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Research in support of the 2011 environmental safety case for the Low Level Waste Repository

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ABSTRACT

This paper provides a summary of the research programme undertaken in support of the Low Level Waste Repository's 2011 environmental safety case (ESC). The programme has been developed, based on an understanding of safety issues and the requirements of the ESC. The research requirements to underpin the safety case have been identified by means of an auditable process, and subjected to scrutiny by both the regulators and a peer review group. Key research priorities for the future are identified.

KEYWORDS: repository, research.

Introduction

THE Low Level Waste Repository (LLWR), located near the village of Drigg in Cumbria, is the United Kingdom's principal facility for the disposal of solid low-level radioactive waste. The LLWR is owned by the Nuclear Decommissioning Authority (NDA) and operated on behalf of the NDA by a site licence company (SLC), LLW Repository Ltd. Under the terms of a permit, granted by the Environment Agency, the LLWR was required to submit an environmental safety case (ESC) for the LLWR no later than 1 May 2011. The ESC presents the arguments and evidence concerning the environmental safety of disposals of solid radioactive waste at the LLWR, at present and in the future, consistent with the Environment Agency's *Guidance on Requirements for Authorisation* (GRA) (Environment Agency *et al.*, 2009). In this paper, a summary is provided of the LLWR's research programme undertaken in support of the ESC. The ESC itself (Low Level Waste Repository, 2011*a*–*q*) and supporting documents, including those describing the results of the research programme, are available on the LLWR's website (http://www.llwrsite.com/environmental-safety-case). All of the references cited in this paper are available either from this website or by writing to the LLWR (see note to references).

A key focus of the paper is on the processes used to identify and prioritize components of the research programme and to ensure that the resulting programme is amenable to scrutiny. A technical summary is provided both of the LLWR's recent and future programme. A broad view is adopted of what is defined as 'research' and what is defined as 'assessment'. Any technical activities undertaken in support of the ESC that are not assessments (direct evaluations of system performance) are treated as research and are discussed in this paper. However, we exclude discussion of the LLWR's monitoring programme (Low Level Waste Repository, 2011*i*).

A previous safety case for the facility was submitted in 2002 (British Nuclear Fuels Limited, 2002). That safety case was reviewed by the regulators and found wanting in a number of respects (e.g. related to the lack of optimization and the relatively high radiological impacts that

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were calculated) (Environment Agency, 2005). Subsequent to the completion of the 2002 safety case, a range of technical studies was undertaken to address technical issues raised by the regulator and to improve understanding of certain issues. When management of the LLWR became the responsibility of United Kingdom Nuclear Waste Management (UKNWM) in 2008, the programme of research was reviewed and a programme set out that would support the delivery of a new ESC in 2011. This review and the resulting programme of work is the focus of this paper.

Overview of the site

Figure 1 shows a view of the LLWR site looking south. Starting in 1959 and for the first thirty-six years of operation, disposals were made by tumble tipping of drummed, bagged and loose wastes into seven trenches. The last trench was closed in 1995. From 1987 onwards, disposal operations were upgraded. Remedial work was carried out on the trenches; this included installation of a low-permeability cut-off wall (to limit lateral movements of groundwater and radionuclides) to the north and east of the trenches, interim capping of the filled trenches and upgrading of the leachate drainage system.

An engineered, concrete disposal vault was constructed, vault 8, which is now almost full to its originally planned capacity. Construction of vault 9 started in 2008 and was completed in December 2010. Most wastes in vault 8, and those currently being placed in vault 9, are contained within steel half-height International Organization for Standardization (ISO) containers or third-height ISO containers. Cement grout is used to fill remaining void space within the ISOs.

The vaults are constructed in heterogeneous Quaternary sediments that are some tens of metres thick and overly Permo-Triassic sandstones. Flow occurs from the repository first downwards through locally saturated sediments and then to the southwest towards the coast. A key component of research has focussed on building confidence of the understanding of the hydrogeology and in calibrating an appropriate groundwater flow model.

