TIME-DEPENDENT BIOSPHERE PROCESSES IN NUCLEAR FUEL WASTE DISPOSAL ASSESSMENTS

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ABSTRACT

This paper identifies time-dependent processes that, operating over very long periods of time, could affect the rate or pattern of radionuclide migration through the biosphere from an underground nuclear fuel waste vault, and suggests ways of dealing with these processes in an assessment model. Glaciation (including glacially induced faulting and succession) is identified as the only process requiring explicit time-dependent modelling. Glaciation will be modelled by defining a small number of discrete biosphere states, performing a separate, time-independent assessment of each state in turn, and basing the final assessment on the state for which the most severe consequences are predicted. This approach provides a manageable and credible first step in evaluating the effects of glaciation on radionuclide migration through the biosphere.

INTRODUCTION

Atomic Energy of Canada Limited (AECL) is currently assessing the concept of nuclear fuel waste disposal in a vault excavated deep within plutonic rock on the Precambrian Shield. (1) Mathematical models have been developed to describe the movement of radionuclides from the vault through the geosphere to the biosphere, using a systems variability approach in which the input parameter values are distributed to reflect measurement uncertainty and variations in time and space, and the output is expressed probabilistically. (2-5) Preliminary assessments have been carried out to a simulation cut-off time of 10^7 years. Over this period, the Shield environment will likely undergo profound changes in response to natural and anthropogenic forces. The effects of these changes must be taken into account in the assessment if they are capable of significantly altering the rate or pattern of radionuclide migration from the vault to man.

In this paper, we identify the time-dependent processes that could affect the consequences to man of an underground nuclear fuel waste vault, and suggest ways of dealing with them in the assessment model. The evaluation will concentrate on processes in the biosphere, which is defined to include the saturated overburden, soils, surface waters, atmosphere, and plant and animal life including man.

The prediction of the state of the Shield environment far into the future is an extremely difficult undertaking. The forces driving environmental change are, at best, poorly understood, and, at worst, unpredictable. In addition, the time-dependent behaviour of the various biosphere parameters during a given transitional event must be deduced from proxy data, and so cannot be predicted with any certainty. A detailed, time-dependent treatment of transitional processes may therefore not be warranted, since the results would not be credible. Here we propose an alternative approach that provides a manageable, credible first step to evaluating the effects of time-dependent processes. The approach is based on the following guidelines:

(i) Processes should be modelled time dependently only if their temporal variations have a significant effect on the consequence to man.

(ii) The modelling should be carried no further than absolutely necessary into the future, since the credibility of the predictions will decrease as the simulation cut-off time increases.

(iii) The prediction of future events should be based on the assumption that past variations in the biosphere will be repeated. This will likely be the case if there is no interference from man. Man's present and future potential for altering the biosphere is great; however, the nature of human impact is impossible to predict, and attempts to model it would be futile.

(iv) Full advantage should be taken of the concept of a reference group living near the discharge zone and consuming contaminated food, to reduce the number of future scenarios that need to be evaluated.

(v) The stochastic nature of the assessment should be exploited by addressing as many time-dependent processes as possible through variations in parameter values or distributions rather than through explicit modelling.

(vi) Wherever possible, transitional events should be modelled using an approach that minimizes changes to the existing structure of the assessment model.

TIME-DEPENDENT PROCESSES

The geologic record of the earth reveals a biosphere that is fundamentally time dependent, with time scales ranging from hundreds of millions of years down to days and hours. In this section, time-dependent processes that have affected the Shield in the past are identified, and evaluated with respect to their potential to affect radionuclide migration in the future. The processes can be grouped into four categories according to the way they are treated in the assessment model.

Processes That Do Not Require Modelling

Tectonism. Profound tectonic events, each lasting about 100-200 million years, occurred in different areas of the Shield about 3·1, 2·4, 1·7, 1·4 and 0·9 billion years ago. (6) However, there has been no major tectonic activity on the Shield for about 100 million years, and there is no reason to expect a resumption of activity in the next few million years.

Marine Inundation. In the intervals between tectonic events, the Shield was occasionally covered by inland seas, and subject to the deposition of marine sediments. (6) However, the last widespread inundation of the Shield occurred about 150 million years ago, and in all likelihood will not recur in the next few million years.

Tectonic Drift. The only appreciable drift of the North American continent during the past 100 million years has been in longitude, at a mean rate of about 1 cm/a. (7) This motion is too slow to induce any significant change, climatic or otherwise, in the biosphere over the next few million years.

Volcanism. The only location on the Canadian Shield where volcanic activity could possibly occur during the next few million years is near the Ottawa-Bonnechere graben, a rift system that experienced intrusive activity as recently as 125 million years ago, and that may still be active. (8) Volcanism will have no direct impact on the biosphere away from this region.

