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An introduction to geosphere research studies for the UK geological disposal programme

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ABSTRACT

This paper gives an overview of the geosphere research studies being undertaken by the Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority. The approach of the RWMD in the current generic phase of the UK managing radioactive waste safely (MRWS) programme is to maintain an understanding of key processes and to carry out research and development into techniques so capability can be built. Although RWMD can demonstrate a general understanding of geosphere processes at this stage in the UK project, it is recognized that this will need to be made site-specific as the MRWS programme progresses. An understanding of the geosphere at the selected site(s) will be an important part of the future programme. Where possible, the RWMD will participate in international studies so that relevant site-based information can be accessed. In this way, the RWMD will be prepared for site-specific work in stage 5 of the MRWS process.

Keywords: geological disposal facility, GDF, managing radioactive waste safely, MRWS, environmental safety case, ESC, radioactive waste disposal.

Introduction

Confidence that a geological disposal facility (GDF) for the UK's inventory of higher activity radioactive wastes can be developed is built on the understanding of how the multiple barriers that would be present within a geological disposal system can work together to ensure safety for a wide range of geological environments. Isolation is an inherent feature of geological disposal, and containment (retaining radionuclides) is provided by both engineered and natural barriers. The geosphere, the rock and groundwater between a GDF and the near surface to surface environment supports containment in two ways: it can provide physical and chemical protection to the engineered barrier system (EBS) and thereby prolong containment within the EBS; and it can provide for an extremely slow mobility of radionuclides that are released through the EBS in the very long term.

The RWMD's generic environmental safety case (ESC) (Nuclear Decommissioning Authority, 2010*a*) provides more details on the safety functions provided by the geosphere after the GDF is closed and to long times in the future. The geological barrier:

(1) isolates the waste from people and the natural surface environment by providing a radiation shield;

(2) protects and buffers the EBS from dynamic human and natural processes and events occurring at the surface and in the upper region of the cover rocks (e.g. major changes in climate, such as glaciation);

(3) protects the EBS by providing a stable mechanical and chemical environment at depth that does not change quickly over time and can thus be forecast with confidence;

(4) provides rock properties and a weakly dynamic hydrogeological environment that

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controls the rate at which deep groundwaters can move to, through and from the backfilled and sealed facility, or completely prevent flow;

(5) ensures that chemical, mechanical and hydrogeological evolution of the deep system is slow and can be forecast with confidence;

(6) provides properties that retard the movement of any radionuclides in groundwater. These include sorption onto mineral surfaces and properties that promote matrix diffusion, hydraulic dispersion and dilution of radionuclide concentrations;

(7) allows the conduction of heat generated by the waste away from the EBS so as to prevent unacceptable temperature rises; and

(8) disperses gases produced in the facility so as to prevent mechanical disruption of the EBS.

Geosphere understanding

There are many different geological settings in England and Wales that may potentially be suitable for the GDF. The RWMD has selected three illustrative geological settings based on rock types that have already been identified as being potentially suitable for the geological disposal of intermediate-level waste (ILW)/low-level waste (LLW) and high-level waste (HLW)/spent fuel (SF) and that are the focus of GDF development in several other countries: higher strength rocks, lower strength sedimentary rocks and evaporites.

Higher strength rocks typically consist of crystalline igneous or metamorphic rocks or geologically older sedimentary rocks, where any fluid movement is predominantly through divisions in the rock, commonly referred to as discontinuities (e.g. open connected faults and fractures). Granite is a good example of a rock that would fall into this category.

Lower strength sedimentary rocks typically consist of geologically younger sedimentary rocks where any fluid movement is predominantly through the matrix of the rock mass itself. Many types of clay are good examples of this category of rocks.

Evaporites typically consist of halite (rock salt), anhydrite (anhydrous calcium sulfate) or other minerals that originated as sedimentary strata by evaporation from surface water bodies.

Table 1 summarizes the characteristics of these different host rocks in terms of mechanical, hydrogeological, geochemical and thermal properties.

