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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Pathways to Man for Radionuclides Released from Disposal Sites on Land [and Discussion]

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Pathways to man for radionuclides released from disposal sites on land

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To predict the potential radiological impact on man of the disposal of radioactive wastes it is necessary to identify all the events and processes that could cause releases of radionuclides into the environment, to estimate their probabilities of occurrence and to calculate their consequences, for both individuals and populations. This paper briefly reviews the types of releases that have to be considered for land disposal sites and describes the mathematical models used to calculate rates of transport of radionuclides through the environment and doses to man.

The difficulties involved in predicting environmental conditions in the far future are discussed, in the light of the ways in which the results of consequence calculations will be used. Assessments of land disposal of long-lived and highly radioactive wastes are briefly reviewed, with the aim of identifying the most important radionuclides and exposure pathways, and the areas where the models and their databases require improvement.

1. Introduction

This paper deals primarily with pathways to man for radionuclides released from deep geological repositories on land for long-lived and highly active wastes. However, much of the discussion is equally relevant to shallow land burial facilities for wastes containing smaller amounts of long-lived radionuclides.

The aim of the paper is to summarize the state of the art of predicting long-term radionuclide transfer through man's environment and doses to man, and to indicate priorities for future work. As a preliminary the ways in which radionuclides may be released from land disposal sites are briefly reviewed.

2. Radionuclide release mechanisms

In a comprehensive radiological assessment of any waste disposal method it is necessary to consider all the events and processes that could lead to the transport of radionuclides back to man, or could influence transport rates. Some of these events and processes are natural; others are caused by the effects of the waste on the geological repository; yet others are human-induced. The events and processes differ widely in their probabilities of occurrence, as well as in their effects. To deal with them in an assessment it is usual to group them into a number of scenarios (i.e. possible future states of the waste disposal system) whose risks can then be predicted by using appropriate mathematical models. These scenarios can be categorized according to their probabilities of occurrence and the way in which they will be handled in dose and risk calculations (CEC 1984; IAEA 1985). For all types of geological repository there will be one scenario that is virtually certain to occur. In geological formations containing moving groundwater this 'normal' scenario is one in which radionuclides are released very slowly from waste packages and are very gradually transported by groundwater back to man's environment. For evaporite formations the normal scenario may well be one in which no release of radionuclides occurs. It is important to recognize that in defining the normal scenario it is not assumed that the disposal system (i.e. the waste, the repository, the geological formation and the biosphere) does not change with time. The scenario consists of the most probable sequence of events.

The second type of scenario to be considered is one in which there are perturbations to normal conditions, but these are not so great as to make it necessary to model radionuclide release and transport in a completely different way. An example would be the case where a seismic event leads to fracturing, enhanced groundwater flow, and thus faster movement of radionuclides through the geosphere. The third major type of scenario is one in which there is no rapid, catastrophic release of radionuclides, but the release is caused by a mechanism quite different from normal. The prime example here is accidental human intrusion into a repository, for example during exploratory drilling for mineral resources (or at a shallow land burial site during excavations for building).

The fourth category of scenario consists of events that are very unlikely indeed but could lead to rapid, large-scale releases of radionuclides. Examples of such events are the impact of giant meteorites and the occurrence of extrusive magmatic activity. The probabilities of occurrence of these events are so low, and their non-radiological consequences so high, that they are not usually considered in detail in radiological assessments of land disposal, or in risk assessments of any other type of nuclear or non-nuclear facility. For this reason these scenarios will not be considered further in this paper.

From this brief review of the types of radionuclide release and transport scenarios it is evident that, in comprehensive assessments, it will be necessary to consider many pathways that could lead to radiation doses to man. For many of the geological formations under consideration for waste disposal, the normal scenario involves release via groundwater into freshwater bodies (aquifers, rivers, lakes). Doses could then be received through drinking water, use of water for irrigation and other agricultural purposes, consumption of freshwater fish and, eventually, through marine exposure pathways. In human intrusion scenarios it may be necessary to consider external exposure and inhalation through being close to contaminated drilling mud or handling drill cores. In addition, because a full assessment must include estimates of doses and risks to the most exposed individuals and to populations as a whole, the models used should cover the area local to the point where radionuclides are initially released into man's environment, the region around it, and the remainder of the biosphere. In other words, it is necessary to attempt to model the whole environment.