Meteorite Impact. The probability that a meteorite strike will damage the disposal vault is so small ($\sim 10^{-11}$ a^{-1}) that meteorite impact is not likely to affect the transport of radionuclides during the time required for the longest-lived fission products to decay. (9)

Denudation and Fluvial Erosion. Both denudation and fluvial erosion occur at a rate of about 10^{-5} m/a on the Shield. (10) The impact of these processes on the movement of radionuclides in the biosphere is therefore likely to be small, and can be minimized by careful vault siting.

Seismic Activity. Historically, seismicity on the Shield has tended to occur along well-defined structural features, and to cluster near junctions of different features. (11) These areas are probably locations of enhanced stress in the rock and are the likely sites of future stress relief. The vibratory motions associated with seismic activity are not expected to have any significant effect on the biosphere.

Processes That Are Unpredictable

Magnetic Reversals. Based on the historical record (12), a reversal of the earth's magnetic field can be expected within the lifetime of the vault. Although a reversal may trigger biotic change, the nature of the change cannot be predicted. No discernible effects accompanied the three short reversals that have occurred in the last 400 000 years. If man's technology continues to advance, it is likely that measures can be taken to counteract any detrimental effects of a reversal. For these reasons, it is recommended that magnetic reversals not be modelled in the assessment.

Genetic Evolution. Genetic evolution occurs continually, under steady-state climatic conditions as well as in response to a particular forcing such as glaciation. Evolution is an unpredictable process, and can include the formation of new species or the extinction of existing ones. However, given past rates of evolution, it is likely that natural selection will result in only minor changes to the Shield biosphere over the next million years.

Effect of Human Activities. Man's future interaction with the biosphere is difficult to predict. Technology is advancing at such a rate that it is conceivable that it will lead to control of the biosphere in the not too distant future, through the genetic manipulation of plants and animals, and the control of climate, including glaciations. Man may also be able to control the rate of radionuclide migration through the biosphere, or mitigate the effects of any radionuclides that reach the immediate human environment. On the other hand, man may return to a primitive state as a result of nuclear war, exhaustion of natural resources, severe degradation of the environment, or problems associated with overpopulation. In any of these scenarios, the biosphere will suffer a parallel change, at least temporarily.

In the face of this uncertainty, any attempt to predict man's effect on the evolution of the biosphere would be futile. The alternative is to assume that man's future activities, whether for better or worse, will probably not alter the biosphere in any fundamental way over long periods of time. The biosphere will then continue to evolve as it has in the past. The recent increase in concentration of particulates and radiatively active gases such as CO_2 in the atmosphere may disrupt the normal evolution of the global climate. (13) However, the replacement of fossil fuels with alternative sources of energy over the next few decades or centuries means that the current rate of increase of CO_2 is unlikely to be maintained far into the future. The excess CO_2 in the atmosphere will then be removed by the oceans, and the climate will revert to a state similar to that which exists today. There is no need to model this scenario explicitly since the entire cycle will be completed within 500 years, long before the radionuclides from the vault reach the biosphere.

Since the reference group in the assessment is assumed to eat contaminated food and drink contaminated water, the biosphere in the immediate vicinity of the discharge zone can be assumed to be under the control of man to the extent that agriculture, whether primitive or advanced, is practiced. Therefore, only biospheres consistent with agricultural practice need to be considered.

It is possible that man may intrude directly into the vault through drilling, mining or the use of explosives. Accidental intrusion is unlikely because of the small size of the vault relative to the total area of the Shield, its great depth, and its location in a type of rock that is plentiful at the surface and of low economic value. Similarly, deliberate intrusion as a result of sabotage or curiosity is unlikely because of the magnitude of the operation, which could not be carried out without the knowledge of the authorities. Deliberate intrusion to salvage the materials placed in the vault is a possibility, but a society advanced enough to want the materials should also be aware of the hazards involved and take steps to minimize them. The consequences of drilling a well into the bedrock in the vicinity of the vault are calculated explicitly in the assessment model.

Processes That Can Be Modelled Probabilistically

Short Time-Scale Fluctuations. The atmosphere exhibits a continuous spectrum of fluctuations at scales ranging from hours to decades, which are reflected in the other biosphere components. (14) Fluctuations with a period of 50 years or less (the amount of time over which the dose to the reference individual is integrated) should be parameterized in the transport models and not appear explicitly in the assessment model. Longer time-scale fluctuations can be handled probabilistically. For example, the local short-term climate of the Shield could be affected by the large amounts of aerosol injected into the stratosphere by remote volcanic activity (15) or meteorite impact. (16) This type of time variation can be handled stochastically through an appropriate specification of the distributions for air temperature and precipitation.

