^{-2} y^{-1}, obtained at harvest from the unit area irrigated.

Concentrations in meat and other animal products such as milk, cheese, and eggs, are calculated using transfer factors which are empirical measures relating the quantities of a radionuclide ingested by an animal to the concentrations present in food products derived from the animal. The example below considers the animal to consume only fodder but the method is easily extensible to consider a variety of diets.

$$C_{\text{animal\_product}} = TF_{\text{product}}\left(C_{\text{fodd}} ING_{\text{fodd}} + C_{\text{water}} ING_{\text{water}} + \frac{C_{\text{soil}} ING_{\text{soil}}}{(1-\theta_{\text{t}})\rho + \theta\rho_{\text{w}}} \right) \qquad \text{(Eq. 4)}$$

Where:

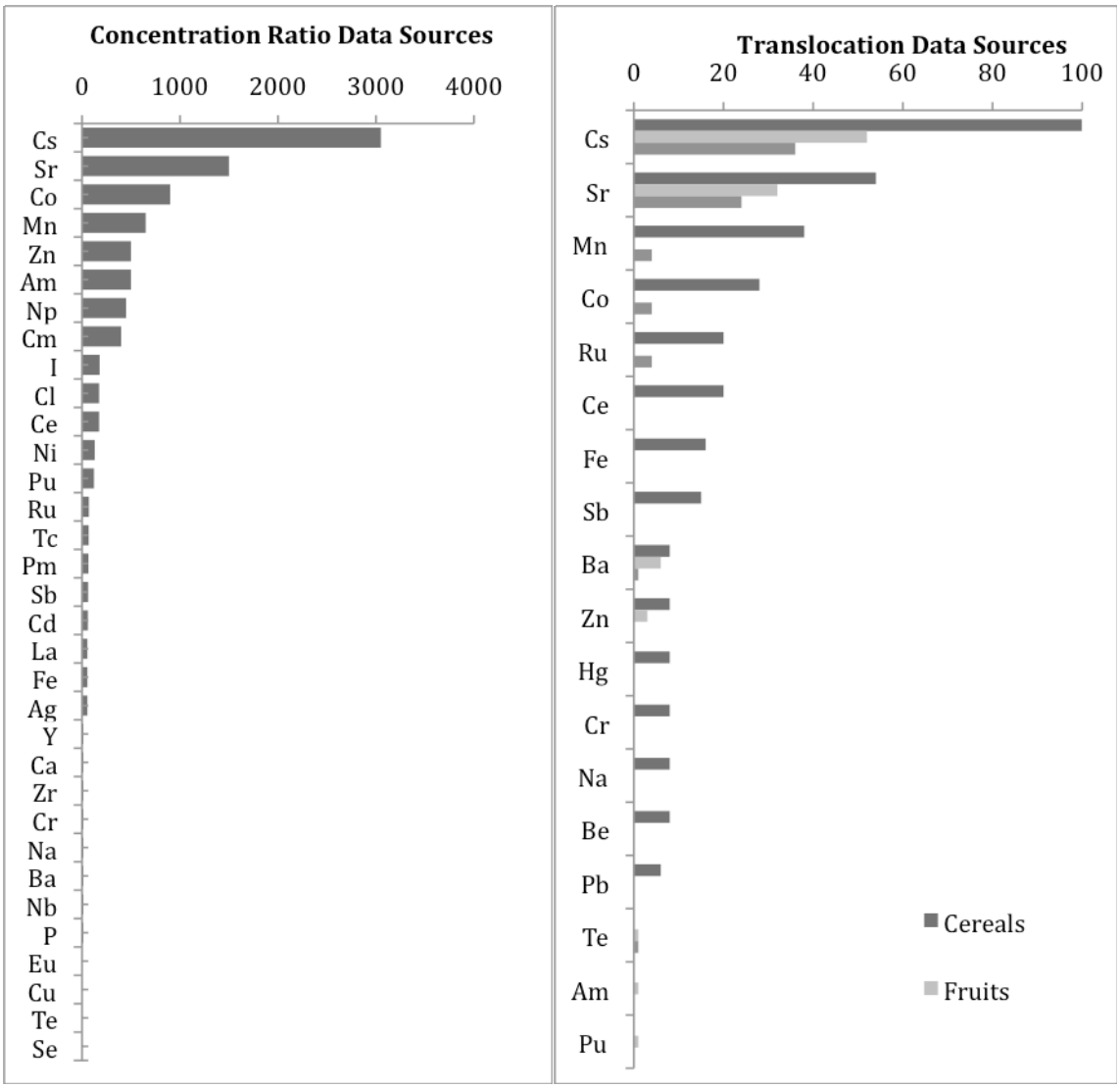
- TF_{product} is the transfer factor (d kg^{-1} fresh weight of product) for a specific animal product (i.e. milk, beef, eggs) associated with ingestion of contaminated food and water,
- C_{fodd} is the radionuclide concentration in the fodder (Bq kg^{-1}),
- ING_{fodd} is the ingestion rate of fodder by the animal from which the animal product is derived (kg d^{-1}),
- ING_{water} is the ingestion rate of water by the animal from which the animal product is derived (m^3 d^{-1}),
- C_{soil} is the radionuclide concentration in soil (Bq m^{-3}),
- ING_{soil} is the ingestion rate of soil by the animal (kg d^{-1}) from which the animal product is derived,
- θ is the water-filled porosity of the soil,
- ρ_{w} is the density of water (kg m^{-3}).

