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Paper

A BIOSPHERE MODELING METHODOLOGY FOR DOSE ASSESSMENTS OF THE POTENTIAL YUCCA MOUNTAIN DEEP GEOLOGICAL HIGH LEVEL RADIOACTIVE WASTE REPOSITORY

B. M. Watkins,* G. M. Smith,* R. H. Little,* and J. Kessler†

Abstract—Recent developments in performance standards for proposed high level radioactive waste disposal at Yucca Mountain suggest that health risk or dose rate limits will likely be part of future standards. Approaches to the development of biosphere modeling and dose assessments for Yucca Mountain have been relatively lacking in previous performance assessments due to the absence of such a requirement. This paper describes a practical methodology used to develop a biosphere model appropriate for calculating doses from use of well water by hypothetical individuals due to discharges of contaminated groundwater into a deep well. The biosphere model methodology, developed in parallel with the BIOMOVS II international study, allows a transparent recording of the decisions at each step, from the specification of the biosphere assessment context through to model development and analysis of results. A list of features, events, and processes relevant to Yucca Mountain was recorded and an interaction matrix developed to help identify relationships between them. Special consideration was given to critical/potential exposure group issues and approaches. The conceptual model of the biosphere system was then developed, based on the interaction matrix, to show how radionuclides migrate and accumulate in the biosphere media and result in potential exposure pathways. A mathematical dose assessment model was specified using the flexible AMBER software application, which allows users to construct their own compartment models. The starting point for the biosphere calculations was a unit flux of each radionuclide from the groundwater in the geosphere into the drinking water in the well. For each of the 26 radionuclides considered, the most significant exposure pathways for hypothetical individuals were identified. For 14 of the radionuclides, the primary exposure pathways were identified as consumption of various crops and animal products following assumed agricultural use of the contaminated water derived from the deep well. Inhalation of dust (11 radionuclides) and external irradiation (1 radionuclide) were also identified as significant exposure modes. Contribution to the total flux to dose conver[sion factor] from the drinking water pathway for each radio[nuclide was] also assessed and for most radionuclides was foun[d to be less] than 10% of the total flux to dose conversion fact[or] across all pathways. Some of the uncertainties rel[ated to the] results were considered. The biosphere modeling [methodology has] been applied within an EPRI Total Systems P[erformance] Assessment of Yucca Mountain. Conclusions and [recommen]dations for future performance assessments are pr[esented].
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Key words: contamination, environmental; ground[water]; analysis; dose equivalent

* QuantiSci, Ltd., Chiltern House, 45 Station Road, Henley-on-Thames, Oxfordshire RG9 1AT, England; † Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, California, 94304-1395.
For correspondence or reprints contact: J. Kessler, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, California, 94304-1395.

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INTRODUCTION

In the United States of America (U.S.), o[ne of the] reasons for the arising of high level radioact[ive waste] (HLW) is the generation of electricity through [the oper]ation of nuclear power plants. Ultimately, there [is a need] for a long-term disposal solution for spent [fuel, and] investigations are underway to assess the sa[fety of a] potential location for a deep geological repo[sitory for] HLW at Yucca Mountain, Nevada. Although [the U.S.] Department of Energy (DOE) is responsibl[e for the] disposal of spent fuel, the generators of the v[aste (the] electric utilities) need to be sure that ther[e are no] technical issues that would make the Yucca [Mountain] site unsuitable from public safety and envir[onmental] protection perspectives. For this reason Electr[ic Power] Research Institute (EPRI) undertakes research [using] appropriate computer codes and modeling calcu[lations to] make safety assessments of the total repositor[y system] (called total system performance assessments, o[r TSPAs]) of the candidate site (Kessler et al. 1996).

Recent legal, congressional, and regulatory [develop]ments within the U.S., including publication of t[he recom]mendations by the Committee on the Technical [Bases for] Yucca Mountain Standards of the National Ac[ademy of] Sciences (NAS), suggest that the surface environ[ment (the] biosphere) at Yucca Mountain should be give[n more] consideration in safety assessments (NAS 1995), s[omething] which has not been fully undertaken in the past c

absence of such a requirement. This paper describes work undertaken by QuantiSci on behalf of EPRI in applying a methodology to illustrate how impacts from radionuclide releases to the surface environment might be used in a performance assessment. The study did not include groundwater modeling since it was only concerned with examining the radionuclide pathways leading to human exposure following the release of contaminated groundwater into the surface environment through abstraction of water from a well sunk into a contaminated aquifer. Fuller details can be found in Smith et al. (1996). The EPRI study has drawn upon biosphere modeling developments that have been undertaken in many parts of the world, especially Europe, and in particular on the work of the Reference Biospheres Working Group within the second phase of an international cooperative study called BIOMOVS II (Biosphere Model Validation Study) (BIOMOVS II 1996a).

Safety assessments for proposed radioactive waste repositories undergo extensive technical and public examination. For this reason, it is important to have a clearly specified, justified, and traceable account of the approach taken and methods used for developing a biosphere model for dose calculations. To address this, the EPRI biosphere study consisted of the following tasks:

- development of a list of potential features, events and processes (FEPs) which could contribute to the transport and behavior of radionuclides in the biosphere and use of an Interaction Matrix, to help document the relationships between these FEPs, specifically for Yucca Mountain;
- specification of an appropriate conceptual and mathematical model of the Yucca Mountain biosphere based on an assumed context for a safety assessment for the site;
- a review of data for a wide range of processes related to radionuclide behavior in the biosphere, with special reference to radionuclides of iodine, neptunium, and technetium;
- a brief review of issues related to the definition of those groups of people for whom dose calculations are carried out (called critical groups or potential exposure groups);
- dose calculations carried out using a software application called AMBER (Brice 1996); and
- consideration of some key factors that contribute to uncertainties in the results.

This work resulted in the development and testing of a practical methodology for the biosphere modeling part of the Yucca Mountain TSPA carried out by EPRI. The biosphere work was undertaken in parallel with the development of the generic BIOMOVS II Reference Biospheres methodology (BIOMOVS II 1996a).

The biosphere methodology applied to Yucca Mountain (illustrated in Fig. 1) requires the following:

- a description of the context for the assessment;
- the use of an independently produced and a specific FEP list together with an Interaction Matrix to help with the specification of the conceptual and mathematical models;
- identification of the potentially exposed group people for whom doses are calculated;
- calculation of results and analysis of the impl tions of the dose calculations; and
- recognition of the uncertainties involved.