Processes That Require Time-Dependent Modelling

Glaciation. The Precambrian Shield has undergone repeated continental glaciation over the past two to three million years. The periodic variations in the earth's orbital parameters, which drive the glaciations, are expected to cause between 10 and 30 ice advances during the next one million years. (17) The ice volume record shows a general trend toward increased extent of continental ice with time, so it is likely that a vault located on the Canadian Shield will be covered with ice during each future advance. (18)

The Shield biosphere will undergo catastrophic changes during each advance and retreat of the ice, and the associated effects on radionuclide transport must be taken into account. Temperature and precipitation regimes, the volume and pattern of surface and subsurface water flow, geomorphology, soils, the type of plant and animal life, and human cultural practices will all vary profoundly during a glacial cycle. (19) Although the biosphere recovers quickly once the ice recedes, the patterns of surface water flow, the areas covered by glacial deposits, and the soil and vegetation types may be quite different after each ice advance. The discharge zone that is active before the onset of glaciation may be overlain by a lake, a river, a moraine, or fluvial, lucustrine, or windblown sediments in successive interglacial and interstadial states. Glacially induced changes in hydrogeology may create new discharge zones.

Faulting. No significant new faults are expected to be generated on the Shield within the next few million years. However, future rejuvenation of old Shield faults is likely because cyclic glacial loading and unloading represents one of the largest recent perturbations to crustal stresses. Faulting could increase the permeability of the rock in the geosphere barrier, and affect ground and surface water flows, including the depth to the water table. Faulting can therefore affect radionuclide migration through the biosphere, and must be considered in the assessment of time-dependent events. Since most faulting that will occur over the next few million years will be glacially induced, we will treat faulting in an integrated manner as one aspect of glaciation.

Succession. Succession occurs continually, under steady-state climatic conditions as well as in response to a particular forcing such as glaciation. The Shield shows a characteristic pattern of soil, plant and drainage development following the retreat of a glacier. (20) It is reasonable to assume that present succession patterns will continue until another glacial advance occurs, and that a similar succession will be re-established after the ice retreats.

INCORPORATING GLACIATION INTO A WASTE MANAGEMENT ASSESSMENT

Most scientists today accept orbital forcing as the pacemaker of the ice ages. (21) Periodic variations in the earth's orbital parameters induce associated variations in the amount of solar radiation received at the top of the atmosphere, which in turn controls the global climate. (22, 23) In the absence of human intervention, these Milankovitch cycles provide a credible means for predicting the timing, duration and magnitude of future glacial states. (24) It is unlikely that future glaciations can be predicted exactly, but it should be possible to produce a representative sequence of climate events. Physical and cultural parameters describing the biosphere and human behaviour throughout a glacial cycle can be predicted in a quasi-deterministic manner from the study of previous glaciations, and from the study of regions of the earth that are currently subject to glacial conditions. (17, 25)

The most straightforward way to incorporate glaciation into the assessment would be to follow radionuclide migration through a biosphere that varies in response to the climatic fluctuations predicted by the Milankovitch theory. The simulation would begin with the selection of values for all relevant parameters for current interglacial conditions. An initial distribution of radionuclides would be assumed, and the transport equations integrated for all pathways of importance. The distribution of radionuclides predicted at the end of the first time step is used as the initial condition for the second. New parameter values are chosen from the distributions appropriate to the predicted climatic conditions, and the integration continued.

Three major difficulties arise in implementing this scheme:

(i) Not all of the information required to perform the simulation may be available. Our understanding of the effects of glaciation on the biosphere are too incomplete and the data too inconsistent to use for detailed time-dependent modelling. (26) Parameter values and distributions would be difficult to estimate for conditions other than interglacial. Moreover, some of the migration pathways are poorly understood in other glacial states. For these reasons, it would not be credible to attempt detailed time-dependent modelling of radionuclide transport through the biosphere during a glacial cycle.

(ii) It is not clear that algorithms for the solution of the transport equations could be made flexible enough to handle time-dependent co-efficients and arbitrary initial conditions.

(iii) Although the biosphere itself suffers severe consequences during glaciation, it is not clear if the glacial cycle has any significant effect on radionuclide migration through the biosphere, or any detrimental effect on the dose to man. The effort required to implement detailed time-dependent modelling may therefore not be warranted.

Discrete State Approach

Given these difficulties with detailed time-dependent modelling, a number of simpler alternative methods for incorporating glaciation into the assessment model were evaluated. (19) It has been decided to adopt a discrete state approach, in which the continuous range of possible future biospheres is broken down into a small number of distinct steady-state units. The pathways by which radionuclides could reach man during each state will be identified, and the relevant parameter values and distributions defined. The effects of glaciation on radionuclide transport will then be evaluated by performing a separate, time-independent assessment on each state in turn, assuming that each state persists throughout the entire simulation period. The final assessment will be based on the results for the state that produces the most severe consequences.