A suitable geological setting is fundamental to geological disposal. A site should be both geologically stable in order to ensure safety and

TABLE 1. Characteristics of different host rock types.

Characteristic	Higher strength rocks	Lower strength sedimentary rocks	Evaporites
Mechanical	High strength. Pattern of fracturing is important for stability during excavations, but will also heavily influence the GDF layout.	Low to medium strength, affecting type of excavation support needed.	Strength depends on composition. Deforms in a viscoelastic manner.
Hydrogeological	Fracture-dominated flow. Permeability will be controlled by properties of individual fractures and connectivity of fracture system.	Generally very low permeability – solute transport likely to be dominated by diffusion, although advective flow is also possible.	Permeability extremely low or undetectable. Persistence of evaporites indicates that mobile groundwater is absent.
Geochemical	Chemically stable and likely to have groundwater with low to moderate salinity. Fracture-fill minerals may have strong capacity for sorption.	Groundwater composition may vary from slightly saline to brine. Chemically stable with significant buffering and sorption capacities.	Mobile groundwater is absent in normal evolution scenarios. If brines are present, host rock will have low sorption capacity.
Thermal	Lower thermal conductivity, implications for increasing spacing of waste packages.	Thermal conductivity low but strongly dependent on porosity. Some clay minerals have low thermal stability.	High thermal conductivity, implications for decreasing spacing of waste packages.

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also predictable to the extent required for assessing performance. A stable geological setting is one that is not likely to be subject to sudden or rapid detrimental changes over long timescales because of its buffering capacity with respect to internal and external perturbations. In the context of geological disposal, a site is considered to be geologically stable if perturbing geological events and processes can either be excluded, or shown to be sufficiently rare, slow or the consequences sufficiently small that safety will not be compromised over the required time frame.

The natural processes which may impact on the geosphere in a UK geological setting over the timescale of the next million years or so which are particularly relevant to geological disposal are (1) tectonics, (2) uplift or subsidence (shown in Fig. 1) and erosion, and (3) the impacts of future climate, particularly the potential impacts of future glaciations.

These natural processes and their potential impacts with respect to the three illustrative geological settings are described in the *Geosphere Status Report* (Nuclear Decommissioning Authority, 2010*b*). From historical knowledge and research, these processes are understood, and therefore their impacts can be predicted to an extent. Further, the geosphere at depths under consideration for a GDF (i.e. a depth between 200 and 1000 m) is less dynamic than shallow geological or surface environments. Processes occur more slowly at depth, therefore estimations of long-term behaviour and evolution can be made with some degree of confidence.

The construction of the GDF will have both an immediate and a long-term impact on the geosphere. In the context of the ESC the different categories of perturbations are identified (thermal, hydrogeological, mechanical, chemical, gas) and how they might affect the safety performance of a GDF is described in the *Geosphere Status Report* (Nuclear Decommissioning Authority, 2010*b*) Many of the processes are coupled, e.g. a thermal process may induce hydrogeological effects for example by inducing buoyancy driven groundwater flow, or a chemical effect by altering the mineralogy and consequent radionuclide retardation properties. The main types of interaction have been identified for different waste types and geological settings. Understanding of these effects and a capability to represent them appropriately in models is currently being developed.

Understanding of the geosphere draws on a number of sources. These include: (1) research and development (R&D) on the geosphere carried out in academic institutions in the UK and overseas; (2) R&D carried out by or for Nirex (now NDA RWMD) over a period of 25 years; (3) R&D carried out by or for the NDA since it was established; (4) R&D carried out by other organizations that are investigating geological disposal of radioactive wastes. This includes studies undertaken by overseas waste management organizations; and collaborative studies often partly funded through the European Commission (EC) or coordinated by the International Atomic Energy Agency (IAEA) or the Nuclear Energy Agency (NEA).

Three ongoing international collaborative projects of particular relevance to understanding the geosphere that the NDA RWMD is participating in are:

(1) Demonstration of coupled models and their validation against experiment (DECOVALEX) is an international research programme funded by a consortium of regulators and radioactive waste disposal agencies and is developing and testing models of coupled thermo-hydro-mechanical-chemical (THMC) processes. This project is ongoing.