DATA SUPPORTING BIOSPHERE MODELING

The process of selecting parameter values for use in performance assessments is challenging for two primary reasons; the first is whether there is any credible and referenceable data in the literature for the appropriate parameter and the second is whether any data that do exist are appropriate to the repository in question. Uptake in biological systems varies widely and care should be taken when using numbers gathered under certain conditions in a certain location in other contexts. This section will illustrate the difficulty involved in these questions with data from the 2009 IAEA-TECDOC-1616: Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments [5].

Fig. 2 illustrates the variation in the quantity of concentration ratio data for different nuclides. Cs and Sr in particular are well studied, but many nuclides, including some nuclides considered as posing a risk from waste repositories are practically unstudied. It should be noted that this figure does not break down the data by quality, and even where some data exist the question of applicability still remains.

Fig. 3 takes another element dependant parameter, the translocation factor, which was defined above as the fraction of absorbed activity that is translocated to the edible portion of the plant by the time of harvest. Many crop related parameters are not only nuclide specific but are also broken into several broad classes of crop types such as root vegetables, green vegetables, grains, and fruits. This can increase the number of element specific parameters required by a factor of four, yet an examination of Fig. 3 shows that The data to support these distinctions is hard to come by. Again it should be emphasized even where data do exist, their applicability to the problem at hand is not assured.



Figs. 2 and 3. Sources of Concentration Ratio data by element and Sources of Translocation Factor data by element and plant type. (Data from IAEA [5], with permission)

Fig. 4. is a representative section of another table from the same recent IAEA-TECDOC, it illustrates the extent of transfer factor data available for a variety of animal derived food products. For cells shaded in gray no data is available.

Element	Beef	Sheep meat	Goat meat	Pork	Poultry	Egg	Cow milk	Goat milk
Ag		1						
Am	1	1				1	1	2
Ba	2		1		2	1	15	3
Be							1	
Ca	3				2	1	15	12
Cd	8	1			2		8	1
Ce		1				1	6	1
Cl	1							
Co	4	2			2	2	4	1
Cr							3	2
Cs	58	41	11	22	13	11	288	28
Fe	4			1		2	7	St
I	5	1		2	3	4	104	24
La	3							
Mn	2	1		1	2	3	4	St
Mo	1				1	3	7	4
Na	2	1			1	2	7	St
Nb	1		1		1	1	1	1
Ni							2	2
Np								1
P	1			1		1	St	St
Pb	5	2					15	
Po					1	1	4	2
Pu	5	2				2	n/a	

Fig. 4. Availability of Transfer factor data (from IAEA [5], with permission)

CASE STUDY: EPRI IMARC PERFORMANCE ASSESSMENT

Given the paucity of data displayed in the previous section the challenge of parameter selection in performance assessment is clear. How is it possible to produce the results of Fig. 1 when for many of the studied nuclides, insufficient data exist on which to base parameters? This section examines the sources of parameters used in the most recent iteration of the EPRI IMARC model by attempting to track all values to their original sources: a difficult task as EPRI often cites its previous reports as its sole source. 538 data points, representing uptake parameters for thirteen nuclides, were tracked.

