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Biosphere studies supporting the disposal system safety case in the UK

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ABSTRACT

Higher activity radioactive wastes remain hazardous for extremely long timescales, of up to hundreds of thousands of years. Disposing of such wastes deep underground presents the internationally accepted best solution for isolating them from the surface environment on associated timescales. Geological disposal programmes need to assess potential releases from such facilities on long timescales to inform siting and design decisions and to help build confidence that they will provide an adequate degree of safety. Assessments of geological disposal include consideration of the wastes, the engineered facility, the host geology and the surface and near-surface environment including the biosphere. This paper presents an overview of recent post-closure biosphere assessment studies undertaken in support of the Nuclear Decommissioning Authority Radioactive Waste Management Directorate disposal system safety case for geological disposal of the United Kingdom's higher activity radioactive wastes. Recent biosphere studies have included: (1) ensuring that the United Kingdom's approach to consideration of the biosphere in safety case studies continues to be fit for purpose, irrespective of which site or sites are considered in the United Kingdom's geological disposal programme; (2) updating projections of global climate and sea level, together with consideration of the potential importance of transitions between climate states; (3) considering geosphere–biosphere interface issues and their representation, including redox modelling and catchment-scale hydrological modelling; and (4) identifying key radionuclides and developing a series of reports describing their behaviour in the biosphere together with an evaluation of associated implications for post-closure assessment calculations.

Keywords: waste, biosphere, assessment.

Introduction

The principle of disposing of radioactive waste in an engineered facility deep underground is to ensure multiple robust and durable barriers to contaminant releases, enabling radionuclides to decay before reaching the accessible environment. Some of the contaminants are very long-lived, so that potential degradation of barriers and release and migration of contaminants need to be considered within an environmental safety case. Key regulatory criteria for evaluating the performance of a geological disposal facility (GDF) are expressed in terms of potential doses and risks that might arise to the most exposed members of future populations. Such exposures will occur in the biosphere and will be largest in the vicinity of any releases to the biosphere. Therefore, safety cases associated with geological disposal need to consider the biosphere (Fig. 1) and its representation on very long timescales (up to hundreds of thousands of years), including

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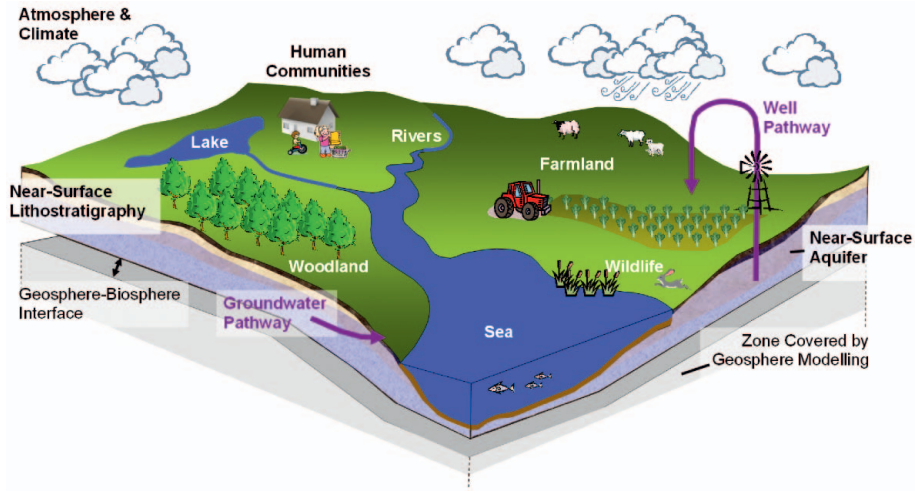

FIG. 1. Schematic representation of the biosphere, based on Nuclear Decommissioning Authority (2010*a*).

potential exposures to human populations and non-human biota.

The Nuclear Decommissioning Authority Radioactive Waste Management Directorate (NDA RWMD) current approach to representing the biosphere is described in the *Biosphere Status Report* (Nuclear Decommissioning Authority, 2010*a*) that supports the disposal system safety case (DSSC) (Nuclear Decommissioning Authority, 2010*b*). The report draws together more than twenty years of assessment knowledge and supporting studies to describe and justify the way in which the biosphere is represented in the DSSC. The NDA RWMD has kept its approach to the representation of the biosphere under review to help ensure that it is up−to−date, taking into account the latest science and best practice, in preparation for evaluating potential sites as the managing radioactive waste safely (MRWS) process (Department for Environment Fisheries and Rural Affairs *et al*., 2008) progresses. This paper provides an overview of recent post-closure biosphere assessment studies that have contributed to this overall objective.