3. Models for radionuclide transfer through the environment and dose prediction

3.1. *General*

The type of model most frequently used to predict rates and patterns of radionuclide transfer through the environment after releases from geological repositories is the linear compartment model. In these it is assumed that as soon as a radionuclide enters a compartment, instantaneous

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mixing occurs so that there is a uniform concentration of the radionuclide over the whole compartment. Each compartment must therefore be chosen to represent a region of the environment for which this assumption is reasonable. Depending on the situation being considered, compartments can be as large as the global atmosphere or as small as a child's thyroid. In general the tendency should be to reduce the number of compartments to the minimum consistent with the validity of the instantaneous mixing assumption. Transfer between compartments is described by 'transfer coefficients' that represent the fraction of activity transferred from one compartment to another in unit time. These transfer coefficients can be functions of time, so that, for example, changes in compartment sizes can be taken into account.

The advantages of compartment models are that they are mathematically straightforward, can be fairly easily interfaced with models for radionuclide release into the environment and, in the case of short-term predictions, are not too difficult to validate. In addition, these models can readily deal with actinide decay chains, which are a major concern in assessments of disposal of long-lived and highly active wastes. To illustrate how a compartment model for use in geological disposal assessments is structured, developed and validated I shall use as an example the BIOS model developed at the National Radiological Protection Board (NRPB) (Lawson & Smith 1985), with partial funding from the Commission of the European Communities (CEC). Similar models are in use in other countries (see, for example, SKBF/KBS 1983; Matthies *et al.* 1984; Wuschke *et al.* 1981) and other organizations in the U.K. (Kane & Thorne 1984).

3.2. *BIOS model*

3.2.1. *Structure of the model*

The highest doses to individuals from disposal on land will arise where radionuclide concentrations are highest, which is likely to be in the vicinity of the release to the biosphere. Hence in developing a model such as BIOS the greatest attention is paid to the locality of the release. The local part of the model must permit the calculation of radionuclide concentrations in all the local environmental compartments that could lead to irradiation of man, and must take into account radionuclide transport into the region beyond the release. Also, because releases may occur over very long periods (thousands of years or more), allowance must be made for feedback into the local area of radionuclides that have been more widely dispersed, and possible changes that may occur in the environment during and after the release must be incorporated into the calculations.

Depending on the type of release and the characteristics of the local environment, major contributions to collective dose may come from the local area where concentrations of activity are comparatively high. On the other hand, significant population exposure may also arise in the long term from more widely dispersed activity. It is neither feasible, nor necessary, to provide the same degree of detail in the part of the model dealing with this wider dispersal as is given to the local part. Two broad areas are sufficient: regional and global, provided that the major transport mechanisms and environmental compartments are included, so that contributions to collective dose from all exposure in all places at all times can be calculated.

Compartments representing the major global reservoirs for activity, and the transport between them, can be represented in a global model. This part of the biosphere model is used to calculate the contributions to collective dose arising from relatively low concentrations of activity leading to low doses to large numbers of people. The model for the region between the local and global compartments (the regional model) is necessary to provide an accurate representation of transport between the local and global compartments, and to allow the calculation of collective doses arising at intermediate levels of individual dose. It is also possible that in some circumstances maximum individual doses could arise in this area.

The requirements outlined above led to the broad structure of the BIOS model, which is illustrated in figure 1. The transport processes included in each part of the model are described briefly below.