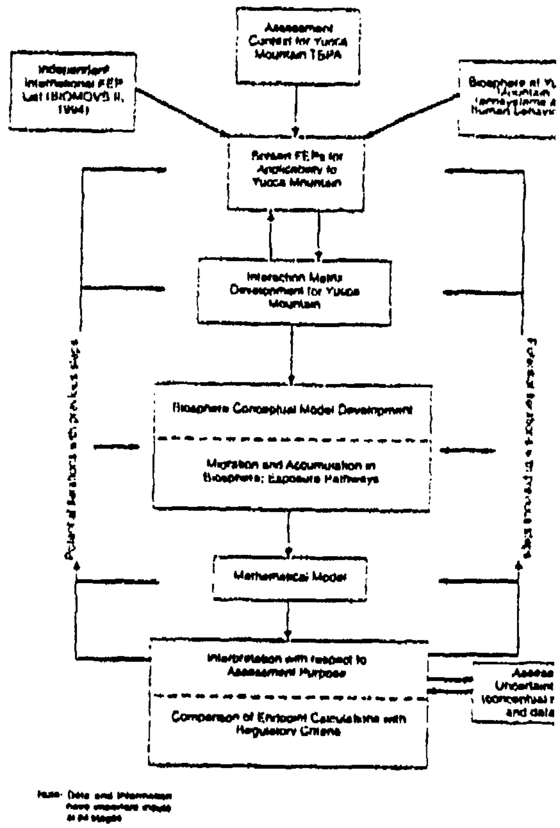

Fig. 1. Adaptation of the reference biosphere methodology t Yucca Mountain TSPA.

Each of these topics is summarized below, but a stages it should be recognized that to develop and jus an adequate biosphere model may require more than iteration of some of the various steps shown in Fig. 1. example, new data or information may be made avail for the assessment at any stage. This will need inter tation and application within the assessment, resultin additional consideration of the treatment of the rel FEPs and possibly in a revised model and feedback i the overall safety assessment. This paper discusses complete iteration of the biosphere methodology demonstrate its practicability and adequacy.

ASSESSMENT CONTEXT FOR YUCCA MOUNTAIN

Before any calculations are undertaken in a perf mance assessment it is important to know the purp

and scope of the work which is to be carried out and to document this information together with any assumptions made. This process is summed up by the phrase "assessment context." The assessment context answers three fundamental questions about the performance assessment, namely: what is one trying to assess? why is it being assessed? and what degree of conservatism should be adopted? In quantitative terms the assessment context should answer questions about what has to be calculated and why. In qualitative terms, the assessment context should specify the "assessment philosophy" that governs the level of conservatism (where appropriate) to be used in the development of conceptual models and selection of parameter values. For example, if the assessment is to be performed to demonstrate compliance with regulations, then the assessment philosophy should match the philosophy used to develop the regulations. A formal statement concerning the overarching context of an assessment has often been lacking in the past, resulting in confusion, for example, about the precise nature of the quantities to be calculated and in incoherent approaches to dealing with uncertainties. An assessment context should be established for each part of a safety assessment—for the near-field, geosphere, and biosphere. For a full performance assessment, it would be important to ensure that the overall assessment context is consistent for all these various parts. For the biosphere, the assessment context would ideally provide statements and information about the purpose and endpoints of the assessment; the repository system; site context; source terms; the interface between the geosphere and biosphere; time-frames for which calculations should be made; and assumptions about the future human society that might be living at the time of radionuclide discharge into the environment. For each component of the assessment context there could be a number of different purposes or associated information (see Table 1). Work on these alternative assessment context components is currently being carried out within the International Atomic Energy Agency (IAEA) coordinated research project called BIOMASS (BIOsphere Modeling ASSessment Methods) (IAEA 1997).

Setting the biosphere assessment context is especially important in the case of Yucca Mountain given the likely future requirement to calculate dose and human health impacts more explicitly. In order to illustrate the biosphere assessment methodology developed for EPRI, a relatively simple assessment context was assumed. Five important components were included in the assessment context information and, for the purpose of this exercise, were defined as follows:

1. *Assessment Purpose:* demonstration of compliance with regulatory requirements concerning human radiological protection for the post-closure phase of a potential Yucca Mountain HLW repository. Assessment philosophy generally "cautious" [for a general discussion of what is meant by 'cautious' see BIOMOVS II (1996a)];
2. *Radiological Endpoints:* indicative estimates of annual individual effective dose to members of the hypothetical exposure group to show doses are less

Table 1. Alternative components of an Assessment (
(IAEA 1997).

Component	Alternatives
Assessment purpose and philosophy	Demonstrate regulatory compl regulatory development Guide site selection System optimization Contribute to public confidenc Contribute to confidence of po and scientists Guide research priorities Proof of concept Philosophy: range from "cautic "equitable" (BIOMOVS II I
Assessment end-point(s)	Individual dose/risk Collective dose/risk Doses to non-human biota Modifications to the radiation c Fluxes into or through parts of biosphere Estimates of uncertainties or co
Repository system	Depth Host medium Waste type
Site context	Biosphere location (e.g., inland Topography (e.g., mountain, va Climate Spatial domain
Source term and geosphere-biosphere interface	Discharge into surface water bo deeper and upper sediments Discharge into soil zone Well drilled into near surface a Groundwater, gaseous and erosi
Timeframes	Factors: institutional control per environment changes; geolog changes; radionuclide half-liv
Societal assumptions	Current or future human behavi exploitation

than a regulatory standard based on risk, b linear dose-risk relationship. The details of to be calculated have a strong influence on w be included in the model, while judgements level of detail and treatment of uncertai affected by why the assessment is being m

3. *Geosphere-Biosphere Interface:* assumed o cur in groundwater from a deep well sunk aquifer within the assumed plume of radion
4. *Societal Assumptions:* technologically dev order to sink the deep well; the well water u domestic (consumption, bathing) and ag (crop irrigation and livestock watering) n foods consumed by the hypothetical expos produced locally using current farming prac
5. *Climate:* warm and dry, as at present, i.e., n or environmental change considered.

Three components of an assessment context Table 1 that were not explicitly specified in study are repository system, site context, a frames. The repository system was taken to be repository proposed for Yucca Mountain and context [which includes climate assumptions (1997)] was taken to be the ecosystems an

behavior currently found in the Amargosa Valley. Concerning time-frames, no limitation or cut-off time was adopted, as suggested in NAS (1995). Timescales for dose impacts depend primarily on the timing of the releases from the geosphere, which are assessed by geosphere modelers, and not significantly on biosphere conceptual model assumptions.