The disposal area is 400 m from the high water mark at its closest point, so that in the long term the site is vulnerable to coastal erosion. Taking account of the range of expected sea level rise, it is expected that the facility will be eroded by the sea within a few hundred to a few thousand years. The LLWR has discussed this issue with the Environment Agency and received advice

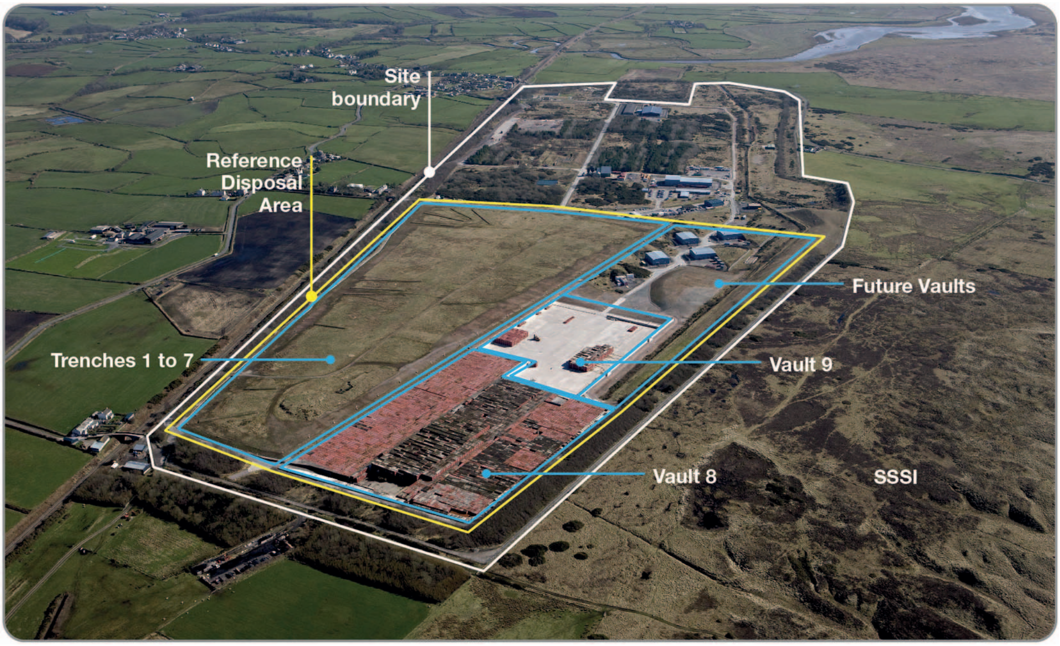

FIG. 1. The Low Level Waste Repository site in March 2011 (SSSI denotes a Site of Special Scientific Interest).

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that such erosion is an acceptable risk, provided that the requirements set out in regulatory guidance are fully complied with, including that disposals are optimized and the assessed impacts are consistent with the guidance level. As part of the ESC, the radiological impacts that might arise from coastal erosion have been assessed and shown to be consistent with the regulatory guidance (Low Level Waste Repository, 2011*l*).

Process

Overall approach

An important aspect of the research programme is the focus on the needs of the ESC rather than on scientific issues of academic interest. The overall objective of the programme is to resolve those uncertainties that will best help in producing a robust ESC. This may involve working on specific issues to allow a less cautious approach to be pursued in assessment calculations, or it may require study of some aspect of the repository site, for which it is not possible currently to demonstrate sufficient understanding. In all respects, the programme of research has been set out, based on a clear understanding of the safety- and performance-relevant issues.

Regulatory guidance

The ESC has been developed in the light of the regulatory guidance (Environment Agency *et al*., 2009). This sets out a number of requirements relevant to research and site characterization. Requirement 11 states that:

"The developer/operator of a disposal facility for solid radioactive waste should carry out a programme of site investigation and site characterisation to provide information for the environmental safety case and to support facility design and construction",

and in supporting text, it is noted that:

"The developer/operator will need to show that the geological environment is characterised, understood and can be analysed to the extent necessary to support the environmental safety case."

A similar requirement applies to the biosphere and mention is made of the relevance of the characteristics of the site under reasonably foreseeable future conditions. Under requirement 3, which sets out the need to produce an ESC, it is made clear that the ESC should describe "all aspects that may affect environmental safety, including the geology, hydrogeology and surface environment of the site, the characteristics of the waste..., the design of the facility and the techniques used to construct, operate and close it."