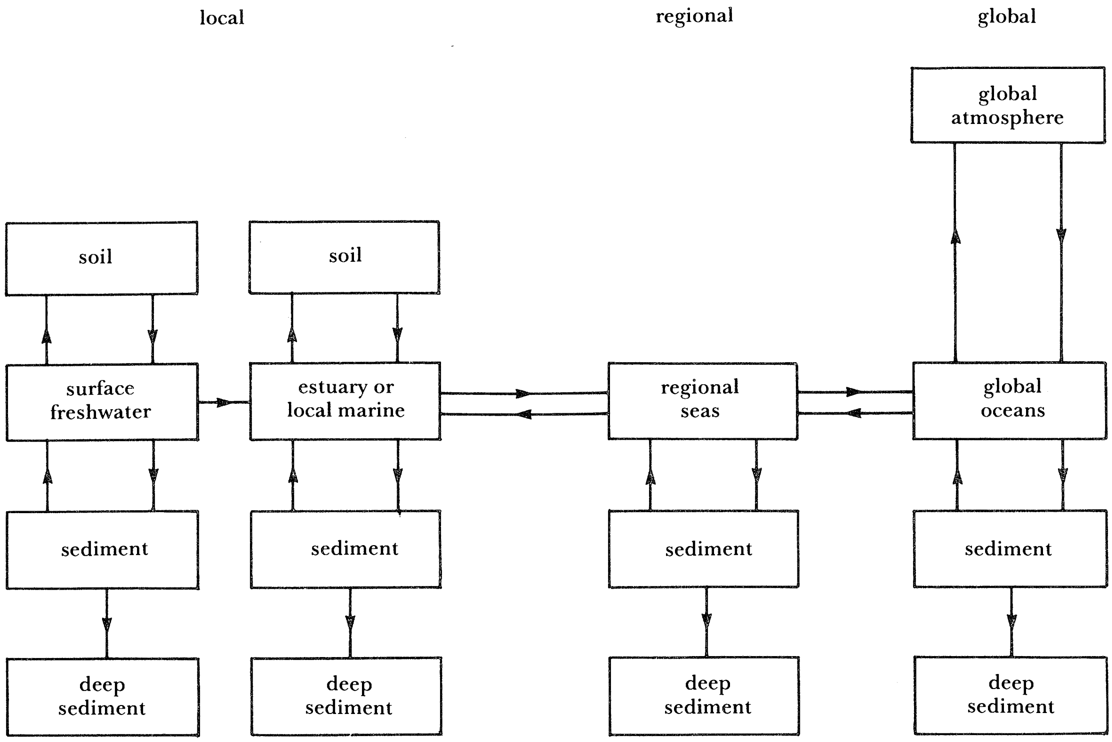

FIGURE 1. Schematic diagram of BIOS model.

3.2.2. *Freshwater environment*

Radionuclides transported from an inland repository via groundwater can enter freshwater bodies such as lakes and rivers directly, or via soil compartments. During subsequent transport downstream to the sea, the radionuclides will interact with freshwater sediments, and may also be transported to adjacent land areas as a result of flooding, irrigation practices or sediment movement. If the water is used in domestic or industrial supply, radionuclides will re-enter river systems via drains. All these transport processes are included in BIOS. Furthermore, any number of freshwater compartments may be specified, and connected in any order, so that discharges into and transport through river–lake systems can be modelled.

3.2.3. *Terrestrial environment*

Radionuclides may enter the terrestrial environment directly from the geosphere, or from the atmosphere, fresh water, or the sea. The transport processes modelled include interception by plant surfaces (pastures and crops), root uptake, transfer into grazing animals, and

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radionuclide migration down through soils and back into freshwater bodies. It is also necessary to consider the slow return from deep soil to surface soil as a result of processes such as animal activity and the intermittent rising of the water table during periods of heavy rain. In addition, lakes and rivers may silt up, with the result that their beds become available for use as farmland. In BIOS this is modelled through the use of a transfer coefficient from the sediment compartments to soil compartments, the coefficient being determined from the rate of accumulation of bottom sediments in rivers and lakes, and the depth of the relevant water compartments.