The treatment of physical processes in this approach is fairly straightforward. However, since we must calculate the dose to a member of the reference group, it is necessary to make some assumption regarding human behaviour during the advance and retreat of the ice. Since the reference group is assumed to live in the vicinity of the discharge zone (where the largest doses will occur), the problem becomes one of locating the discharge zone throughout the glacial cycles. In the interstadial states leading up to the next glacial advance, the discharge zone will remain at the location assumed for the present interglacial conditions. During full stadial conditions, the presence of the ice, and glacially induced changes in the surface and groundwater hydrology, will deactivate the original discharge zone. Ground-water recharge beneath the glacier, and permanently frozen ground on its peripheries, will prevent the radionuclides from reaching the surface altogether. It is therefore reasonable to assume that the concept of a discharge zone and a reference group can be suspended, and that no assessment is required, during stadial conditions. However, radionuclide behaviour beneath the ice sheet must be understood if the consequences to man are to be correctly predicted once the glacier retreats.

With the retreat of the ice, conditions in the vicinity of the vault again become suitable for both human habitation and radionuclide discharge. The largest potential dose will occur if the reference group returns immediately following the retreat of the ice, to take up agricultural practices consistent with the predicted conditions of climate, soil and drainage patterns. Although it is possible that glacially induced hydrological or geological changes near the vault could result in changes in the location of the discharge area, the highest doses will occur under the assumption that radionuclide migration continues to be channelled through the original discharge zone. Account may have to be taken of changes in the character of the discharge zone due to the passage of the ice; for example, the discharge lake may be larger or smaller in volume, the terrestrial part of the zone may be overlain by new sediments, or faulting may have increased the permeability of the rock.

The discrete state approach, although not rigorous, provides a manageable first step towards including the effects of glaciation in the assessment. A time-independent structure can be used to assess each state, so that the mathematical problems associated with time-dependent co-efficients and arbitrary initial conditions are avoided. The predictions of the discrete state approach will be at least as credible as those of detailed time-dependent modelling since there is no need to predict environmental change far into the future. Similarly, it is much easier to define representative parameter values for a few states than to deduce a time-dependent sequence of values extending through several glacial cycles. The discrete state results can guide subsequent time-dependent modelling, if it is found that a more detailed assessment of glaciation is required.

There exist some glacially induced events that cannot be handled by the discrete state approach. These are events that cannot be resolved by the model because they occur too abruptly, or occur as the biosphere is switched between two time-independent states; or events that cannot be described using the standard transport equations basic to the assessment model because they cause a discontinuous redistribution of radionuclides in the biosphere. For example, contaminated sediments from the discharge lake may be gouged out by glacial action and spread over land that is later used for farming. A second example is hydrodynamic blowout, in which transient hydraulic gradients induced by a moving ice front could cause the abrupt ejection of large amounts of contaminated groundwater. (27) A third example is glacially induced faulting, which could cause an abrupt change in radionuclide migration rates by altering the permeability of the rock or the depth to the water table.

All isolated events that could result in an increase in radionuclide concentration must be identified and evaluated individually. It may be possible to parameterize some of these processes within the framework of the assessment model. For example, the use of contaminated sediments for farming could be modelled by using the material with the highest concentration among terrestrial soil, lake sediment and seepage faces as the substrate for plants. Similarly, faulting could be modelled by changing the appropriate parameter values discontinuously between time steps. However, a separate evaluation of some isolated events may have to be conducted outside of the assessment model.

The information required to implement the discrete state approach to time-dependent modelling is currently being assembled by a group of researchers at McGill University under contract to AECL. The data include

(i) the minimum number of biosphere states required to represent all future biospheres;

(ii) the migration pathways by which radionuclides could reach man during each state, including glacially induced pathways that could increase the rate of radionuclide migration to man, or that could lead to an accumulation of radionuclides in some compartment of the biosphere;

(iii) values of the parameters that are required to model radionuclide transport through the biosphere during each state; and

(iv) changes that could occur in the physical and chemical character of the discharge zone during the glacial cycle.

SUMMARY

During the lifetime of a nuclear fuel waste vault, the Shield environment may undergo profound changes in response to natural and anthropogenic forces. Any significant effects that these changes have on the rate or pattern of radionuclide migration to man must be taken into account in the assessment of the performance of the vault.

A large number of transitional processes were evaluated with regard to their potential for altering radionuclide transport through the biosphere. It is concluded that the effects of all processes, apart from glaciation and glacially induced faulting and succession, could either be neglected altogether, or handled within the current probabilistic framework of the assessment model. Glaciation will be modelled by defining a number of discrete biosphere states, performing a separate, time-independent assessment of each state, and basing the final assessment on the state for which the most severe consequences are predicted. This approach provides a manageable and credible first step to evaluating the effects of glaciation on radionuclide migration through the biosphere.

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