(2) The Cyprus natural analogue project (CNAP), seeks to understand the long-term impacts of alkaline water on clay and focusses on the moderately alkaline pH range, approximately pH 10–11 (Alexander and Milodowski, 2011). The aim of the Cyprus study is to investigate clays which have been in contact with natural waters of a similar chemistry in order to investigate whether there are any long-term mineralogical changes. The main phase of field work for the project was completed in autumn 2010, the phase III project report has recently been published (Alexander *et al*., 2011).

(3) The long-term cement studies (LCS) project investigates ordinary Portland cement (OPC) and low alkali cement–rock interaction effects through laboratory studies, investigation at a field scale is conducted at the Grimsel underground test laboratory in Switzerland and there is supporting modelling.

Site characterization

In the future, one or more of the candidate sites will be characterized to determine whether it is suitable to host a GDF. The area of geosphere

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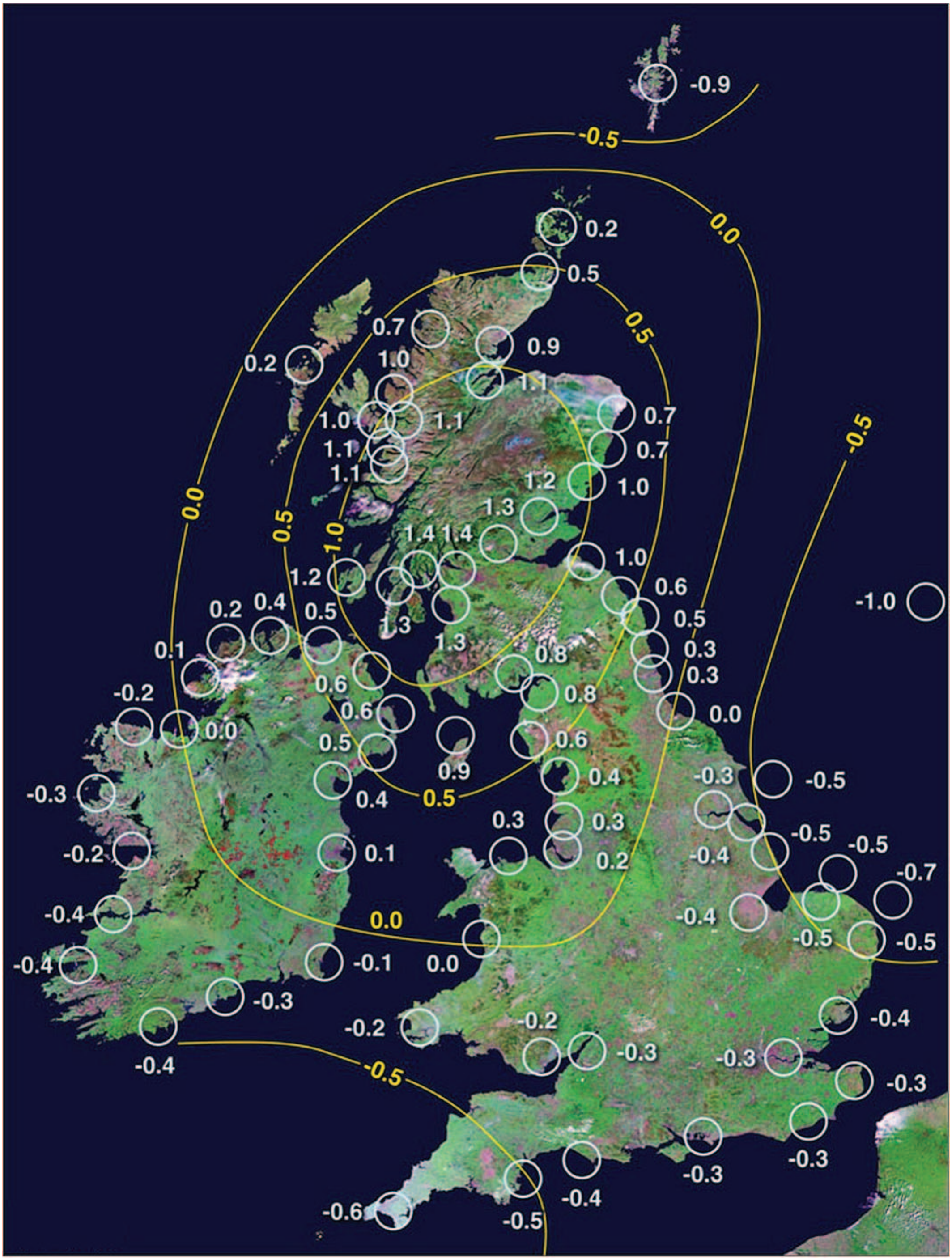