There is a clear regulatory expectation that adequate work should be done to characterize and understand the current state and future evolution of the repository and its surroundings. This does not mean that all uncertainties must be removed; indeed, the guidance makes it clear that it is inevitable that estimates of radiological impact and other aspects of a safety case will be subject to uncertainty.

Designing the research programme

In 2008, a complete review of the key technical issues and technical areas relevant to the ESC was undertaken as a basis for deciding on a programme of work. As an input to the development of the programme, a number of aspects were considered:

(1) results from work undertaken in support of a preliminary assessment submitted to the Environment Agency in 2008 (Baker, 2008);

(2) issues raised by the Environment Agency in issues assessments forms, prepared by the EA as part of their review of the 2002 PCSC (Grimwood, 2006; Lean, 2007), received informally and/or set out in the Environment Agency's review of the 2002 PCSC (Environment Agency, 2005);

(3) recommendations arising from previous research;

(4) the outcome of a process of technical review, undertaken as part of due diligence when UKNWM took over the management of the LLWR.

A series of workshops were held to discuss appropriate technical approaches in some key areas. These workshops covered: geology and hydrogeology; assessments and safety case development; biosphere and human intrusion; assessment of non-radiological impacts; near field and gas; inventory; optimization; the operational environmental safety case; and coastal erosion.

All of the workshops were attended by LLWR staff. In most cases, external experts from contractors or from academia also participated in discussions. The objective of each workshop was not to agree or define the future work

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programme, but to identify a range of potential studies together with their pros and cons. Subsequently, a research programme was set out by the LLWR drawing on technical information from the workshops. Research activities were included in the programme where:

(1) resolution of an issue or uncertainty was required in order to provide a satisfactory safety case;

(2) it was not possible to demonstrate an adequate understanding of the repository system without further work;

(3) there was a view that uncertainties in input data could be reduced in a reasonable and practicable manner.

In addition, the research activities were screened and formulated so that they had a reasonable chance of success and could provide results on a timescale compatible with the delivery of an ESC in 2011. The programme was documented and made available for external scrutiny (see below) (Baker, 2009). Provision was made for various hold points in the programme at which progress could be reviewed and decisions made as to whether further research was required.

Peer review

The approach to the ESC and the design of the underpinning research programme have been subject to scrutiny by a peer review group. The peer review group was given information about the content of the programme as it developed. They have therefore been able to influence the LLWR's programme at an early stage. A summary of the peer review group's current views on research, including future priorities, is set out in Bennett *et al.* (2011). The LLWR's response to the peer review is provided in Low Level Waste Repository (2012).

Regulatory review

Monthly meetings are held between the LLWR and the Environment Agency and, at some of these meetings, the formulation of and results from the research programme are discussed. This has provided a mechanism for the LLWR to understand regulatory views and requirements. Until 2010, an annual report on research was produced and submitted to the Environment Agency for review. This also provided a mechanism for early comment and discussion.

Recent programme

In this section, an overview is provided of the key components of the recent research programme.

Inventory

Information on the currently disposed inventory and the inventory that will be disposed is a fundamental basis of a satisfactory safety case. Prior to 2008, a considerable amount of work was undertaken to understand the disposed inventory based on analysis of historical records and analogue waste (Lennon *et al.*, 2008; Wareing *et al.*, 2008). This included work to identify the locations of key disposals where significant radionuclides are concentrated and also to:

(1) undertake a review of the non-radioactive inventory to identify any substances which might be present in the disposed inventory, but which are not identified in the national inventory (Dickinson and Kelly, 2009);

(2) consider information from a series of interviews with former staff at the LLWR and Sellafield to determine any implications of past (i.e. in the 1960s or 1970s) practices to the understanding of the disposed inventory (Dickinson and Smith, 2011);

(3) devote considerable effort to understanding the future inventories of ^{14}C and ^{36}Cl and their waste associations (Baston *et al.*, 2011), given that they are key contributors to long-term radiological impact.

This programme of work has improved and built confidence in the inventory. For example, it was determined that any impact of issues raised by former staff was likely to be encompassed within the uncertainties that had previously been determined for the trench inventory.