Activity may also be brought to the surface inadvertently through borehole drilling. Samples from drilling activities could be closely examined before it is discovered that they are contaminated, thus giving rise to doses to a few individuals. Most of the material might then be dumped close to the drilling site, where the liquid fraction could enter freshwater and the solids become mixed with soil. If the borehole has been sunk to provide a water supply, then the subsequent transfer of activity can be assumed to be similar to that for abstracted river water.

3.2.4. *Marine environment*

In the case of a repository sited on the coast, radionuclides could enter coastal waters directly. In other cases transfer will be by rivers (through estuaries), and transport to the sea both in water (either dissolved species or suspended particulates) and in sediments needs to be included. Once radionuclides are in the ocean, the processes to be considered are advection, diffusion, interactions with suspended and bed sediments, and uptake by marine organisms that are consumed by man. In BIOS this is again achieved by using a compartment approach, in which a larger number of compartments are used to represent coastal seas close to the release point than to represent the rest of the world's oceans.

3.2.5. *Atmospheric and global circulation*

Environmental transport of radionuclides through the atmosphere is not a major transport mechanism for all the more likely releases from land disposal sites. However, sea-to-land transport of all radionuclides (via sea spray) does need to be included in the local marine environment, and for the long-lived, mobile radionuclides (primarily ^{14}C and ^{129}I) it is necessary to consider transport from ocean surfaces to the global terrestrial environment via the atmosphere. In BIOS, global dispersion is not considered explicitly because there are particular models for global circulation of ^{14}C and ^{129}I that allow a simpler approach to be used (Bush *et al.* 1983; Smith & White 1983). The approach is to define a global atmosphere compartment, in which the concentrations of ^{14}C and ^{129}I are determined according to their transport across the ocean surface, and to use parameters chosen to be consistent with the special models referred to above. It is then assumed that all terrestrial carbon and iodine is in equilibrium with the atmosphere. This assumption is reasonable in the long term for long releases.

3.2.6. *Exposure pathways*

The output of BIOS consists of:

(i) concentrations of each radionuclide in each environmental compartment, as a function of time;

(ii) time-integrated concentrations of each radionuclide in each compartment;

(iii) annual individual doses in each compartment for each pathway and each radionuclide, as a function of time;

(iv) collective dose rates in each compartment for each pathway and radionuclide, as a function of time;

(v) as (iv) but summed over compartments;

(vi) as (iv) but summed over radionuclides and compartments;

(vii) collective dose rates summed over compartments; radionuclides and pathways; and

(viii) as (iv)–(vii) but with collective doses integrated over various time periods, including infinity.

Table 1. Exposure pathways included in the bios model

inhalation:	resuspension of soils, river and lake sediments, beach sediments
	air contaminated through global circulation
	sea spray
ingestion:	drinking water
	freshwater fish
	terrestrial foodstuffs (milk, meat, crops)
	marine foodstuffs (fish, crustaceans, molluscs, seaweed, plankton)
	desalinated water
external irradiation:	soils
	sediments
	fishing gear

The exposure pathways included in bios are listed in table 1. For a particular application not all of these pathways may be relevant. It should also be noted that care is required in summing doses over pathways, so as not to implicitly consider situations that are impossible (e.g. simultaneous use of the same piece of land for two types of farming).

Within bios, and all similar types of model, intakes of radionuclides are converted to doses to man by multiplying by the appropriate factors of dose per unit intake. These factors are also derived by using compartment models, but in this case the system modelled is human metabolism. I mention this here because it is a point that is often forgotten by those involved in environmental modelling, who frequently focus only on the data requirements and uncertainties in their own models.

4. Model validation

Model validation is a separate activity from model verification. The latter consists of checking that equations have been correctly included and solved within a computer code, and is often carried out through model–model comparisons and benchmarking exercises. Validation, on the other hand, consists of demonstrating that the model correctly represents the real world. Ideally it should be carried out by comparing the predictions of the model with field observations. Models of the type described above are clearly too broad in their scope to be validated as a whole. Furthermore, the timescales with which they are intended to deal are too long to make full validation possible. The best that can be achieved is a partial validation. This can be done in two, complementary, ways.