FIG. 1. A map of the UK and Ireland illustrating the mean rates of uplift and subsidence (presented as millimetres per year) during the Late Holocene (over the last 1000 years) i.e. the background geological trend not including any twentieth century acceleration (Shennan *et al*., 2009).

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research is linked closely to site investigation and characterization. In order to optimize site characterization, all waste management organizations have had to consider the types of information that should be collected and the ways in which this information is to be used to support the safety case. Therefore, in Nuclear Decommissioning Authority (2010*b*) the site characterization process is described and how it is used to develop understanding of the geosphere is outlined.

The *Site Characterization Status Report* (Nuclear Decommissioning Authority, 2010*c*) provides more detail about the RWMD's planned site characterization activities. A summary is given in Fig. 2, which shows how the site characterization sub-stages proposed by the RWMD map onto the MRWS process.

A series of site descriptive models (SDMs) will be produced as part of the site characterization process that integrate measurements and geoscientific principles into an adequate understanding. Each will address an aspect of the site and its setting. Ultimately, the different discipline-based SDMs must be brought together to provide an overall geoscientific understanding of the site. It is expected that the overall understanding will consist of: (1) measurements in sufficient detail to show the site as it is now ('initial state'); (2) interpretative models that integrate measurements into an adequate understanding of relevant processes; (3) a model that forecasts the long-term evolution of the site; (4) a model that forecasts the effect on the geosphere behaviour of constructing and operating a GDF; and (5) realistic estimations of uncertainties in all measurements and models and identification of alternative conceptual and interpretative models.

Site investigation activities need to provide data that will allow the RWMD to develop an understanding of the site for use in an ESC. It is recognized that it will neither be necessary nor possible to obtain a complete understanding of the present-day characteristics of the site and its expected evolution. An appropriate treatment of uncertainty forms an important part of the RWMD's programme. There are several types of uncertainty that need consideration:

(1) Uncertainties concerning the representation of processes in models and computer codes to represent the geological disposal system. This type of uncertainty is commonly described as conceptual model uncertainty.

(2) Uncertainties associated with the values of the parameters that are used in the implemented