BIOSPHERE FEP LIST AND INTERACTION MATRIX FOR YUCCA MOUNTAIN

A problem that frequently faces biosphere modelers is how to justify what is included and what is excluded in the model. In the methodology that has been developed, there are two useful tools which can be used. The first is to produce a list of all the various features, events, and processes (FEPs) that could be included in a conceptual understanding of the biosphere system being considered. The second is a method of conceptualizing how the various processes interact with one another and, if radionuclides are present, how they are transported within the system.

Biosphere "FEP List"

The use of a list of FEPs is an essential starting point in the process of appropriate model development. A FEP list is a procedure for subdividing a complex analysis of the biosphere into smaller components that are more easily managed, both conceptually and analytically. Once the fundamental building blocks of the analysis are chosen, they are organized by determining and quantifying the relationships between them. Establishing the structure of the components and their inter-relationships makes subsequent steps in developing a model easier and provides confidence that the analysis is substantially complete since reasons for FEP inclusions and omissions are traceably and transparently recorded and this therefore has technical, managerial, and quality assurance benefits.

There are many uncertainties associated with the long-term evolution of the biosphere and, in particular, the unknown and unpredictable influences of future human actions. Since these cannot be predicted, various assumptions must be made. The important point is to document the assumptions and to adopt a consistent and logical approach to the process of model building. It is very useful to begin with a pre-existing independent list of potentially relevant FEPs since this assists with auditing and checking for completeness. It also provides a degree of independence in terms of what has been included in the safety assessment. That is, if the list of potentially relevant FEPs has been drawn up independently and treatment of each FEP has to be documented, then the safety assessment is forced to address all the issues, either by dealing with them explicitly, or by showing why they are omitted. The "FEP List" used as a starting point in the work reported here was the one developed before completion of the BIOMOVS II project (BIOMOVS II 1994). [This international FEP list was revised in 1996, after the completion of the EPRI work (BIOMOVS II 1996a).] Each FEP in the list was viewed, in the light of the assessment context and wh[at is] known about the general Yucca Mountain biosphere. [A] decision for its inclusion or omission was recorded. [It is] important that the FEP list is reviewed again at a l[ater] stage in the development of the conceptual model so [that] decisions made about the inclusion or exclusion of FEPs can be changed in the light of experience or [new] information. The full list of FEPs selected for the Yu[cca] Mountain assessment context outlined above, with [rea]sons, is given in Smith et al. (1996). It is an impor[tant] point that future changes in the assessment context, s[uch] as changed regulatory requirements, may result in m[inor] changes in the appropriate treatment of FEPs, but [the] methodology would still be relevant.

Interaction matrix

A useful tool to help with conceptual model de[vel]opment and justification is an interaction matrix. [The] procedure was originally developed in the contex[t of] rock engineering systems (Hudson 1992; Eng et [al.] 1994). The methodology starts with a top down appro[ach] to dividing the system under consideration into con[stit]uent parts by clearly identifying the relationship betw[een] the features, events, and processes present in the syst[em]. This can be done without direct reference to the "F[EP] List" generated earlier, since, at later stages in [the] methodology, the matrix and the "FEP List" contents [are] audited against each other. The main components of [the] system are identified and listed in the leading diag[onal] elements (LDEs) or segments of the matrix. In [the] example Interaction Matrix developed specifically [for] Yucca Mountain all the LDEs are main "Features" of [the] system. The interactions between the LDEs are [then] noted in the off-diagonal elements (ODEs). These in[ter]actions between "Features" are generally "Processes" [in] the Yucca Mountain example. Fig. 2 illustrates [the] procedure with a 2 × 2 matrix and also demonstrates [the] clockwise convention for recording interaction/influe[nce] direction. The greater the number of LDEs in the mat[rix,] the greater the number of interactions (processes) [that] can be clearly identified in the ODEs. More than one F[EP] can be included within any particular element of [the] matrix (LDE or ODE), and a FEP can appear in m[ore] than one element. For example, erosion is a potenti[ally] important process relevant to more than one ODE in[ter]action. Of course, each reference is to erosion i[n a] separate part of the system being modeled. When c[on]sidering the interactions it is important to ensure that t[hey] are direct interactions and to identify which elemen[t is] the cause and what is the effect. More than two eleme[nts] in the matrix can be involved in describing a sin[gle] process. A connected chain of interactions through [the] matrix is called a pathway. Thus, in a properly c[on]structed Interaction Matrix all relevant FEPs and th[eir] interrelationships are identified.

Interaction matrices are useful not just for biosphere system description, but they can be develo[ped] for other components of a safety assessment as well

Component A 1,1	Influence of A on B 1,2
Influence of B on A 2,1	Component B 2,2

Fig. 2. Illustration of a 2 × 2 interaction matrix.

care is taken to ensure that the output of one part of the assessment is consistent with the input for the next part, then the matrices can be joined together to produce an overall matrix of the whole system. More or less LDEs can be used, or the system can be sub-divided and an interaction matrix developed for each sub-division. The limit of thirteen matrix elements suggested by BIOMOVS II (BIOMOVS II 1995, 1996a) for any one part of the system or performance assessment is a guideline to make representation easier rather than a restriction on the complexity of the problems that can be represented by the procedure.

The next stage in the methodology is to check that all the FEPs in the "FEP List" are included somewhere in the Interaction Matrix, then to record the reason why those that have been omitted are excluded. A final step in the development of the Interaction Matrix is to record which FEPs are included in each Matrix element. This may result in identification of some additional FEPs that can be added and defined in the second iteration of the list. The final result is an Interaction Matrix incorporating all the FEPs to be included in the conceptual biosphere model and the interactions between them, plus a full list of FEPs with documentation showing where each one has been included in the Interaction Matrix, or why it has been omitted. This process of independently developing a "FEP List" and an Interaction Matrix, then checking one against the other, provides added assurance that all relevant FEPs will be included in the conceptual biosphere model.

The Interaction Matrix developed for the Yucca Mountain biosphere exercise [adapted from BIOMOVS II (1996a)] is illustrated in Fig. 3. It included 11 main "Features" (LDEs) and a multitude of "Processes" (ODEs). For example, LDE [1.1] represents the "Source Term," which is the radionuclide concentrati aquifer. The "Variable Saturated Zone" [5.5] ex beneath the surface soil all the way down to the " Saturated Zone" [2.2]. It is important to point o study was not concerned with near-field or modeling. Since groundwater is considered p geosphere, the processes which lead to ground tamination were not represented or modeled.