The first way is to check that all the relevant processes have been included in the model, if only in a simplified fashion. This is done by allowing experts in particular fields (e.g. terrestrial ecology, marine geochemistry) to review both the model and its database. Preferably it should be done on an international basis. The second way is to validate the separate parts of the model directly, from field observations; for example, models of transfer through terrestrial food-chains can be validated by using fallout data and measurements around nuclear facilities (see, for example, Haywood *et al.* 1980), whereas both fallout data and information on the distribution of natural radionuclides can be used to validate models of the interactions of radionuclides with deep-ocean sediments (GESAMP 1983).

Partial validation by means of expert review works fairly well. However, it is a time-consuming process because experts in particular fields will not immediately appreciate the aims and purpose of the model as a whole, or the reasons why the specific parts of the model in which they have an interest have to be simple representations of complex systems. Direct validation of parts of the model has two principal difficulties. The first of these is that field data will have been used in developing the model and it may not be possible to find new data sets for use in validation. The second difficulty stems from the need to deal with local, regional and global environments. Published data on radionuclide transfer always relate to specific sites, and generally not those where waste repositories might be located. Thus it is necessary, on the one hand, to extrapolate to obtain data appropriate for validation of the local part of the model, and, on the other hand, to average to obtain data for validation of the regional and global parts. Both processes require care and inevitably introduce uncertainties into the validation exercise.

5. Uncertainties

The uncertainties involved in modelling radionuclide transfer through the biosphere and in predicting doses to man from waste disposal on land can be divided into three categories:

(i) those related to predictions of future biosphere conditions (for example, climatic changes);

(ii) those related to changes in human characteristics, habits and locations;

(iii) those asociated with the approximations introduced by reducing the complex processes occurring in the transfer of radionuclides through the environment to a few mathematical equations.

These categories of uncertainties differ in both the extent to which they can be reduced by further research and in the way in which they are treated in assessments of the radiological impact of waste disposal options.

Uncertainties in the third category indicated above can be reduced by further research, and the remaining irreducible uncertainties can be quantified by use of laboratory and field data. This situation does not exist for uncertainties in either the first or second categories. For uncertainties related to predictions of future biosphere conditions, there is some scope for reduction through research (generally not related to radioactive waste disposal) and considerable prospects for scientific agreement on the range of future conditions to be considered. Thus it should be possible to include enough biosphere scenarios within an assessment to span the range of likely future conditions, even if information is lacking on their probabilities of occurrence.

Uncertainties about human characteristics, habits and locations are more difficult to deal with. When estimating maximum risks to individuals the approach used is to assume that an individual is present at the location where risks would be highest, and that this individual has habits and characteristics (metabolism, etc.) similar to those of people today (NRPB 1983; NEA

1984). The rationale for this approach is that it ensures that no individual in a future generation is subject to a risk that would be regarded as unacceptable now. The approach works well for scenarios in which the highest doses will be received through consumption of water or food, and depend primarily on predicted radionuclide concentrations in environmental materials. However, it is more difficult to apply to scenarios involving inadvertent intrusion because assumptions must be made about actions taken before and after the discovery of the waste.

For populations the situation is more complex because the results of collective dose and risk calculations are to be used in comparisons between disposal options. For such comparisons to be valid the estimates must be as realistic as possible and uncertainties must be quantified. It is clearly not possible to predict changes in the location and habits of populations over the time periods of concern in assessments of geological disposal, nor changes in human characteristics. (For example, 10^5 years ago marked the start of the development of human speech, so how can we tell what society will be like 10^5 years from now?) The best that can probably be achieved is to indicate the range of uncertainty in calculated collective doses and risks, with the range extending from zero risk (corresponding to the assumption that all cancers can be cured) to an upper value based on pessimistic assumptions about population sizes, habits and locations. By this means it will at least be possible to demonstrate that comparisons between disposal methods on the basis of the long-term population risks they involve is unlikely to lead to a clear preference for one method or another, or indeed one site or another. It will also provide valuable perspective on assessment results and on the uncertainties in modelling radionuclide transfer through the environment.