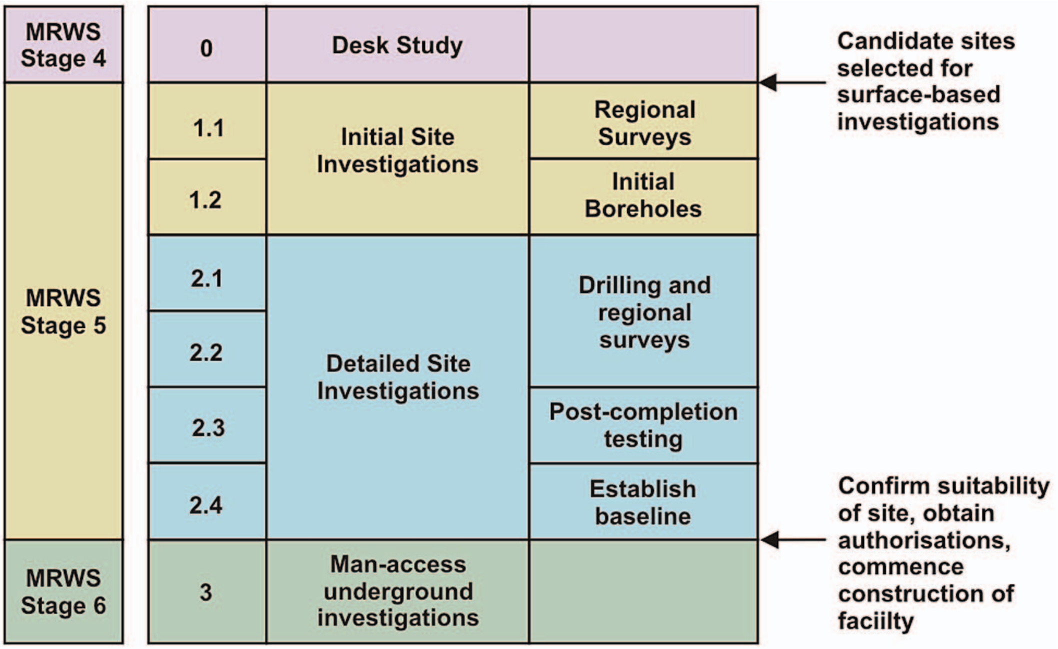

FIG. 2. Detail of the planned site investigation activities.

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models. These are variously termed parameter or data uncertainties.

(3) Uncertainty in future states of the geological disposal system. These are commonly described as scenario or system uncertainties.

The RWMD will continue to work alongside other international geological disposal programmes and will keep a watching brief on other sectors that undertake site characterization in order to maintain an up-to-date understanding of site characterization activities and available techniques. Generic R&D into a small number of techniques, for which work to date has demonstrated that further work may be necessary, will also be undertaken. Generic R&D is currently being undertaken into a number of areas including sealing of boreholes, coupled geophysical modelling and sampling of colloids, microbes and organics.

Site characterization: underground operations

As outlined in the NDA RWMD position paper *Planning for Underground Investigations* (Nuclear Decommissioning Authority, 2009), the MRWS White Paper (Department for Environment Fisheries and Rural Affairs *et al.*, 2008) identifies stage 6 by the term 'underground operations' and makes clear that the work to be undertaken during this stage will include long-term underground investigations, as well as construction activities. The aim of this investigation work, identified in the White Paper, is to confirm a site's suitability to host a geological disposal facility that complies with safety and environmental regulatory requirements.

The White Paper notes that even if a planning application were to be made solely for underground investigations, it would be necessary to demonstrate that the location was likely to be appropriate for facility construction. Following on from this, it notes that the implementing organization is to explore whether a single planning application covering underground investigations and geological disposal facility construction could be possible. This would be dependent in part upon the sufficiency of information gained from prior surface-based investigations.

The RWMD will ensure the requirements for underground investigations at a preferred site will be clearly identified through discussion with regulators, the host community and other interested parties during and following completion of surface-based investigations. Importantly, this will include taking account of the results from using the information obtained from the surface-based investigations in developing the engineering design and evolving the safety case for the disposal facility. It will only be at that stage that the scope of site-specific underground investigations required to develop a robust design and safety case can be specified. The RWMD will clearly wish to satisfy itself and the regulators that the programme of work planned to be undertaken in stage 6, if yielding favourable results, would be sufficient to enable regulatory approval of the construction of the disposal facility.

It is envisaged that there will have to be considerable confidence in the suitability of the preferred site to host a geological disposal facility based upon surface-based investigations in order to justify the cost and environmental impact of conducting underground investigations. The Geological Society conference *The Geological Disposal of Radioactive Waste* (http://www.geolsoc.org.uk/gsl/policy/policy_meetings/geological_disposal) considered the techniques used by Earth scientists to understand the types of geological conditions found below the surface and predict the characteristics of underground sites before they have been excavated. Papers presented at this conference demonstrate the continual improvement in the confidence that can be obtained from a wide range of surface-based investigation techniques.