During the second iteration of the "FEP Interaction Matrix, it was considered that irriga abstracted from the deep well would not be su to agricultural use since this is not current agricultural practice in the area. This led to a s tion of the Interaction Matrix by eliminati associated with irrigation water, as shown in l

The convention of defining ODEs to desc nuclide migration means that radionuclide pathways can be traced and translated directl conceptual model (see the thin arrows on Fi exposure pathways can also be defined (see thi on Fig. 4). For example, contamination in the sc [1.1] is used for water supply [1.10] and throu activities [10.10] is used, among other agricult tices, for irrigating [10.6] surface soil [6.6]. clides accumulating in the surface soil are t ferred via uptake and rain splash [6.8] to fl Human radiation exposure [11.11] then arises d consumption (i.e., by ingestion) [8.11]. Full de cerning the definition of the LDEs and ODE iterative process using the "FEP List" have vided in Smith et al. (1996).

HYPOTHETICAL EXPOSURE GROUP

In 1995, the committee on the Technical Yucca Mountain Standards recommended a h based standard using a linear, no-threshold c between radiation dose and health risk (NAS their report, the group of people for whom do ments should be carried out is called the critic The NAS committee report discussed various a to the identification of critical groups but di equivocally recommend a single approach. The is that it is not possible to predict the future a with respect to biosphere conditions or human the time of the potential radionuclide releas biosphere, especially for long term assessment geological disposal. All assumptions are hypoth the critical group cannot be identified with ce the way that it might be possible to do so for pr releases.

If one examines the approach to critic definition in other countries with waste disposa it can be seen that there are differences in r guidance/criteria, potential future biospheres, r locations and types, and in assessment approac single international description of one group which might be exposed to future releases wou sufficient for all safety assessments. As part of

1.1 **SOURCE TERM (Contaminated well water)**	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10 Water supply	1.11 Direct exposure
2.1	2.2 **PERMANENT SATURATED ZONE (Sink)**	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11
3.1	3.2	3.3 **SURFACE WATER (Sink)**	3.4 Sedimentation Erosion Diffusion Advection	3.5 Recharge Erosion	3.6 Flooding Diffusion Sedimentation Erosion Irrigation	3.7 Aerosols formation Degassing Evaporation	3.8 Interception Uptake Irrigation / Flooding External contamination	3.9 Consumption	3.10 Water supply	3.11 Direct exposure
4.1	4.2	4.3 Resuspension Diffusion	4.4 **SEDIMENTS**	4.5 Conversion Advection	4.6 Conversion Advection Dredging	4.7	4.8 Uptake	4.9 Uptake External contamination	4.10	4.11 Direct exposure
5.1	5.2 Percolation	5.3	5.4 Conversion Bank collapse	5.5 **VARIABLE SATURATED ZONE (Lower Soil)**	5.6 Capillary rise Weathering Gas transfer	5.7	5.8 Deep root uptake	5.9	5.10 Materials resource	5.11 Direct exposure
6.1	6.2	6.3 Erosion Run-off	6.4 Conversion Bank collapse	6.5 Infiltration	6.6 **SURFACE SOIL (Upper Soil)**	6.7 Suspension Evaporation Gas transfer Volatilisation	6.8 Uptake Rain splash	6.9 Soil contamination	6.10 Land uses Materials resource	6.11 Direct exposure
7.1	7.2	7.3 Precipitation Deposition	7.4	7.5	7.6 Deposition Precipitation Wind erosion Weathering Condensation	7.7 **ATMOSPHERE (Air)**	7.8 Deposition Precipitation Gaseous uptake Seasonality Condensation	7.9 Inhalation External contamination Seasonality	7.10 Weather influences	7.11 Direct exposure
8.1	8.2	8.3 Desorption	8.4 Weathering Desorption Sediment processes	8.5 As 8.6 but for deep root flora	8.6 Weathering Desorption Soil processes [illegible]	8.7 Transpiration Respiration Volatilization / Desorption Morphological effects Burning	8.8 **FLORA**	8.9 Consumption	8.10 Materials resource	8.11 Direct exposure
9.1	9.2	9.3 Excretion	9.4 Bioturbation Excretion	9.5 Bioturbation	9.6 Excretion Bioturbation Soil structure	9.7 Exhalation Flatulence	9.8 Fertilisation Direct contamination	9.9 **FAUNA**	9.10	9.11 Direct exposure
10.1 Abstraction	10.2	10.3 Engineering works Extraction Discharge Water treatment	10.4 Dredging Construction	10.5 Excavation Construction	10.6 Agricultural practices on soil processes Excavation Construction	10.7 Filtration Ventilation	10.8 Agricultural practices and ecosystems Construction Furniture Energy source Clothing	10.9 Agricultural practices and ecosystems Furniture Clothing	10.10 **HUMAN ACTIVITIES**	10.11 Definition of exposure pathways Food preparation
11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9	11.10	11.11 **DOSE TO CRITICAL GROUP (Exposure)**

Fig. 3. BIOMOVS II reference biosphere interaction matrix modified for the Yucca Mountain biosphere.