Context and approach to representation of the biosphere

A central component of the biosphere studies undertaken in recent years has been the inclusion of a task to review the NDA RWMD approach to biosphere assessments and the context within which such assessments are undertaken. The task aims to maintain perspective in relation to the biosphere studies programme and provide the context and framework for associated technical tasks. Reports published to date encompass a description of the NDA RWMD approach to biosphere assessment (Egan *et al*., 2008) and a report that further discusses the context for assessments (Egan, 2009) within the framework of updated regulatory guidance (Environment Agency and the Northern Ireland Environment Agency, 2009). The regulatory guidance defines what is required of an assessment (i.e. it sets the assessment context), but those requirements have to be satisfied by making use of the best available science and technology. The reports emphasize that consideration of the biosphere is needed for two reasons. Firstly, it is the receptor for any contaminants and the location of key performance indicators, as described above. It can therefore be considered to represent a 'measuring tool' used to quantify the performance of the engineering and geosphere barriers rather than constituting a barrier in itself. Secondly, it defines boundary conditions for the geosphere. Hence it influences the deeper groundwater system and represents a potential source of disturbance of that system under changing environmental conditions.

All aspects of performance assessment are subject to significant uncertainty, particularly associated with the long timescales that need to be considered. This is especially the case for the biosphere, where the uncertainties are less constrained in comparison with the near field

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and geosphere components of the assessment. Assessments therefore do not attempt to predict what will occur, but instead aim to provide broad indicators of environmental safety for a range of different future evolution scenarios, with those scenarios intended to comprise a broad envelope of possibilities for future evolution. Biosphere assessments therefore, aim to strike a balance between complexity and robustness, with necessarily stylized representations aiming to be both plausible and to err on the side of conservatism. This means that biosphere assessments undertaken in the UK have focussed on contaminant releases via both gas and groundwater to an inland lowland agricultural location, which maximizes both environmental concentrations of radionuclides and usage of local potentially contaminated resources.

Biosphere change

The biosphere will change on the timescales of relevance to post-closure safety of geological disposal, primarily driven by natural and human-influenced climate and landscape evolution. Projections of long-term climate draw on the European Commission's BIOCLIM (2004) study, which indicated that a warmer climate is expected to persist for at least 100,000 years in the UK, with the next glaciation event being delayed until beyond 170,000 years after present (Fig. 2). Climate science, including modelling of the Earth's climate on long timescales and the development of approaches for downscaling climate projections to regional and local scales, continues to develop. The NDA RWMD continues to follow ongoing developments in this area. Overall, the more recent work supports the position that a very long period of interglacial conditions will persist in the UK.

The potential need for an explicit representation of biosphere change within assessment models was considered within this context (Thorne and Walke, 2010). For an inland, lowland terrestrial context, it was concluded that the biosphere will be subject to relatively limited changes on a timescale of 100,000 to 200,000 years (i.e. prior to the next full glaciation). Beyond this timeframe, less reliance will be placed on quantitative arguments and the need to explicitly represent biosphere change will strongly depend on the geological context. These conclusions are also related to geographical context and warrant review when potential sites are available e.g. to consider the potential importance of processes such as sea-level rise and coastal erosion.

Geosphere–biosphere interface

In assessing potential releases to the biosphere, there is necessarily an interface between the science and modelling associated with radionuclide transport through the geosphere and that associated with its behaviour in the biosphere (Fig. 1). The representation of the biosphere within RWMD assessments currently includes near-surface aquifers, which are the location of