The RWMD considers that there are significant benefits in integrating underground investigation activities and disposal facility construction activities, both in terms of planning permission and locations, when compared with a completely separate facility specifically for underground investigations. Consequently, when it is necessary to make assumptions for planning purposes, an approach that integrates ongoing investigations with construction will be adopted as a base case assumption.

Furthermore, as noted above, the requirements for underground investigations will depend strongly on the results of surface-based investigations conducted previously at the preferred site. A flexible approach is therefore being maintained as to the extent and nature of the requirements. In addition, the RWMD will maintain links and cooperation with a network of underground research facilities located in rock-types of relevance. This will provide access to the techniques and results of research relevant to features and processes in underground openings

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and can inform a judgement on the need to conduct equivalent research under the specific conditions of a preferred site.

The RWMD recognizes that in the even longer term after the initial construction of the disposal facility, as excavations of new disposal vaults and tunnels progress, the work of assessing the suitability of the newly accessed rock volume will continue. Also long-term underground research and monitoring are envisaged to be required at suitable locations in the facility to support updates to safety cases in respect of continued authorization of disposal at the facility and to ensure that operations and the eventual backfilling, sealing and closure of the facility are carried out in an optimal manner.

Research needs for current phase of GDF programme

Specific objectives for the RWMD geosphere research and development during the current preparatory studies phase on the GDF programme are to: (1) underpin the understanding of the expected evolution of the geosphere in response to natural processes; and (2) underpin the description of the impact of the GDF on the natural geological setting at the selected site, for example by understanding the size and properties of any chemically disturbed zone around the GDF.

The RWMD divides the future work programme into two subtopics: studies of the natural evolution of the geosphere and studies of the interactions between the GDF and the geosphere. Each can be further divided into a number of work areas as shown in Fig. 3.

Natural evolution of the geosphere

The natural geological setting is a key barrier in the system. The geological barrier is continually evolving. In order to build confidence in the performance of the geosphere in a multi-barrier

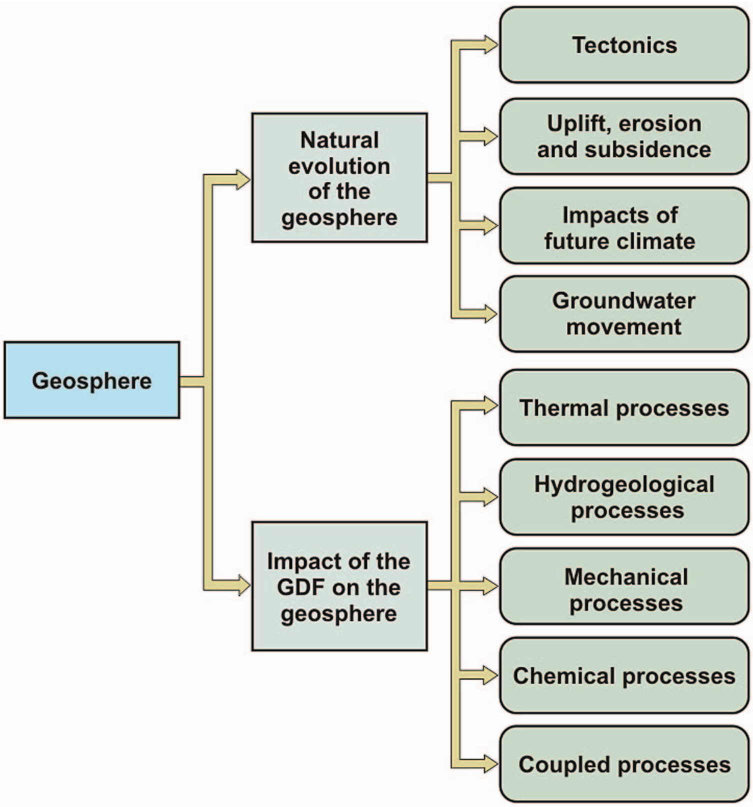

FIG. 3. Structure of the RWMD's geosphere research and development programme.