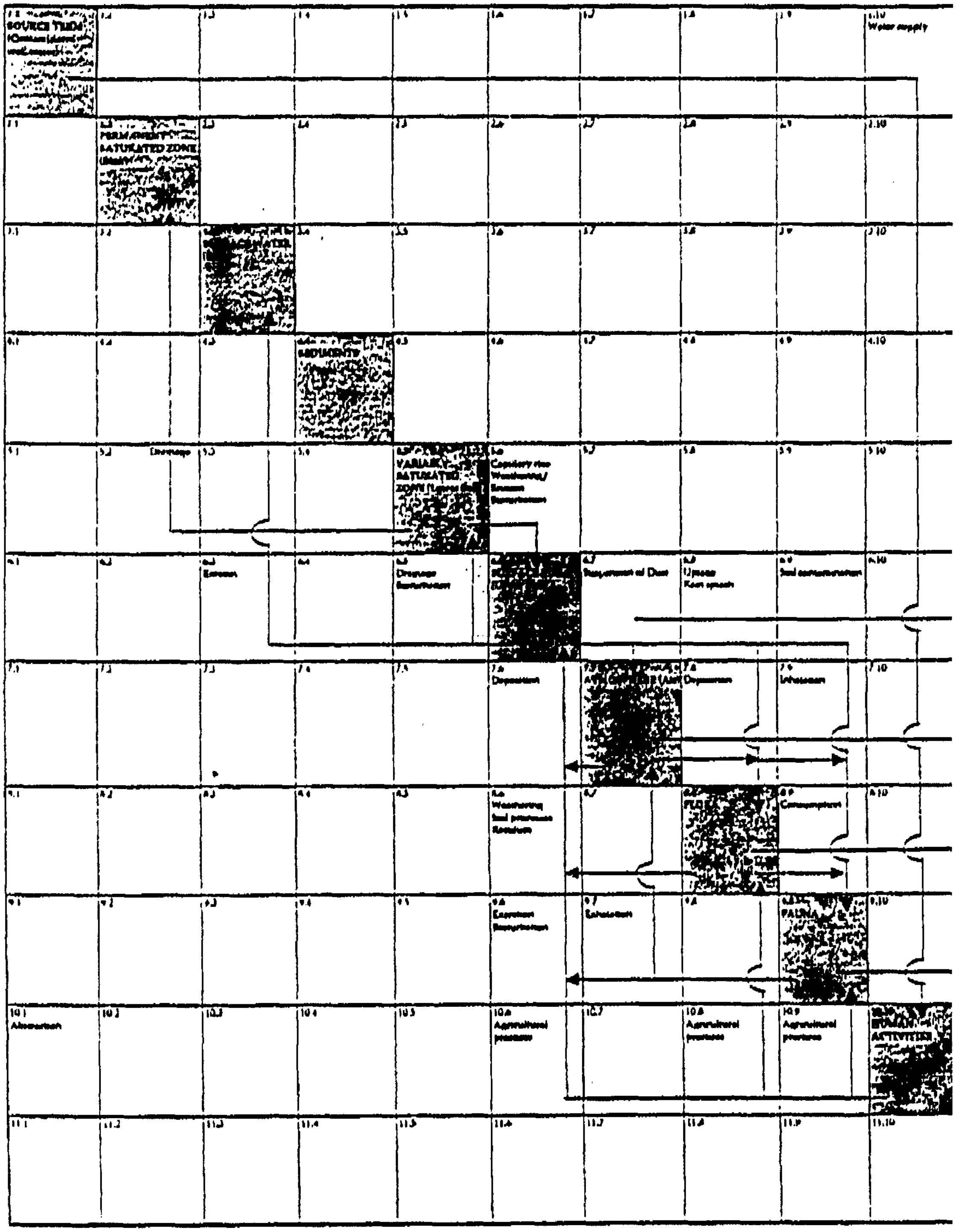

Fig. 4. BIOMOVS II reference biosphere interaction matrix modified for Yucca Mountain biosphere, no surface body is assumed. The thin arrows refer to nuclide migration processes; the thick arrows refer to exposure pathw

for EPRI, and in parallel with the BIOMOVS II study, a review of various national and international approaches to potential exposure group definitions was undertaken and the relationship between critical/exposure group size and tolerability of risk was explored (Smit The definition of the potential exposure gr used in the dose calculations described belo for illustrative purposes. However, EPRI e

definition and use of a range of exposure groups to explore potential impacts of radionuclide releases to humans.

All the issues related to potential exposure groups are being discussed in various national and international committees and working groups and the topic is the subject of a task group in the IAEA BIOMASS co-ordinated research program (IAEA 1996). It is expected that open discussion of the different approaches and issues will result in an agreed methodology for defining potential exposure groups for use in waste disposal performance assessments.

BIOSPHERE MODEL DEVELOPMENT, HYPOTHETICAL EXPOSURE GROUP ASSUMPTIONS, AND ILLUSTRATIVE DOSE CALCULATIONS FOR YUCCA MOUNTAIN

Biosphere model development

The biosphere conceptual model was developed from the Interaction Matrix shown in Fig. 4. Concentrations of radionuclides in the atmosphere, fauna, and flora were assumed to be in equilibrium with the dynamically calculated concentrations in the upper soil and in the abstracted water. This approach is justified for two reasons. First, the processes affecting the concentrations in the atmosphere, flora, and fauna are rapid compared with those affecting concentrations in the donor media. Second, assuming equilibrium tends to maximize radionuclide concentrations in soils. This is consistent with the generally "cautious" assessment philosophy used in this example. Given these assumptions, the conceptual model can then be refined and this is shown in Fig. 5. There may be losses from the system from which there is no feedback pathway and such losses can be represented in the model as a "sink." The final stage in model development was the representation of the conceptual model by a mathematical model using appropriate mathematical equations for the transfer processes. A flexible software application developed by QuantiSci called AMBER was used (Brice 1996). AMBER can be used to

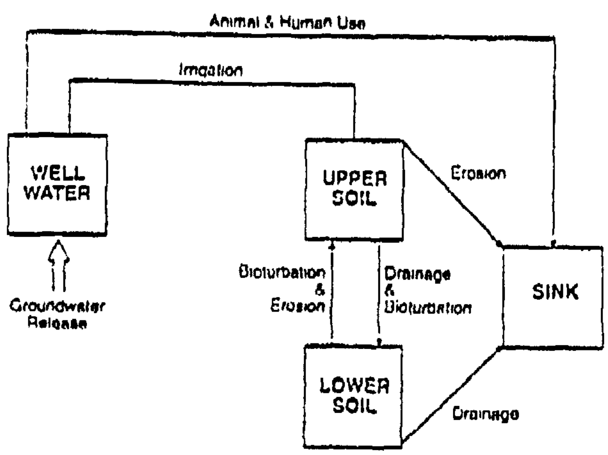

Fig. 5. Conceptual model for the Yucca Mountain biosphere transfer processes.

build dynamic compartmental models to represen migration and fate of contaminants in surface and surface environments and the user can rapidly con generic or case specific models and tailor them to specific needs.

Hypothetical exposure group definition for Yucca Mountain

It is acknowledged that there is still uncert concerning the selection of appropriate potential e sure group assumptions relevant to Yucca Mour partly because of on-going regulatory development also partly due to availability of all relevant site-spe information. In the EPRI study, just one radionu release mode was considered, namely release to gro water. It would be possible, however, to consider di ent mechanisms for release from the geosphere ar look at the different impacts. For example, there cou direct discharge of contaminated groundwater dir into the surface environment. This would require identification of a different potential exposure grou for each type of release.

From the exposure pathways shown in Fig. 4, for the purposes of the biosphere dose calcula presented below, the following assumptions for hypothetical exposure group were made (consistent the assessment context and considered to be approp to a cautious assessment philosophy):

- the regulatory objective is to assess average nual individual doses to those most likely t affected in the vicinity of the repository account was taken of human intrusion delib or inadvertent; the need to consider temporal spatial averaging is acknowledged);
- radionuclide release to the biosphere is via taminated groundwater supply taken from a well;
- the hypothetical exposure group belongs farming community (consistent with a caut assessment philosophy) with behavior patt based on current farming practices at Amar Valley;
- the components of the hypothetical expo group's diet and lifestyle allow doses receive members of the exposure group to be sum across all relevant exposure pathways;
- exposure modes are inhalation (gases, dusts, a sols), external irradiation (contaminated surfa bulk materials, immersion) and ingestion variety of foodstuffs, as well as inadvertent in tion of soil (see Table 2); and
- the hypothetical exposure group consumes local produce derived from contaminated m represented in the model compartments (inclu root and above-ground vegetables, fruits, gra meat, liver and related animal products, m water, soil).