Near field understanding

Modelling the evolution of chemical conditions

It is important to model the evolution of chemical conditions, taking account of microbiological processes in order to understand the rates of volume change of degradable wastes such as cellulose and to understand how radionuclides may behave as a result of changing pH and redox conditions. A computer model of groundwater flow and chemical reaction, the *Generalised Repository Model* (*GRM*), has been used in the past for this purpose (Low Level Waste

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Repository, 2011*f*). The previous *GRM* model has been updated to take account of new data and the latest repository design and used to make such estimates (Low Level Waste Repository, 2011*f*). Estimates of uranium solubility, for example, from this model have been used to inform the choice of the corresponding assessment parameters (Fig. 2).

Heterogeneity

It is considered that heterogeneity in chemical conditions within the repository could be a significant issue and that there might be a bias in models that assume a homogeneous treatment. A range of approaches have been used to address the issue:

(1) Conceptual models have been developed for different waste types to address the effects of physical and chemical heterogeneity on the container scale (Small *et al.*, 2011). These models consider the chemical reactions that occur in waste containers containing different types of waste.

(2) The *GRM* has been used to investigate the effects of heterogeneity by representing the spatial variation of waste types in vault 8 (Low Level Waste Repository, 2011*f*). This makes it possible to identify different regions of the vault with different chemical characteristics

(3) Modelling has been undertaken to investigate the reaction of carbonate species derived from organic-rich wastes with surrounding cement grout. This modelling used a computer program to address chemical reaction and the transport of carbon dioxide from a waste puck containing cellulosic wastes through a fractured grout (Wilson and Metcalfe, 2009).

Release and chemical reactions of uranium

Uranium was selected for study because uranium series radionuclides were considered likely to be key contributors to radiological impact. In certain past disposals to the LLWR, uranium was believed to be present as discrete inclusions within a magnesium fluoride slag wasteform. A programme of work has been completed to confirm the form of uranium in such disposals (Thompson *et al.*, 2010). This included a scanning electron microscopy (SEM) study to identify the form of uranium within the wasteform and simple experiments to determine the rate of dissolution and uranium release from the wasteform. The SEM study has confirmed the presence of spherical and angular uranium inclusions up to 30 μm in size. X-ray diffraction analysis indicated the uranium to be in the form of UO_2. Uranium concentrations in leaching experiments under groundwater conditions were consistent with the slow release of uranium from the dissolution of these inclusions, with the rate limited by the dissolution of the fluoride. Figure 3 shows trench leachate data for magnesium and fluoride, consistent with the dissolution of magnesium fluoride and recrystallization to calcium fluoride.

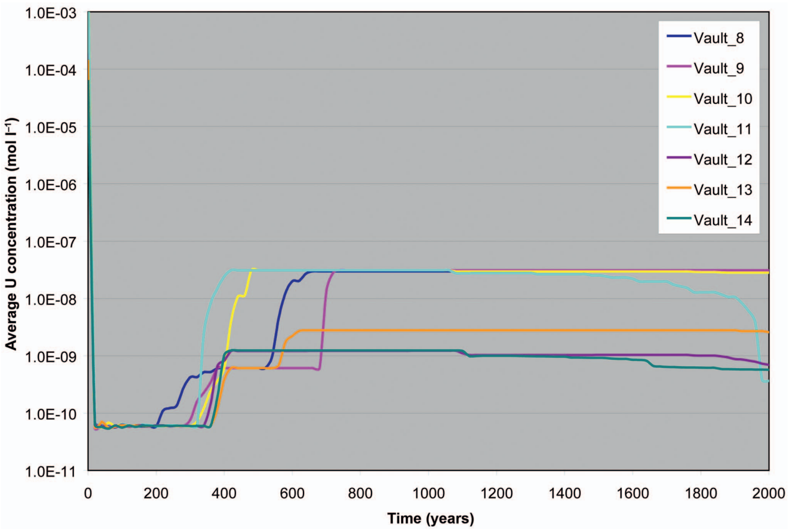

FIG. 2. Estimates from *GRM* of the average uranium concentration in each vault as a function of time.

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Work has been undertaken to address the sorption of uranium (IV) and uranium (VI) to a range of near-field substrates including soil, cement, concrete and corrosion products (Clacher, 2010). This work has supported the choice of appropriate parameters in assessment calculations.

