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Recent developments in assessment of long-term radionuclide behavior in the geosphere-biosphere subsystem

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A B S T R A C T

Decisions on permitting, controlling and monitoring releases of radioactivity into the environment rely on a great variety of factors. Important among these is the prospective assessment of radionuclide behavior in the environment, including migration and accumulation among and within specific environmental media, and the resulting environmental and human health impacts. Models and techniques to undertake such assessments have been developed over several decades based on knowledge of the ecosystems involved, as well as monitoring of previous radionuclide releases to the environment, laboratory experiments and other related research.

This paper presents developments in the assessment of radiation doses and related research for some of the key radionuclides identified as of potential significance in the context of releases to the biosphere from disposal facilities for solid radioactive waste. Since releases to the biosphere from disposal facilities involve transfers from the geosphere to the biosphere, an important aspect is the combined effects of surface hydrology, near-surface hydrogeology and chemical gradients on speciation and radionuclide mobility in the zone in which the geosphere and biosphere overlap (herein described as the geosphere-biosphere subsystem). In turn, these aspects of the environment can be modified as a result of environmental change over the thousands of years that have to be considered in radioactive waste disposal safety assessments. Building on the experience from improved understanding of the behavior of the key radionuclides, this paper proceeds to describe development of a generic methodology for representing the processes and environmental changes that are characteristic of the interface between the geosphere and the biosphere. The information that is provided and the methodology that is described are based on international collaborative work implemented through the BIOPROTA forum, www.bioprota.org.

1. Introduction

In post-closure radiological safety assessments of disposal facilities (repositories) for radioactive wastes, models are developed for, and applied to, the transport of radionuclides through the engineered barriers and surrounding host rock towards the biosphere. Assuming eventual degradation and failure of the engineered barriers, radionuclides could migrate through the host rock towards more superficial strata. Even where the host rock extends all the way to outcrop, its properties will differ in the near-surface zone from those at greater depths. These differences can include, but are not limited to, differences in the degree and style of fracturing due to superficial loading and unloading (e.g. due to the advance and retreat of ice sheets) or penetration of a weathering front. In many contexts, the host rock will be overlain by other strata with characteristics that differ markedly from the host rock. These may include old sedimentary rocks and/or more recent, unconsolidated deposits of Quaternary origin (QD). In either case, the most superficial materials are likely to include soils and recently deposited sediments.

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Whereas the role of the engineered barriers and host rock is generally to prevent or retard the migration of radionuclides (IAEA, 2011), in the more superficial strata retardation may be of less importance compared with dilution and dispersion, though retardation in these superficial materials may nevertheless be a relevant factor to take into account. Although the safety of geological disposal facilities is generally considered to rely primarily on isolation of the wastes from the accessible environment, in determining the radiological impacts of any releases of radionuclides in relation to the regulatory criteria typically employed (annual effective dose or risk to humans; dose rates to non-human biota) there is a need to evaluate the degree of dilution and dispersion in the superficial strata, together with any re-concentration that may occur (e.g. as a result of bioaccumulation).

To some extent, the degree of dilution and dispersion that occurs in the superficial strata may be explored in the geosphere models deployed in the safety assessment, e.g. by 2D or 3D modeling of the radionuclide plume, with the degree of refinement in the modeling dependent upon the stage reached in the site selection, investigation and utilization process. However, there is likely to be a need to explore in more detail what happens in the top few tens of meters where upwelling groundwaters interact with surface water bodies and/or infiltrating meteoric water.

Once the processes of near-surface dilution and dispersion have been evaluated, radionuclide concentrations in environmental media such as soils, sediments and surface water bodies can be determined. These concentrations form the starting point for biosphere models used to estimate radionuclide migration and accumulation within and among media in the accessible environment, including living organisms, and radiation dose rates to humans and non-human biota. Although there is extensive experience in such modeling and a substantial relevant database that has been accumulated over several decades, modeling of the underlying domain in which dilution and dispersion mainly occurs is less well developed.