Table 2. Exposure modes and associated exposure pathways for the potential exposure group.

External irradiation from:	Inhalation of:	Ingestion of:
Soil/sediment (upper soil)	suspended soil/sediment (upper soil)	cow meat*
Water (from well)		cow liver*
		cow milk*
		pig meat*
		sheep meat*
		chicken meat*
		chicken liver*
		grain*
		root vegetables*
		green vegetables*
		fruit*
		water (from well)
		soil/sediment (upper soil)

* Exposure is due to contamination derived from the upper soil and well water compartments.

Table 3. Radionuclides considered in the EPRI study.

Parent	Progeny
^{79}Se	
^{94}Nb	
^{99}Tc	
^{129}I	
^{135}Cs	
^{240}Pu	^{236}U ⇒ ^{232}Th ⇒ ^{228}Ra ⇒ ^{228}Th
^{236}U	^{232}Th ⇒ ^{228}Ra ⇒ ^{228}Th
^{232}Th	^{228}Ra ⇒ ^{228}Th
^{228}Ra	^{228}Th
^{228}Th	
^{237}Np	^{233}Pa ⇒ ^{233}U ⇒ ^{229}Th
^{233}Pa	^{233}U ⇒ ^{229}Th
^{233}U	^{229}Th
^{229}Th	
^{242}Pu	^{238}U ⇒ ^{234}U ⇒ ^{230}Th ⇒ ^{226}Ra ⇒ ^{210}Pb ⇒ ^{210}Po
^{238}U	^{234}U ⇒ ^{230}Th ⇒ ^{226}Ra ⇒ ^{210}Pb ⇒ ^{210}Po
^{234}U	^{230}Th ⇒ ^{226}Ra ⇒ ^{210}Pb ⇒ ^{210}Po
^{230}Th	^{226}Ra ⇒ ^{210}Pb ⇒ ^{210}Po
^{226}Ra	^{210}Pb ⇒ ^{210}Po
^{210}Pb	^{210}Po
^{210}Po	
^{243}Am	^{239}Pu ⇒ ^{235}U ⇒ ^{231}Pa ⇒ ^{227}Ac
^{239}Pu	^{235}U ⇒ ^{231}Pa ⇒ ^{227}Ac
^{235}U	^{231}Pa ⇒ ^{227}Ac
^{231}Pa	^{227}Ac
^{227}Ac	

Note: Each radionuclide in a decay chain is modeled explicitly, unless its half-life is less than 25 d. If its half-life is less than 25 d, it is assumed to be in secular equilibrium with its parent in all biosphere media. The radiological effect of the radionuclide is added to that of its parent.

Biosphere calculations

In order to undertake the actual biosphere calculations, appropriate data for radionuclide dependent and independent processes were collated. The radionuclides considered and the associated decay chains are given in Table 3. Twenty-six different radionuclides were modeled because they are all relevant to long term releases from high level radioactive waste repositories. Account was taken of the ingrowth of any decay product radionuclides over the very long time scales being considered in the assessment calculations. Because of the relatively rapid timescale for important biosphere processes, any progeny with a half-life greater than 25 d v
modeled. It is recognized that even shorter
may need explicit consideration for the b
example, to deal with processes involving
half-life of 3.8 d. However, in this investi
products with a half-life of less than 25 d w
to be in secular equilibrium with their paren
of the environment. Their radiological effe
dose per unit activity ingestion) were taken
by adding them to the those of their parent
radionuclides includes some not normally c
geosphere modelers. This is because geosph
usually takes account of factors such as
retardation and consequences of differe
forms. Since any output from geosphere m
not available for the work reported here all th
relevant radionuclides had to be considered
nuclides ^{129}I, ^{99}Tc, and ^{237}Np have been ider
radionuclides of interest in previous safety
so prior to undertaking any dose calculatio
tion concerning a number of element-dep
sphere parameter values for these three r
were reviewed. For these three, and other r
of interest, site-specific data for Yucca Mo
used where sufficient information was avai
wise data were selected from published da
and this selection was based on a "cautious"
philosophy approach (Smith et al. 1996).

RESULTS

The starting point for the calculations wa
of each radionuclide from the contaminated g
into the well. Table 4 presents the flux to dose
factor (Sv y^{-1}/mol y^{-1} released in well wate
pathways and (b) the drinking water on
calculated using the mathematical model set
AMBER software application. Results repre
nual individual effective flux to dose conver
for average members of the hypothetical expo
In a full safety assessment the predictions fo
to the well would be derived by geospher
using a separate groundwater contamina
code.

Table 5 provides information for each r
concerning the top three exposure pathwa
percentage contribution from each pathway
dose conversion factor together with the c
from the drinking water only pathway. From t
can be seen that the drinking water pathway is
to give highest doses to members of the h
exposure group. For fourteen different radio
highest flux to dose conversion factors arise
ways leading to ingestion of various crops (
radionuclides) and animal products (six of t
clides). For eleven of the radionuclides in
contaminated dust is the most important expo
For one radionuclide, ^{94}Nb, the most importa
mode is external irradiation. When a wide

Table 4. Dose conversion factors for unit flux to the well.