6. Important radionuclides, pathways and processes

In early work on land disposal of long-lived and highly active radioactive wastes, the models used to predict rates of radionuclide transfer through the biosphere were rather simple and did not include all the possible pathways. The tendency was to focus on those pathways that were most direct, in particular on drinking water for inland repositories and on seafood consumption in the case of coastal repositories. These assessments indicated that the radionuclides that are likely to give rise to the highest doses are those that are either very long-lived or which grow in from long-lived parent radionuclides, and which were assumed to migrate relatively rapidly through the geosphere. For example, several studies showed that ^{129}I, ^{99}Tc, ^{226}Ra and ^{237}Np were likely to give rise to the highest doses to individuals from disposal of spent fuel or vitrified high-level waste.

Since the early studies both models and their databases have been improved, but the general pattern of results in terms of the dominant radionuclides has not changed a great deal. For example, in the recent KBS study of disposal of spent nuclear fuel in crystalline rock formations in Sweden (SKBF/KBS 1983) ^{129}I (half-life 16 Ma) is predicted to be the most important contributor to both individual and collective doses from spent fuel disposal. The dominant exposure pathways for individuals are the consumption of drinking water and consumption of freshwater fish obtained from a lake close to the repository. For collective doses there is a substantial contribution from these, local, pathways but in the very long term it is circulation of ^{129}I throughout the global environment that dominates the cumulative collective dose. It is important to recognize that this global circulation dose is made up of extremely small doses to a large number of people, and is independent of the characteristics of the disposal site.

To investigate the environmental transfer processes and parameters that have most effect on predicted doses, NRPB has carried out a number of example calculations with the BIOS model (Lawson & Smith 1985). The two radionuclides considered are ^{239}Pu (half-life 24000 years) and ^{99}Tc (Half-life 213000 years). Plutonium tends to become fixed to soils and sediments, whereas technetium is relatively mobile in the environment. Figure 2 shows schematically the