Long-term experiments

Long-term vault and trench experiments (LTVE and LTTE) (Low Level Waste Repository, 2011*f*) have been set up and continue to be monitored. The objective of such experiments is to monitor the evolution of real vault and trench wastes over periods of decades and understand gas production, corrosion, cellulose degradation, the development of microbial communities and the evolution of chemical conditions. Data on corrosion rates and cellulose degradation have been used to support the treatment of the near field in assessment calculations. Figure 4 shows cumulative gas generation rates from the LTTE, which have been used to derive a cellulose hydrolysis rate for use in *GRM*. Future destructive analysis of one or more of the experiments is under consideration.

Organic complexants

To support the choice of appropriate waste acceptance criteria, a review has been completed of the different complexants that might be present and their potential effects on radionuclide solubility. In particular, those complexants that should be subject to declaration or limited are identified (Randall *et al*., 2011). The organic complexant of most potential concern is EDTA, which is used in decontamination agents. Some other complexants are released from the waste-form slowly, biodegrade or are not generated under the chemical conditions at the LLWR.

Site understanding

Additional boreholes

It was recognized that although a large number of boreholes were available at the LLWR site, there were relatively few in the region between the LLWR site boundary and the coast, a key region with respect to understanding migration of contaminants from the site. A further 14 boreholes were drilled outside the site and mostly in this region with the objective of improving knowledge of geology and hydrogeology in that area (URS, 2009).

Geophysical survey

A geophysical survey has been carried out to help characterize the internal structure of the Drigg Spit and the ground between the Low Level Waste Repository and the sea (Halcrow, 2010). The geophysical techniques employed included electrical resistivity imaging, ground penetrating radar (GPR), electromagnetic conductivity (EM) and seismic refraction. The resulting data were combined to produce interpretative geophysical models and eight cross sections were produced to display the results. These data have been used in work to develop the geological model of the site

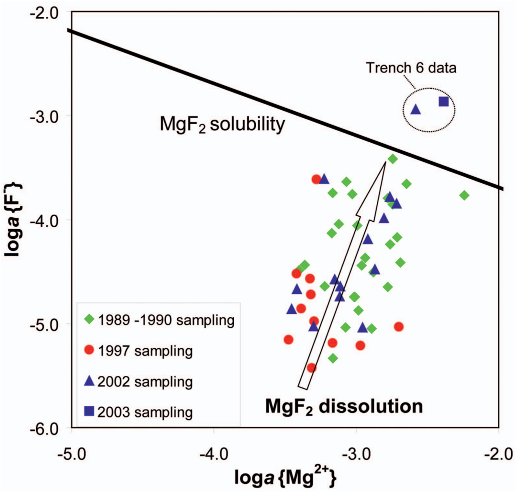

FIG. 3. Trench leachate data for magnesium and fluoride.

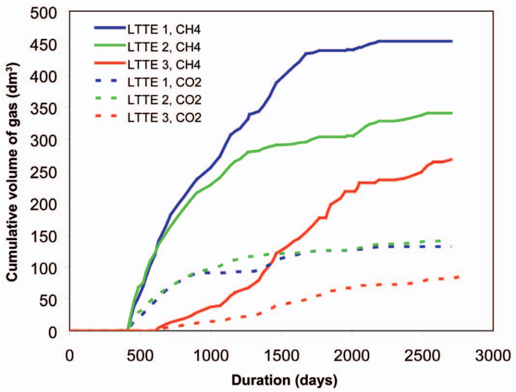

FIG. 4. Cumulative gas generation from the long term trench experiment (LTTE) as a function of time.

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and as an input to estimating the rate of future coastal erosion.

Revised geological model

A revised geological interpretation has been produced and documented in a key supporting report (Michie *et al.*, 2010). In previous work, the sedimentary deposits have been divided into lithofacies units composed of similar material types. A consistent 3D regional geological model has been developed, in which the site and regional scale interpretations have been integrated. The current interpretation now uses a unified set of lithofacies units covering the LLWR and the surrounding region. A new 3D model has been developed using the geophysics and other new data and used to provide surfaces for use in 3D hydrogeological modelling.

Groundwater flow modelling

A programme of work has been completed to develop an updated model of groundwater flow, suitable as a basis for the 2011 ESC (Low Level Waste Repository, 2011*g*). Key aspects of the model include a detailed representation of the engineered system and calibration against observed heads and recharge. It has been used to understand the evolution of groundwater flow and saturation in the repository near field as an input to optimization studies and as the basis for a flow network model for use in the assessment. Transient data on water levels are being used as a further input to calibration.