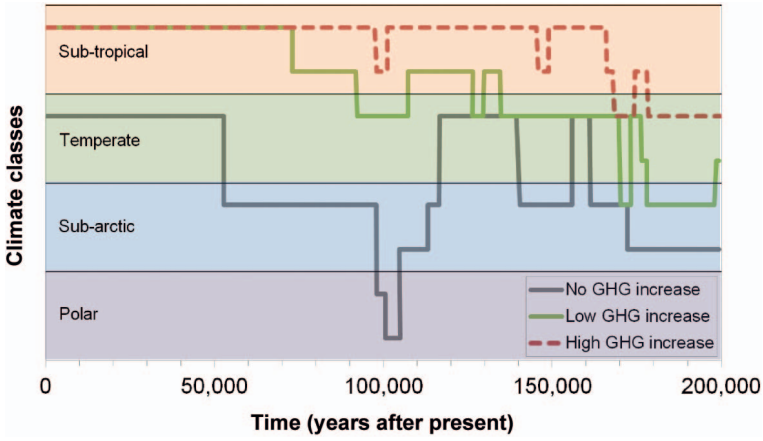

FIG. 2. Projected sequence of climate classes for a central England context for different levels of greenhouse gases in the atmosphere, based on BIOCLIM (2003).

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the interface between deeper, potentially contaminated and more recent meteorically derived groundwaters (Kowe and Norris, 2012). This region is of key importance for determining (1) boundary conditions for the deeper groundwater system, on a regional scale; (2) the degree of potential dilution of contaminated groundwater, on a more local scale; and (3) the potential nature and locations of discharges to the surface.

The need for, and appropriate approach to, catchment-scale hydrological and hydrogeological modelling will depend on the specific characteristics of potential sites. The regional hydrology will define boundary conditions for the deeper groundwater system, whereas near-surface aquifers receiving potentially contaminated groundwater and their associated regions of natural groundwater discharge will require consideration on a smaller scale. Indeed, contaminated groundwater may discharge some distance from the location of surface works associated with a GDF.

Site characterization will provide a wealth of information concerning meteorology and surface hydrology. Catchment-scale hydrological models can help in interpreting such information, providing confidence in the level of understanding of surface hydrology and near-surface hydrogeology in support of environmental impact assessment as well as providing an input to its representation at the assessment level, recognizing that the hydrological characteristics of a site in the future may differ significantly from the characteristics at the present day. Recent work has been undertaken to review approaches and codes for interpreting and representing this part of the system (Towler *et al*., 2011), from relatively simple water balance calculations using geographical information systems (GIS) through to more detailed process-based modelling codes including *SHETRAN* (Ewen *et al*., 2000) and *MIKE-SHE* (Hughes and Liu, 2008).

Radionuclide behaviour in the biosphere

Although a relatively stylized approach has to be adopted to the representation of the biosphere in post-closure performance assessment studies, the complexity of the biosphere system and range of potential exposure pathways to be considered mean that a large amount of data is required to characterize the behaviour of radionuclides in the biosphere system. A subset of radionuclides that need to be included in radiological assessments tends to dominate potential impacts and has been identified in the context of the UK disposal concept (Table 1). The RWMD plans to establish a series of generic reviews concerning the behaviour of these radionuclides in the biosphere and the associated implications in terms of the approach to be adopted in assessments and supporting research requirements. Four reports covering the ten radioactive elements identified as being potentially of greatest radiological significance in a UK context have been completed to date, and are described below.

TABLE 1. Key radionuclides for intermediate-level wastes, high-level wastes and spent fuel (with half-lives in years), based on Thorne (2008*a*).

^{14}C (5700)
^{36}Cl (3.01×10^5)
^{79}Se (2.95×10^5)
^{93}Zr (1.53×10^6) → ^{93m}Nb (16.1)
^{94}Nb (2.03×10^4)
^{99}Tc (2.11×10^5)
^{126}Sn (2.3×10^5)
^{129}I (1.57×10^7)
^{135}Cs (2.3×10^6)
^{239}Pu (2.41×10^4) → ^{235}U (7.04×10^8) → ^{231}Pa (3.28×10^4) → ^{227}Ac (21.8)
^{240}Pu (6560) → ^{236}U (2.34×10^7) → ^{232}Th (1.41×10^{10}) → ^{228}Ra (5.75) → ^{228}Th (1.91)
^{237}Np (2.14×10^6) → ^{223}U (1.59×10^5) → ^{229}Th (7340)
^{242}Pu (3.57×10^5) → ^{238}U (4.47×10^9) → ^{234}U (2.46×10^5) → ^{230}Th (7.54×10^4) → ^{226}Ra (1600) → ^{210}Pb (22.2) → ^{210}Po (0.379)

Note that shorter-lived daughters are assumed to be in secular equilibrium with their parent radionuclide.