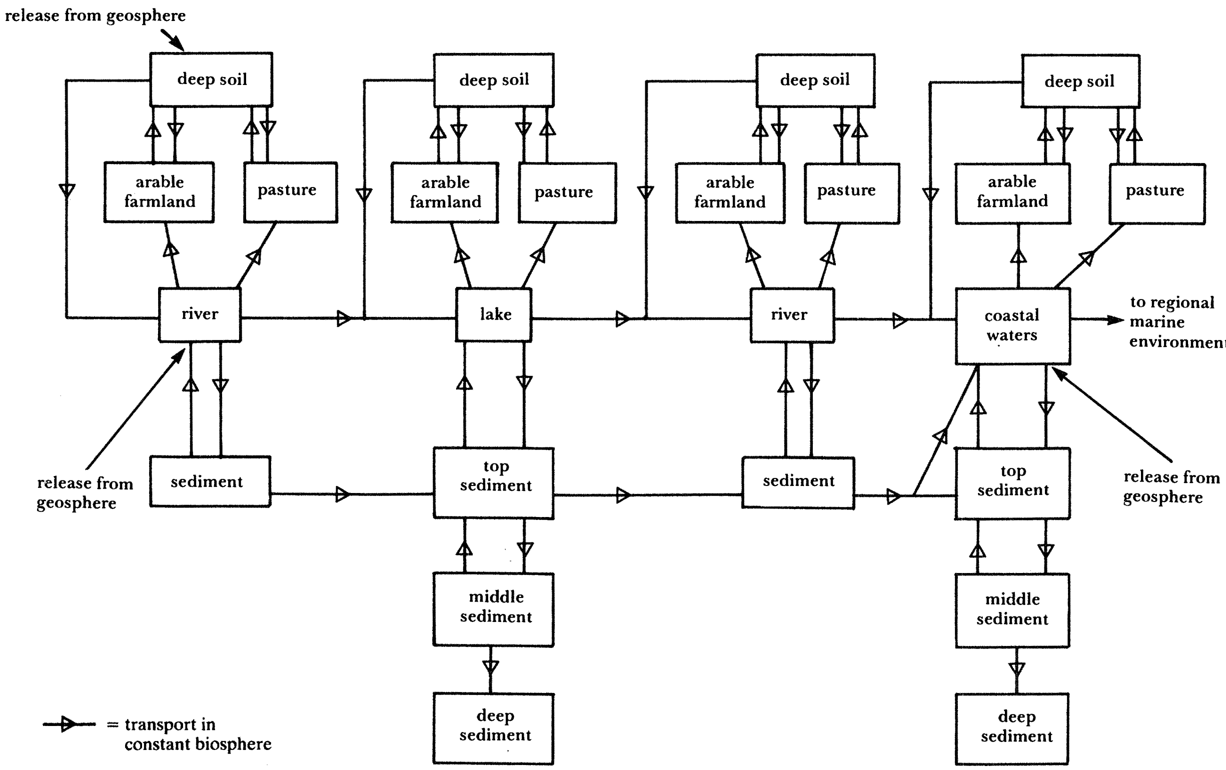

FIGURE 2. Schematic diagram of local biosphere for BIOS example calculations.

characteristics of the local biosphere that were assumed for these example calculations. Table 2 shows some of the results obtained for a release of 1 MBq a^{-1} of each radionuclide for 10^3 years into three different parts of the biosphere. For these two radionuclides, both individual and collective doses are dominated by exposure arising close to the release point. With the assumptions made here, terrestrial exposure pathways are more important than direct consumption of contaminated drinking water when the release occurs directly into a river. However, this would not be true if the river had a lower flow rate. For ^{99}Tc the importance of farming pathways arises from the high factor assumed for uptake from soil into pasture and crops, whereas for ^{239}Pu it is long-term retention in soils that leads to high doses via terrestrial pathways. Despite the relatively high concentration factors of both radionuclides in certain types of marine foodstuffs, doses from a release into the marine environment are calculated to be much lower than those for a release into fresh water or soils. Work carried out in other contexts shows that interactions with marine sediments will be important in determining doses from ^{239}Pu, but much less so for ^{99}Tc (GESAMP 1983).

Overall, the results obtained show that it is necessary to include all the relevant pathways

TABLE 2. RESULTS OF EXAMPLE CALCULATIONS FOR ^{99}Tc AND ^{239}Pu WITH THE BIOS MODEL

compartment into which release occurs	maximum annual individual dose (Sv) and dominant pathway	collective dose commitment (man Sv) and dominant pathway
^{99}Tc		
river	2×10^{-11}, milk	9×10^{-3}, farming[(a)]
deep soil	2×10^{-10}, milk	2×10^{-2}, farming[(b)]
local marine	3×10^{-13}, seafood	3×10^{-5}, seafood
^{239}Pu		
river	6×10^{-9}, inhalation of resuspended soil	5×10^{-1}, drinking water, farming[(a)]
deep soil	6×10^{-7}, inhalation of resuspended soil	10, farming[(b)]
local marine	1×10^{-10}, seafood	2×10^{-3}, seafood

Notes:

[(a)] River water is assumed to be used for irrigation of farmland. Results shown are those for consumption of the farm products that give rise to highest collective doses.

[(b)] Contamination of farmland arises through upward migration from the deep soil. No irrigation is assumed. Results shown are for consumption of the farm products that give rise to the highest collective doses.

and processes, because any one or more could have the greatest effect on predicted doses from a given radionuclide. It should be noted, however, that the studies quoted above have not taken into account the exposure pathway that, if it occurred, would give rise to the highest doses to individuals. This is inadvertent intrusion into a repository, for example by exploratory drilling. While such an event has a low probability, its consequences to a few individuals would be high, and thus it could lead to the highest individual risks.