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concept, the RWMD needs to demonstrate that this evolution will not compromise the ability of the barrier to provide the isolation and containment that is fundamental to ensuring safety.

Natural evolution of the geosphere is widely studied for many applications. In the preparatory studies phase of the programme, there is a wide range of geological settings to consider. The RWMD's approach within a needs-driven programme is therefore not to undertake its own R&D into the natural evolution of the geosphere, but to draw on the advice of experts and obtain reviews of key processes and their significance. In that way the RWMD can target its R&D investment on those topics that are particularly critical to ensuring the safety of the GDF, once more information is available on the location and specific geological characteristics of the selected site(s).

Tectonics

Tectonics is not expected to be a discriminating factor in the site selection process; however, during the current phase of preparatory studies the RWMD plans to document its understanding of tectonics and its probable impacts on safety (this work will include consideration of the relatively small seismic events that occur in the UK and their potential impacts on hydrology). The RWMD will also continue to evaluate national and international studies on this topic to ensure that its understanding is in line with international best practice.

Uplift, erosion and subsidence

During the current preparatory phase of the MRWS project, the RWMD will review and document the current understanding of uplift, subsidence and erosion in the UK. The effects of these processes at the selected site(s) will be evaluated as part of the RWMD's site investigation programme.

Future climate

The future climate work area considers both future warming and cooling, including glaciations. In the current preparatory studies phase the RWMD will review the state of the art in future climate change studies, focussing particularly on the timing and consequences of future glaciation. With respect to the geosphere, the most likely potential impacts of warming are expected to be a rise in sea level with associated changes in groundwater movement and a delay of future ice ages. The current understanding is that the next ice age is now expected to be more than a hundred thousand years into the future. From the perspective of safety of a GDF, an extended interglacial period would mean that geosphere conditions similar to the present day would persist for longer timescales and the RWMD could therefore have greater confidence in the properties of the geosphere in the future. The RWMD will keep up to date with international activities in this field. Future work on the effects of glaciation on biosphere evolution is outlined in the *Biosphere Status Report* (Nuclear Decommissioning Authority, 2010*d*).

Groundwater movement

The topic of groundwater has been widely studied and substantial literature exists. However, investment in the understanding of groundwater movement and hydrochemistry in support of geological disposal in the UK has been very limited over the last 10–15 years. During that time there have been significant advances in analytical techniques, particularly for measuring *in situ* properties and isotopic analysis and also in computing capability, particularly in the capacity for three-dimensional models. During the preparatory studies phase, the RWMD needs to build capability and capacity in this important area. Therefore the RWMD will undertake regular reviews and implement any required development work so that site-specific models can be developed as soon as it is appropriate. Participation in international projects is an important component of this capacity building as it provides the opportunity to develop understanding based on data for real systems. A number of specific topics for review during the current phase have already been identified: (1) spatial heterogeneity, including the characterization of faults, especially their influence on patterns of groundwater flow; (2) palaeohydrogeological studies; and (3) the geosphere/biosphere interface.

Impact of the GDF on the surrounding environment

The presence of a GDF will, of course, affect the surrounding geosphere during construction, operation and the post-closure phase. The extent of the interactions and their significance will depend strongly on the features of the disposal concept and the host rock. Therefore the RWMD's approach during the current phase is

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to maintain its understanding of the key processes and their expected impacts and significance on the different potential host rocks so that this understanding can be used appropriately in decision-making. Once site(s) and concepts(s) have been developed, site-specific processes will be studied in more detail.

It is the coupling of these processes, rather than their individual impacts, which is particularly significant for the performance of a GDF. For convenience, this coupling is shown as a fifth base on Fig. 3. The understanding of coupled processes, described below, is central to the development of this subtopic.