Flux to dose conversion factor (Sv y^{-1}/mol y^{-1})		
Radionuclide[a]	Factor for all pathways	Factor for drinking water only pathway
^{79}Se	7.7×10^{1}	1.4×10^{-2}
^{94}Nb	3.3×10^{1}	2.5×10^{-2}
^{99}Tc	1.7×10^{-2}	9.0×10^{-4}
^{129}I	1.4×10^{-2}	2.1×10^{-3}
^{135}Cs	1.3×10^{-2}	2.6×10^{-4}
^{210}Pb	3.0×10^{5}	2.6×10^{4}
^{210}Po	2.9×10^{6}	4.0×10^{5}
^{226}Ra	7.3×10^{1}	6.9×10^{1}
^{228}Ra	8.0×10^{4}	1.6×10^{4}
^{227}Ac	9.7×10^{4}	1.6×10^{4}
^{228}Th	1.3×10^{5}	2.6×10^{4}
^{229}Th	1.1×10^{3}	6.6×10^{1}
^{230}Th	3.4×10^{2}	8.6×10^{-1}
^{232}Th	1.1×10^{-3}	2.6×10^{-5}
^{231}Pa	5.1×10^{2}	6.8×10^{0}
^{233}Pa	2.1×10^{3}	4.4×10^{2}
^{233}U	1.9×10^{0}	9.5×10^{-2}
^{234}U	9.4×10^{-1}	6.0×10^{-2}
^{235}U	3.2×10^{-4}	2.0×10^{-5}
^{236}U	3.5×10^{-1}	5.9×10^{-4}
^{238}U	2.8×10^{-5}	3.2×10^{-6}
^{237}Np	7.4×10^{-2}	1.6×10^{-2}
^{239}Pu	4.6×10^{1}	3.1×10^{0}
^{240}Pu	1.5×10^{2}	1.2×10^{1}
^{242}Pu	5.3×10^{0}	1.9×10^{-1}
^{243}Am	1.5×10^{2}	8.2×10^{0}

[a] The contribution to dose from the in-growth of progeny in the biosphere is included in the factor given for the parent.

migration pathways and exposure modes is taken into account, the most important radionuclides, ^{99}Tc and ^{129}I, give total dose conversion factors of about one or two orders of magnitude higher than those arising from direct consumption of the groundwater. For ^{237}Np, the flux to total dose conversion factor in proportion to the drinking water dose factor can be higher (see Table 4). These findings are in line with other biosphere assessments that have been undertaken (see for example Watkins and Waters 1994; BIOMOVS II 1996b).

It is important to note, however, that the significance of the results from these biosphere calculations can only be judged in combination with results from geosphere modeling interpreted in the context of the overall performance assessment. However, the illustrative results can be used to provide feedback concerning significant biosphere pathways and thus provide guidance on topics and issues for further consideration.

KEY FACTORS CONTRIBUTING TO UNCERTAINTY

Factors which contribute to the uncertainty of results presented above are related to the assessment context, FEP analysis and conceptual model development, data selection for model application, and other uncertainties which are associated with the performance assessment. Each of these is discussed briefly below.

Issues related to the assessment context

The illustrative results presented in Tables 4 relate only to the particular assessment context above. The issues involved in developing an asse: context are liable to change, especially as regı developments become clarified. Assumptions in c tion with the hypothetical exposure group(s) defi (e.g., human habits, geosphere release area) are p larly difficult, but particularly important. It may l potential exposure group assumptions will not be fied within the regulations, but in any event regı and implementation should follow a consistent : ment philosophy. Assessment context assumptio the biosphere should also be consistent with the ‹ context for the safety assessment.

FEP analysis and conceptual model developme

The FEP analysis and conceptual model de ment illustrated above have assumed that contar release to the biosphere occurs via a deep well ‹ into a contaminated aquifer and that the water is us all domestic and agricultural purposes. Geosphere eling within a safety assessment could explore rele the biosphere by direct discharge of groundwater surface environment in the area to the south of Am: Valley. In this case some aspects of the related FEl exposure pathways would be different although th list and interaction matrix methodology would s applicable. Whatever the release mechanism, th however, the question of how to decide when differentiation is sufficient. FEP simplification or e sion should be undertaken according to informatior scoping calculations, overall assessment results availability of relevant data for models derived fro FEP analysis through the Interaction Matrix.

Data availability for model application

A range of uncertainties is associated with element dependent and element independent data u model applications. For example, there are variab and uncertainties associated with use of generic bolic data; specific soil types; farming practices food/water consumption amounts. Although some ı nuclide and exposure pathway combinations are supported by available data, this is not the case w: combinations. It should be noted, however, that calculations are provided as indicative estimates c pact given particular assumptions in order to pr regulatory insight. Provided a relevant range of ir tive calculations is made, uncertainties associated data use can be accommodated. It is not especially ı to spend major resources to characterize a surface ronment (to better justify specific choices of param when that environment will be subject to signi: change before releases occur.

Performance assessment uncertainties

The results for the biosphere assessment were in EPRI's Phase 3 total system performance assess

Table 5. Results from the illustrative biosphere calculations. The table gives the top three exposure pathways (ai percentage contribution from each pathway to the total dose conversion factor) and the percentage contribution fro drinking water only pathway.

Radionuclide	Top three exposure pathways (and % contribution to total dose conversion factor) 1 (%)	2 (%)	3 (%)	Percent contribu from drinking w only pathway
^{79}Se	Cow liver (72.1)	Cow meat (11.7)	Sheep meat (3.53)	0.02
^{94}Nb	Ext irrad from soil (98.6)	Cow milk (0.65)	Cow meat (0.21)	0.1
^{99}Tc	Fruit (30.2)	Root veg (17.7)	Grain (14.8)	5.4
^{129}I	Fruit (43.9)	Drinking water (15.3)	Grain (13.7)	15.3
^{135}Cs	Cow meat (18.7)	Fruit (13.8)	Root veg (10.7)	2.0
^{210}Pb	Cow liver (32.9)	Chicken liver (24.3)	Fruit (20.4)	8.6
^{210}Po	Chicken liver (34.5)	Fruit (32.2)	Drinking water (13.6)	13.6
^{226}Ra	Chicken liver (42.5)	Cow liver (26.3)	Root veg (5.83)	0.9
^{228}Ra	Fruit (47.3)	Drinking water (20.4)	Root veg (10.8)	20.4
^{227}Ac	Fruit (43.2)	Drinking water (16.8)	Cow liver (12.9)	16.8
^{228}Th	Fruit (49.3)	Drinking water (20.5)	Root veg (11.7)	20.5
^{229}Th	Inhalation of dust (56.1)	Fruit (15.4)	Cow liver (8.13)	6.1
^{230}Th	Chicken liver (40.8)	Cow liver (25.3)	Inhalation of dust (7.18)	0.3
^{232}Th	Inhalation of dust (40.1)	Fruit (11.1)	Root veg (10.5)	2.4
^{231}Pa	Inhalation of dust (53.6)	Root veg (12.5)	Fruit (10.1)	1.3
^{233}Pa	Fruit (53.2)	Drinking water (20.7)	Root veg (11.9)	20.7
^{233}U	Inhalation of dust (62.0)	Fruit (13.1)	Cow liver (6.16)	4.9
^{234}U	Inhalation of dust (29.9)	Chicken liver (17.7)	Fruit (17.5)	6.4
^{235}U	Inhalation of dust (42.1)	Fruit (20.0)	Root veg (10.9)	6.2
^{236}U	Fruit (43.2)	Inhalation of dust (18.7)	Drinking water (17.0)	17.0
^{238}U	Inhalation of dust (43.9)	Fruit (29.3)	Drinking water (11.6)	11.6
^{237}Np	Fruit (54.6)	Drinking water (21.1)	Root veg (12.3)	21.1
^{239}Pu	Inhalation of dust (57.2)	Fruit (17.5)	Cow liver (8.91)	6.8
^{240}Pu	Inhalation of dust (53.5)	Fruit (20.1)	Cow liver (8.84)	7.8
^{242}Pu	Inhalation of dust (76.5)	Fruit (9.39)	Cow liver (5.10)	3.7
^{243}Am	Inhalation of dust (58.9)	Fruit (14.3)	Cow liver (9.89)	5.5