7. CONCLUSIONS

The problems involved in modelling the transfer of radionuclides through the environment and calculating doses to man from land disposal of radioactive wastes are related to a lack of data rather than to a lack of modelling techniques. It is possible to construct models to predict doses to individuals and populations from releases of radionuclides from repositories and to verify these models. Validation of these models is more difficult, but can be partly achieved through traditional methods and expert review. When considering priorities for further research in this area it is necessary to bear in mind that the major uncertainties in predicting doses and risk to populations are inherently irreducible, and that maximum risks to individuals may well arise from scenarios involving inadvertent intrusion into repositories. Thus although the long-term behaviour of radionuclides in the enrivonment is of great scientific interest and is required for other purposes, it seems doubtful whether further research on radionuclide behaviour in the biosphere will greatly aid decisions on appropriate disposal methods for long-lived and highly active wastes.

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Discussion

L. E. J. Roberts, F.R.S. (*Atomic Energy Research Establishment, Harwell, U.K.*). Is there a realistic possibility of unplanned intrusion into a deep repository in the distant future? A technologically less advanced society would lack the means and incentive to do so; a society technically able to conduct deep drilling will also have the means to recognize high levels of radioactivity and to avoid any ill effects.

Marion D. Hill. I think unplanned intrusion is a real possibility because there can be no guarantee that records will be maintained over periods comparable with the half-lives of some of the radionuclides in wastes. Also, it is quite possible that small quantities of waste could be brought to the surface in drilling cores, and that doses could be incurred before these samples have been examined and the presence of radioactivity detected. To my knowledge, drilling samples are not routinely monitored for radioactive content during present-day drilling operations (except those related to investigating potential waste disposal sites).

J. Rae (*Theoretical Physics Department, AERE, Harwell, U.K.*). I am a little concerned about the 'instant equilibrium' assumption for compartments in BIOS. It implies, for example, that a radionuclide introduced in one compartment will first appear in the nth compartment of a chain after n time-steps, no matter how large or small. Is care taken to relate time-step size to choice of compartments so that the assumption is valid?

Marion D. Hill. In the BIOS computer code the time-steps are chosen by the FACSIMILE program which is used to solve the questions, based on the rate constants within the system. The time-steps are short at first, and thus the model predictions are not valid over short time periods. However, the time-steps increase with increasing time after the start of a release into a compartment, and reach a constant size that is consistent with the time taken to reach equilibrium in each compartment.

F. P. Sargent (*Whiteshell Nuclear Research Establishment, Pinawa, Manitoba, Canada*). Would Ms Hill outline the results of NRPB analyses on the sensitivity of predicted risks from waste disposal to variations in waste container properties?

Marion D. Hill. The results of our sensitivity studies indicated that container lifetimes would have little effect on predicted risks, unless they were extremely long, in fact too long to achieve in practice. For high-level wastes there may be merit in using containers that will last until the 'thermal pulse' has passed, i.e. for about 300 years, just to provide a safeguard against the unlikely possibility of groundwater contact during this period. However, I am not aware of any attempts to quantify the benefits of using such containers, taking into account the low probability of early groundwater contact.

R. H. Flowers (*A.F.P.D., AERE, Harwell, Didcot, U.K.*). I would just like to put Ms Hill's reply in perspective, since yesterday I advocated a role for waste containers. If we could have complete confidence in our ability to predict the behaviour of radionuclides in the biosphere in the long term I would be quite content to bury wastes without any attention to near-field containment. But that is not the position and so I maintain that there is good reason to arrange for containment of radionuclides within the near-field, in addition to all the safety features inherent in the performance of far-field and biosphere.

Marion D. Hill. I could accept that containers have a role in providing a predictable near-field environment but would point out that use of essentially redundant barriers to radionuclide movement is not consistent with the ALARA principle of radiological protection.

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