A considerable amount of work has been undertaken to explore the potential effects of spatially varying hydrogeological properties (Low Level Waste Repository, 2011*g*). Figure 5 shows some example results showing clustering of pathlines in association with regions of high hydraulic conductivity.

Coastal erosion

In the last decade, it has been recognized that coastal erosion of the facility is likely to occur on a shorter timescale than previously envisaged; within a few hundred to a few thousand years. An understanding of coastal processes and their rates is therefore important to understanding the timing and potential modes of erosion and in developing appropriate models of radiological impact. Accordingly, there has been increased focus on this technical area and a number of activities have been undertaken as follows:

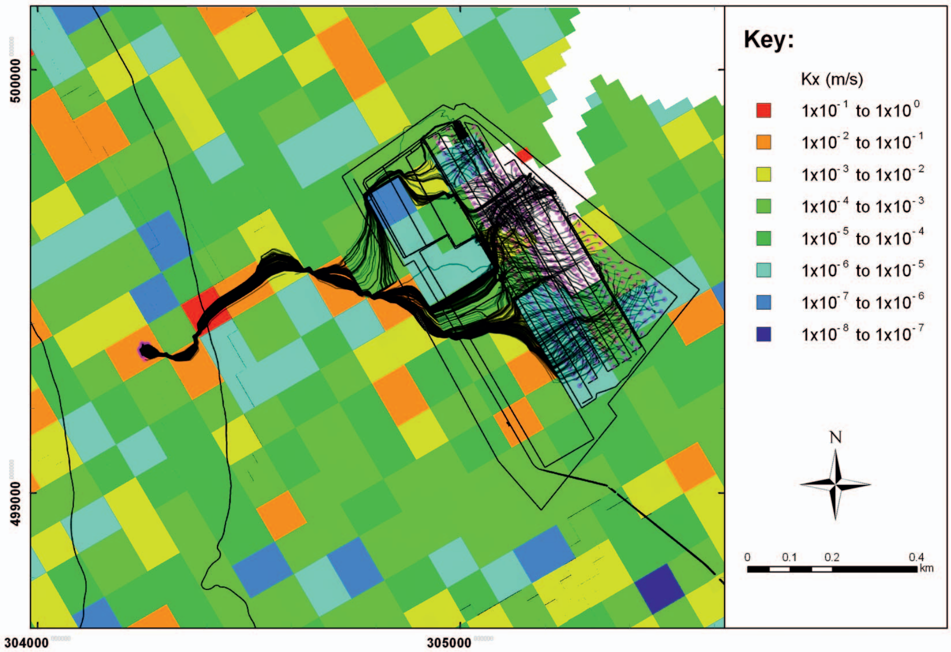

FIG. 5. Pathlines for starting positions in the trenches for a model realization with spatially varying hydraulic conductivity in unit B3.

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(1) systematic collation of all of the data gathered during previous work (Halcrow, 2009) and the comparison of a recent monitoring exercise with previous data (LLWR, 2011*h*);

(2) geophysical characterization of Quaternary sediments along the coastal strip and between the facility and the sea (see above);

(3) modelling to address aspects of the evolution of the Ravenglass estuary, longshore processes and coastal erosion;

(4) production of an updated conceptual model, including review of the scenarios for climate and sea-level change, and their impact on coastal erosion, as a basis for radiological assessment models (Fish *et al*., 2010); and

(5) use of a computer program to model the erosion of the coastline (Royal Haskoning, 2010).