Thermal processes

The most significant thermal perturbation is from the wastes, some of which produce heat as a result of radioactive decay, which could lead to thermal differentials in the groundwater in the surrounding rock, therefore potentially forming buoyant flows. The temperature in the host rock also drives other geosphere processes such as the rates of chemical reactions. Models of the temperature gradient exist and are being used in the programmes of the RWMD's sister organizations overseas. In the UK this type of model has been applied in order to understand the evolution of ILW vaults. During the current phase the RWMD plans to expand its capability so that the temperature profile associated with a co-located facility in a number of different geological settings can be modelled. Once site-specific information becomes available, this information will be tailored to the specific geological setting(s) under consideration in order to inform design and safety case considerations.

Hydrogeological processes

The open spaces in a GDF, including access and ventilation shafts, can affect the local head gradient, change local rock properties such as permeability and fracturing, and lead to desaturation of the rock. After closure, this will affect the resaturation of the facility. Studies of the effects of desaturation are being carried out internationally in underground rock laboratories in different geological settings and in operating underground facilities for a number of purposes. The approach of the RWMD during the current preparatory studies phase is to maintain an understanding of the probable hydrogeological impacts through continued participation in relevant studies overseas, which the RWMD is using to develop capability in this area. The RWMD is currently developing a model of desaturation in a clay environment as part of its work on the DECOVALEX project, the specific example being considered is related to the impact on a ventilation tunnel in the Underground Research Laboratory (URL) at Mont Terri in Switzerland.

Mechanical processes

As with hydrogeological effects, the presence of open spaces in the GDF will affect the stress field in the surrounding rock. Induced fractures may provide preferential paths for groundwater and gas movement (and associated radionuclide transport) in the post-closure phase. The RWMD's approach in the current phase is to keep abreast of developments in this area, and in particular, on the issue of coupled effects. The consequences of these effects will be assessed for the selected site(s).

Chemical processes

The GDF will have a number of impacts on the chemistry of the surrounding rock, including changes introduced by the ingress of oxygen and the different microbial populations that will thrive during the operational phase. One of the most significant chemical changes is expected to be the effect of high pH water from cement-based materials in the GDF on the surrounding rock. The interaction between high pH waters and a number of different rock types was extensively studied in the 1990s. However, the spatial extent of the interaction and the consequences for groundwater movement remain uncertain. The RWMD's understanding of the effect of interactions between rocks and lower-pH water (in the pH range 10–11) is also less well-developed. As this is an area where the RWMD needs to increase its process understanding during the generic phase of the GDF programme, it is participating in two international collaborative research programmes on cement–rock interaction: the LCS project and the CNAP (see previous text).

Coupled processes

An important consideration for both the natural processes of geosphere evolution and for changes arising from the presence of the GDF is that many

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are coupled. For example, the relaxation in stress as an ice sheet retreats may induce fracturing which in turn may draw down dilute, oxygenated water from the surface and so alter the chemical conditions at the depth of the GDF. Chemical changes such as the mineralogical changes caused by cement–rock interaction may seal fractures or pores in the surrounding rock and influence groundwater movement in the region of the facility. Developing an understanding of the expected couplings and a capability to model those effects is therefore central to the RWMD's geosphere research. The specific couplings of significance depend on the details of the concept, design and host geology and cannot be investigated in detail until site- and concept-specific information are available. However, in the current preparatory studies phase the RWMD is developing its understanding of the expected coupling and developing an appropriate modelling capability. An important part of the RWMD's work in this area is its participation in the DECOVALEX project; the RWMD is supporting two groups in order to develop capacity in this area; both groups include experienced researchers and PhD students.

Future studies

Although the RWMD can demonstrate an understanding of geosphere processes at this stage in the UK project, it recognizes that this generic understanding will need to be made site-specific. An understanding of the geosphere at the selected site(s) will be an important part of the future programme. There is an ongoing programme of research and development on the geosphere. The approach of the RWMD in the current generic phase is to maintain an understanding of key processes and to carry out research and development into techniques so capability can be built. Where possible, the RWMD will participate in international studies so that relevant site-based information can be accessed. In this way, the RWMD will be prepared for site-specific work in stage 5 of the MRWS process.

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