In contrast to the deeper geological environment, where biogeochemical conditions vary only slowly over large spatial and long temporal scales, the superficial zone is characterized by more rapid variations, e.g. in geological structure, water flow, redox conditions and microbial activity. These factors can all affect radionuclide transport, but it may not be necessary to represent them all explicitly in models of radionuclide distribution. Indeed, the complexity of the near-surface environment is such that it would not be feasible to represent it in detail over the spatial and, more particularly, temporal scales of relevance in safety assessments of geological disposal facilities. This is well recognized in the biosphere, as conventionally defined, where the approach adopted is to use 'reference biospheres' that are referred to as 'measuring instruments' for use in converting radionuclide fluxes or concentrations into meaningful measures of radiological impact, typically represented by effective dose, risk or absorbed dose rate (IAEA, 2003).

For the superficial zone, which typically extends down to some tens of meters, the issue of how it should be represented in safety assessments is more complex than for either the deep geology or the biosphere. In the deep geological zone, there is generally a requirement to evaluate radionuclide isolation and transport based on the present structure (possibly with limited alterations, e.g. due to seismic effects), though with changing boundary conditions reflecting large-scale changes in climate and landform. Thus, the model may be taken to be predictive of the future conditions of relevance at the site of interest. In contrast, the biosphere systems selected for use in the safety assessment are generally taken to be representative of the range of situations that could occur, with an emphasis on those of greater radiological significance, but there is no implication that they are predictive of the situations that will occur. Furthermore, they are generally characterized in broad terms, such that each biosphere system studied is representative of a range of actual biosphere characteristics that could exist in the future at the site.

In the superficial zone, the initial characteristics should be taken into account in the safety assessment. However, they will alter with time and consideration has to be given to the degree to which that evolution should be modeled explicitly and the timescale over which there should be a transition to more schematic modeling.[1] A practical assessment timescale may be set by external factors (time until the next glaciation is projected to occur or until permafrost is expected to develop at the site) or by other considerations (e.g. the timescale for substantial fluvial incision, which may be a few thousand to many tens of thousands of years depending on the topographic and climatological context). Regulatory guidance may also restrict the timescale over which quantitative safety assessment studies need to be undertaken (e.g. SSM, 2008; STUK, 2010). In addition, the spatial scale of modeling has to be considered, as fine details of the projected distribution of radionuclides may not be needed for an overall evaluation of radiological impacts.

The above discussion relates primarily to deep geological disposal facilities, but many of the same considerations apply to shallow disposal facilities and contaminated sites. In the case of near-surface disposal facilities, radiological impacts may peak on timescales of a few centuries to a few millennia and releases of radionuclides from the engineered structure may be directly to superficial strata similar to those of interest in the case of a deep geological facility. In the case of contaminated land, radionuclides may migrate downward into the superficial strata and then be transported sub-horizontally to eventually emerge at groundwater discharge zones. This is often observed with waste heaps and tailings from uranium and other mining activities, with downslope, subsurface migration of uranium-series radionuclides to local streams and rivers (Thorne, 2012; Brown et al., 2013). Accordingly, it is anticipated that the results obtained and conclusions drawn will find reasonably direct application in these other contexts.

The possible range of ecosystems that could be in receipt of radionuclides from the underlying geological strata (for illustration, see Fig. 1), the extended time frame for assessment and the potential for environmental change during that time frame, both natural and man-made, present substantial challenges to performing appropriate, quantitative radiological safety assessments conforming to the requirements set out in IAEA (2011) and the nationally developed equivalents. Although agricultural ecosystems are often the focus of assessments, semi-natural systems may also require consideration, e.g. radionuclide accumulation in mires that could subsequently be converted to agricultural use required detailed evaluation by SKB (2011).

Section 2 of this paper provides a summary of some of the work that has been done to meet those challenges. This includes developments at the methodological level and other studies that have addressed the characteristics and environmental behavior of particularly relevant long-lived and/or geologically mobile radionuclides found in radioactive wastes, as these have the greatest potential to reach the biosphere.

Section 3 then describes progress in an on-going project organized through the BIOPROTA Forum that builds on the work described in Section 2 and is designed to provide a generic methodology to address all the safety relevant issues arising in the

[1] According to IAEA (2011), containment shall be provided until radioactive decay has significantly reduced the hazard posed by the waste. This may require several ka to substantially reduce the high inventories of shorter-lived radionuclides present in the wastes.