Radon

In calculations undertaken prior to 2008, estimates of exposure to radon, following the hypothetical construction of a house on contaminated spoil arising from future inadvertent human intrusion into the facility, were obtained using a diffusion model including subjectively estimated parameters. It was recognized, however, that an empirical approach was possible based on extensive datasets held by the Health Protection Agency and the British Geological Survey for radon in dwellings and uranium/radium in soil in the UK, and such an approach would provide a more robust relationship between radium concentrations in contaminated ground and radon concentrations that might arise in dwellings built on such ground. To support such an approach, a programme of work was conducted to examine the empirical relationships between uranium/radium in the ground, radon in soil and radon in dwellings (Appleton and Miles, 2009; Cave *et al*., 2010). Data were assembled on concentration of radon in soil gas, concentration of uranium in soil, estimated uranium (eU) from ground-based and airborne gamma-ray surveys and radon concentrations in homes. The work demonstrated that relationships between radon in dwellings and uranium/radium in the ground or radon in soil differ depending on the characteristics of the underlying geological units. It was concluded that the regression models based on analysis of the data for regions of higher permeability bedrock provide a valid approach to the estimation of indoor radon related to ground concentrations of radium or radon gas in the context of the LLWR post-closure safety assessments.

Future programme

As part of the ESC, the LLWR outlined a programme of future work (Low Level Waste Repository, 2011*a*). Some of this programme was focussed on implementation and maintenance of the ESC. In addition, a need was identified to improve understanding in a number of well defined areas. The following are highlighted as issues that may need to be addressed in the future programme:

(1) The near-field behaviour of ^{14}C, including its release from different wasteforms, is of key importance in determining the flux of ^{14}C bearing gas from the facility. Further work might involve focussed experiments on particular types of waste, carefully designed long-term experiments or improved, possibly simpler, modelling of gas generation and other near-field processes.

(2) Experiments to characterize the release of contaminants (key radionuclides and non-radiological contaminants) from different waste types.

(3) Carefully designed experiments to provide a firmer basis for the model of contaminant release from waste in an unsaturated environment, as used in assessments.

(4) A review task will be undertaken to establish the best way of reducing key near-field uncertainties for the particular conditions of the LLWR trenches and vaults as they evolve during operations and closure and in the longer term.

(5) Further analyses of hydrogeological data to better understand the relationships between hydraulic conductivity and lithology beneath and in the vicinity of the site.

(6) Further consideration of the elevated groundwater levels immediately to the west of the site and to analyse the implications of new geological data on the location of discharges.

(7) A review of the potential and value of long-term tracer tests to build confidence in our understanding of contaminant transport. Such tests would need to be extensive and sophisticated, to take account of the effects of spatial variability.

(8) Continued monitoring of the coastline in order to confirm our understanding of the evolution of the coast and mechanisms involved.

(9) Maintain a watching brief on developments in the science and predictions of climate change

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and coastal erosion. If there were significant developments in forward projections of climate change and sea-level rise, or in modelling capabilities in relation to coastal erosion, then the merits of developing further site specific physically based models would be considered.

(10) Our assessments of radiological impact arising from coastal erosion depend on the way in which wastes degrade on the beach, the leaching of contaminants from those wastes and the behaviour of wastes and sediments dispersed in the near shore environment and along the coast. There is scope for a more realistic treatment in our models of the processes of contaminant release, local sedimentary processes and uptake by marine biota that could be applied to the impacts of both radionuclides and non-radiological contaminants.

(11) Review and update of the biosphere model for the incorporation of ^{14}C in plants, especially for gaseous release from the soil. In particular, alternative models will be investigated of the effective dispersion of gases in plant and crop canopies as developed and calibrated for other applications. Connection will also be made to an experimental programme on the uptake of ^{14}C in plants funded by the Radioactive Waste Management Directorate of the Nuclear Decommissioning Authority (RWMD NDA).

Recently, we have established an agreement to enable discussion of research issues and sharing of research results with the RWMD NDA, which will ensure coordination over topics of common interest and promote more efficient allocation of research resources.

Summary

A research programme has been developed based on an understanding of the requirements of the ESC. The research requirements to underpin the safety case have been identified by means of an auditable process subject to scrutiny by both the regulator and a peer review group. The following technical areas are the most significant priorities in terms of the LLWR's recent and near-future research programme:

(1) the impact of heterogeneity on near-field chemical evolution;

(2) the behaviour of ^{14}C in the near field and in the biosphere, in relation to the release of ^{14}C bearing gases;

(3) understanding the interactions between pore-water and contaminants in unsaturated systems;

(4) developing understanding of coastal erosion by continued local monitoring, and further modelling as and when appropriate techniques become available; and

(5) in general, continuing to maintain and build confidence in the models used to represent the repository system and, therefore, provide a firm basis for our estimates of future impacts and waste acceptance criteria at the LLWR.

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