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Chlorine-36, technetium-99 and iodine-129

The isotopes ^{36}Cl, ^{99}Tc and ^{129}I have been considered together (Thorne and Limer, 2009), because of similarities in their biogeochemical characteristics. All three radionuclides are likely to be subject to a very limited degree of sorption in the biosphere, with the exception of iodine in sediments. At the generic level, representation of these radionuclides within assessment models is supported by a broad base of information and the order of variation in total annual effective dose for unit flux from the geosphere or unit concentration in abstracted groundwater when parameter uncertainties are taken into account is typically less than an order of magnitude for inland, lowland agricultural ecosystems, implying a limited requirement for further research at this stage. A specific issue that arose with ^{36}Cl was the potential significance of incorporation in organic matter both in plants and soil. A radionuclide-specific model was developed to investigate this issue (Thorne, 2007*a*) and its performance was compared with other assessment models used to represent the behaviour of ^{36}Cl in terrestrial environments (Bytwerk *et al*., 2011).

Selenium-79

A report on ^{79}Se (Limer and Thorne, 2010) notes that there are substantial uncertainties in the degree of sorption of ^{79}Se in the soil, its uptake by plants from the soil and its volatilization. These uncertainties affect calculated annual effective doses, including those associated with the ingestion of contaminated animal produce, which represents the dominant human exposure pathway.

The mobility of selenium in the soil is affected by redox conditions and there is a body of literature examining the effect of redox on its dynamics in the soil−plant system. Nonetheless, there are areas where generic research might help improve understanding relating to selenium within the soil column, including determination of speciation and sorption associated with specific soil types and soil−water conditions. Some experimental work on this topic was included in the Nirex biosphere research programme (Wheater *et al*., 2007).

A separate report (Thorne, 2009) discusses the potential to model redox conditions in the soil zone in support of assessment calculations, drawing on an understanding of soil water conditions that may be developed through catchment-scale modelling described above. A detailed model for the behaviour of ^{79}Se in soils and plants that takes account of seasonal variations in soil hydrology and redox conditions has also been developed and parameterized in collaboration with Ciemat (Pérez-Sánchez *et al*., 2012).

Carbon-14

Carbon-14 is of potential interest due to both gas and groundwater pathways from a deep disposal facility. The fundamental importance of carbon to biological systems means that different considerations apply in comparison to modelling trace elements. A report has been prepared concerning ^{14}C in the biosphere (Limer and Thorne, 2011), which highlights the importance of appropriate representation of soil retention, degassing, dilution in the canopy atmosphere and plant uptake. The report also highlights the high freshwater to fish concentration ratios typically adopted for ^{14}C. These high values reflect limitations in the applicability of a concentration ratio approach when applied to a major nutrient element, as the main source of carbon for fish is their diet rather than the water in which they are immersed.

Uranium Series (U, Th, Ra, Pb and Po)

A report has also been prepared concerning the behaviour of uranium-series radionuclides in the biosphere, covering uranium, thorium, radium, lead and polonium (Thorne and Mitchell, 2011). Overall, the report emphasizes the extensive knowledge that exists on the environmental behaviour of most uranium-series radionuclides, but also points to areas where information is limited and shows that further consideration needs to be given to the development of integrated modelling approaches to represent the environmental behaviour of ^{238}U series radionuclides. Again, this work has been complemented by studies undertaken in association with Ciemat in which a detailed model has been developed to represent the behaviour of uranium-series radionuclides in soils and plants (Thorne, 2011). This model explicitly allows for losses of the inert gas ^{222}Rn from soils and plants following the decay of ^{226}Ra.

International Collaboration

Other radioactive waste management organizations and regulators have an interest in the

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radionuclides that are of potential importance to NDA RWMD assessments. Therefore, most of the radionuclide reviews discussed above draw on discussions and modelling conducted through the BIOPROTA forum, which provides a means of keeping abreast of the latest biosphere research and modelling (Smith, 2012).