(Kessler et al. 1996). From the overall results of the TSPA, it can be seen that some of the above uncertainties associated with the biosphere calculations, such as poor quality data for a particular radionuclide, may be modified when put in the context of the overall assessment, which may show that the radionuclide is not so important as others. A key observation of many performance assessments is that only a relatively limited number of radionuclides contribute significantly to the total annual individual dose rate both at the time of peak dose and at other times.

The TSPA results also showed that the period of peak release rate is long compared with the time taken for dose rates to peak given the assumption of a continuous constant release to the biosphere. This has important implications for biosphere modeling, potentially reducing the need to model some transients.

Taking account of pathways other than the drinking water pathway does add significantly to dose rate estimates, and additionally the relative significance of individual radionuclides is changed. However, it is consistently shown that radionuclides that are poorly sorbed in the geosphere and those which are long-lived continue to dominate individual dose rates.

Undertaking biosphere assessments for alternative, but potentially relevant, assessment contexts and release mechanisms can be used to help identify radiologically important radionuclides and pathways so that research and data collation efforts can be focused and thus prevent waste of resources.

DISCUSSION AND CONCLUSI

A practical biosphere modeling meth application to the potential Yucca Mountair repository has been described, tested, and do sets out how a biosphere model can be devel assessment of annual individual doses to hypothetical exposure groups from potentia the biosphere of radionuclides from a pro repository at Yucca Mountain via contan water. Other release mechanisms and endj readily be accommodated using the same me approach to take account of different infor other parts of the performance assessn changes to regulatory requirements. The r (Fig. 1) provides a structured protocol for n opment given information on the assessment a knowledge of the biosphere system in t repository location. It also provides a traceat the assumptions made particularly in relatic behavior and environmental changes and impact on radionuclide migration and potent exposure. The Interaction Matrix approac shown to be able to capture all of the potenti FEPs for Yucca Mountain. This is importar demonstrates that identification of all releva be accomplished in a manner that makes more easily understandable to the modeler, tl and the public. Notably, the approach uses as an independently developed "FEP List." A r

documented argument is required to justify how each FEP is included in the model or why it has been excluded. The methodology is flexible enough to allow revisions to assumptions, parameters, and parameter values, and hence both the conceptual and the mathematical models, if regulatory criteria, available input information, and site-specific data change or if new FEPs are added to the list.

The conceptual model developed for EPRI encompassed a variety of exposure pathways. A number of different exposure pathways and radionuclides contributed to the total flux to dose conversion factor. This causes a dilemma in conducting dose assessments for compliance purposes because the precise nature of human habits giving rise to exposures in the far future is unknown. Similarly, assumptions about future human habits affecting food consumption and external exposure will always appear arbitrary and yet will affect the dose assessment. Since it is impossible to predict the future reliably in this context, the calculations of dose to members of a hypothetical exposure group can only ever provide an illustration of the level of future impacts. It is recommended that the regulator should specify a range of potentially relevant illustrative human habit characteristics in advance of any compliance assessment. Which characteristic is critical can only be determined in the light of the safety assessment, and so, rather than refer to hypothetical critical groups, these alternatives could be better called hypothetical or potential exposure group(s). In the calculations reported here, cautious, but not overly pessimistic, parameter values were used so that it is unlikely that other assessment contexts or plausible exposure pathways would result in significantly higher flux to dose conversion factor estimates within the chosen assessment context.

The systematic steps used to develop the Interaction Matrix result in the documentation of how each FEP from an independent list has been included and if excluded the reasons why. In this way, the methodology forces the treatment of issues raised independently of the group carrying out the assessment. The matrix contains all the important components of the system and the interactions between them that are relevant to radionuclide migration and the associated exposure pathways. The development of the Interaction Matrix thus permits a conceptual model to be defined by following the pathways of radionuclide movement. In turn, the conceptual model description makes it easier to understand how the "FEP List" has been implemented, and it can be used to verify that all appropriate FEPs have been included. This means that the independent observer can see how particular FEPs have been treated in the performance assessment.

In the study undertaken for EPRI, annual individual flux to dose conversion factors for average members of a hypothetical exposure group using contaminated abstracted groundwater have been presented for 26 radionuclides assuming unit release rate in the water to the deep well. Results took into account the in-growth of radioactive progeny following release into the bios Results have been presented for the sum over all sure pathways and for the drinking water pathway The contributions of key pathways were also ider It is interesting that the drinking water pathway co utes less than 10% to the flux to total dose conv factor for most of the radionuclides considered and does not dominate potential exposures. Bearing in that the long-term dose estimates should only be c ered as indicators of the potential impact, the ran calculated doses could be considered acceptable giv other possible sources of uncertainty for the c performance assessment. It is also important to recc that results from biosphere calculations cannot be j in isolation since output from both geosphere an sphere modeling must be evaluated in the context overall performance assessment.

Recommended improvements for future a ments relate to the need for additional informati better define the assessment context or models. C cation and specification of regulatory requiremen needed, particularly regarding what is to be ass how to assess it, and how to define the potential exp groups. Progress could also be made through ite with the other parts of the safety assessment (Kessler et al. 1996). Re-examination of FEPs, r developments, and data acquisition should not be do isolation. Focusing on the key radionuclides such a and ^{99}Tc would allow better use of resources for r development and data gathering.

If U.S. Environmental Protection Agency and regulation developments result in the setting of lim health risk or dose rates, then the biosphere part c performance assessment will be very important. A sistent assessment philosophy will be required. It also be important to reduce overall uncertainties. can be achieved by working co-operatively and transparent manner. Participation in international grams will also help through the sharing of ide common problems [e.g., the IAEA co-ordinated res study, BIOMASS (IAEA 1996)]. The objective is a robust safety assessment acceptable to all inter parties—regulators, industry, and the general publi

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