The process began with a thorough review of EPRI [3]: model parameters were tabulated by nuclide and subtype (e.g., the absorbed fraction of iodine in fruit) and citations documented. A not-insignificant fraction of the parameters from EPRI [3] cite no source or EPRI [6] alone as their sole source (227, 42%). A second fraction (198, 37%) reference EPRI [6] in addition to a more recent publication by another organization

(usually BIOPROTA or IAEA) but had no reference to a peer-reviewed journal article. The remainder (113, 21%) cite outright at least one peer-reviewed paper.

Parameters that cite EPRI [6] in EPRI [3] were located in EPRI [6] and references checked. Of the EPRI [6] citations that reference only EPRI [3], 170 (75%, or 32% of the total data set) have no reference or reference only EPRI [7]. Additionally, 26 (12%, or 5% of the total data set) are justified or modeled by the authors. The remaining 31 (13%, or 6% of the total data set) values reference a peer reviewed article or an institutional publication.

Finally, citations in EPRI [6] that reference EPRI [7] were reviewed. Of these 170 citations, 140 (82%, 26% of the total data set) were found to contain no reference while 23 (14%, or 4% of the total data set) are derived or justified in document and 7 (4%, or 1% of the total set) reference a peer reviewed publication.
Of the 538 parameters followed across this study, 139 (26%) reference at least one peer-reviewed article, 210 (39%) reference an institutional publication, 140 (26%) have no reference at all, and 49 (9%) are justified or derived by the EPRI authors.

It is interesting to note that the presentation format of the element specific data changed significantly from EPRI [6] to EPRI [3]. EPRI [6] organized the element specific data by nuclide with a field entitled ‘justification’ which had references and occasional comments e.g. “In the absence of data for chlorine, using data for iodine.” By the 2009 report [3] this field included only references and data was presented by parameter in a table with only the value for each nuclide.

Also of note was the difficulty validating parameters cited to other institutional publications. In our case study, 35 parameters (6%) cited a BIOPROTA database [8]. A copy of this database was obtained by request from BIOPROTA and the references were tabulated. It was difficult to source values from EPRI [3] in BIOPROTA's database, this was due in part to the fact that the database is quite robust, offering a range of values to choose from depending upon the ecology of a site. In all cases, however, the parameters in BIOPROTA 2006 [8] were listed with their original, peer-reviewed journal source. It seems that to allow objective evaluation of the methodology behind such radioecological model parameters, providing these journals as references instead of an evolving database would be optimal.

RECOMMENDED APPROACH

As with any model, the results of a performance assessment are only as good as the parameters and assumptions that go into it. Site-specific element-specific work is the ideal, but often prohibitive in time and expense. There is a need for systematic approaches to bridging data gaps in the absence of nuclide- and environment-specific information, which are defensible and transparent. Some of these methods are technical in nature such as the potential to use of neutron activation analysis to rapidly produce a large number of site-specific concentration ratios while other solutions are more conceptual.

In cases where there is a lack of data, there are three strategies that are followed: using data from a chemical analogue suspected to show similar behavior, commisioning better data, and making conservative assumptions. Conservatism can make some allowances for uncertainty and insufficient data through tactics like using the most conservative value when a range of possible values exist in the literature or neglecting entirely processes that are poorly characterized and would act only to increase repository safety [1]. However it is important that these choices are justified, gaps should be acknowledged and the manner of coping with them explained. Smith and Kato [9] have proposed an elegant flowchart for adapting a generic dataset to a revised dataset suitable for a site-specific assessment. For significant parameters of key radionuclides where site-specific data are "certainly nessesary" the flowchart calls for site investigation where site specific parameters do not exist, but for other parameters using generic datasets, chemical analogues, or expert judgement may be appropriate. Their method is hard to improve on, except to insist on openly documenting the process of parameter selection to allow for review.

Acknowledging the difficulties in performance assessment can be challenging. The key in building a defensible safety case is transparency; it should be clearly stated both where model parameters came from, and why those parameter values are appropriate to the case at hand. When questions of human health and safety are being considered areas where data are lacking should be highlighted as requiring further investigation and not obscured. Presenting and defending the decisions made make a stronger safety case than masking them.

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