Assessment modelling

A consistent approach has been adopted to representing the biosphere in post-closure assessment studies in the context of geological disposal of radioactive waste in the United Kingdom over the past twenty years (Thorne, 1990, 1995, 1998, 2003, 2007*b*; Stansby and Thorne, 2000). Biosphere models have been used to calculate radionuclide flux to dose conversion factors for use in performance assessment studies, and these studies have been complemented by supporting sensitivity analyses. Focus has been on representing releases to a lowland, terrestrial, temperate biosphere system on the basis that potential exposures are reasonably maximized. Calculations have been undertaken in the context of a range of geological environments, demonstrating that the approach can be applied to a range of potential locations for a GDF (Thorne, 2008*b*). The geological environment influences both the degree of dilution of radionuclides in near-surface aquifers and the spatial extent of discharges of contaminated waters to the surface environment. It also influences how those discharges are partitioned between soils and water bodies, such as rivers and lakes.

The approach to representing the biosphere has provided input to the development of international guidance and European studies, notably the recommendations of the International Atomic Energy Agency (IAEA) BIOMASS programme (International Atomic Energy Agency, 2003) and BIOCLIM (2004). The NDA RWMD model for representing the biosphere in performance assessment studies is in the process of being updated. The update provides an opportunity to frame the description and justification of the model consistent with the BIOMASS guidance (Fig. 3) as well as allowing account to be taken of key new sources of information, in particular an update to the IAEA collation of generic biosphere parameter values (International Atomic Energy Agency, 2009, 2010) and the radionuclide

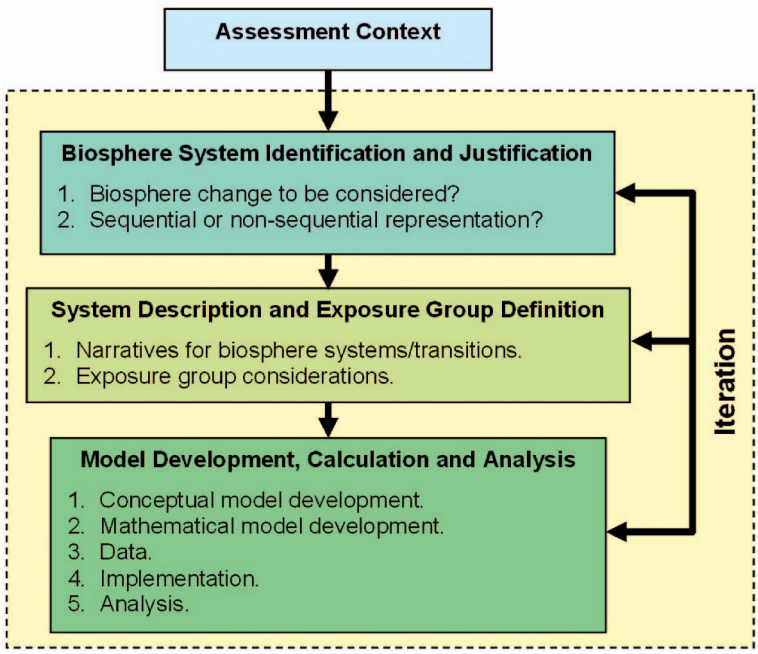

FIG. 3. Approach to developing and documenting the biosphere assessment model, drawing on the IAEA's BIOMASS guidance (International Atomic Energy Agency, 2003).

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reviews described above. Notable developments will include explicit audits against lists of generic features, events and processes (FEPs) of potential relevance to biosphere modelling (Nuclear Energy Agency, 2000; International Atomic Energy Agency, 2003). Explicit consideration will also be given to a range of potential climate states, including warm humid, warm dry, temperate, boreal and tundra.

Conclusions

In recent years the NDA RWMD has made substantial progress in its consideration of the biosphere through focussing on site-generic issues. Requirements for representing the biosphere as the MRWS process progresses have also been considered and work undertaken to help ensure readiness for the next steps in the programme. The NDA RWMD current approach to representing the biosphere is described in the Biosphere Status Report (Nuclear Decommissioning Authority, 2010*a*), which is available via the RWMD bibliography at: http://www.nda.gov.uk/documents/biblio/ together with the supporting contractor reports.

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