LLW Repository Ltd

LLWR Lifetime Project

Progress on Research and Development to July 2010

This document was prepared by the Low Level Waste Repository

LLWR/ESC/R(10)10032 Issue 1 Date: July 2010

	Name	Signature	Date
Author	Andy Baker	[signature]	28/7/2010
Checked by	Richard Cummings	R Cummings	29/7/10
Approved by	Richard Cummings	R Cummings	29/7/10

This page is left blank intentionally.

EXECUTIVE SUMMARY

The Environment Agency (the Agency) is the UK regulatory authority responsible for authorising the disposal of radioactive waste at the Low-Level Waste Repository (LLWR) in West Cumbria. The Agency issued a new Authorisation (BZ2508/BZ2508) for the LLWR on 1 May 2006, which includes a list of improvement and additional information requirements (Schedule 9) that must be fulfilled by the operator, and are currently being addressed.

Item 4 of Schedule 9 requires the LLWR SLC to undertake a programme of research and development (R & D) to support specific improvements in the safety of the site. In response to this, a programme of R & D was submitted to the Agency in July 2006. Annual reviews were carried out in 2007, 2008 and 2009. This document reports progress in the year to July 2010. The main components of the LLWR's R & D programme, directed at supporting the 2011 Environmental Safety Case (2011 ESC) and developing our overall understanding of the environmental impact of the LLWR, are summarised in this document.

During the year to July 2010, the focus has been on completing research and characterisation tasks prior to the data freeze for the 2011 ESC, and ensuring that appropriate assessment models are in place.

A substantial programme of work has continued during the current year with the objectives of improving the inventory. An overall objective is to obtain a better understanding of the wasteform associations of key radionuclides and to characterise the uncertainty in key components of the inventory.

In the near field area, work is being undertaken to:

- revise the model of coupled transport and chemical reaction in the LLWR, previously developed using the GRM software;
- use Scanning Electron Microscopy to determine the form of uranium in Springfields fluoride wasteform, with which a major proportion of the uranium inventory in the trenches is associated;
- determine the sorption of U(IV) and U(VI) to a range of near-field substrates;
- continue monitoring of the Long-term Vault and Trench Experiments (LTVE and LTTE);
- develop an updated conceptual model for the near field; and
- consider further the impact of heterogeneity in the near field.

A range of activities has been pursued to develop understanding of the geology and hydrogeology of the area around the facility. A revised geological interpretation and new 3-D geological model have been developed. These are being used as a basis for further modelling of groundwater flow. A 3-D model of groundwater flow has been refined and calibrated against heads and other observations at the site.

Upscaling calculations have been carried out for the key hydrogeological units. Calculations have been undertaken of groundwater flow in a version of the site-scale model in which key units are assigned spatially varying hydraulic conductivities. The results of calculations with such a model have been compared with the results of calculations in which each unit is assigned homogeneous properties to confirm that, in most cases, results are broadly similar.

Various work has been undertaken to evaluate the data on tritium concentrations in groundwater. Generally tritium concentrations in groundwater are lower than in 2005. Calculations suggest that of order ten percent of the tritium inventory has been lost since wastes were disposed.

Work has been undertaken to further evaluate the correlation between radium concentrations in soil and radon concentrations in houses. 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 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.

A number of activities have been completed or are almost complete in terms of characterising the future evolution of the coast:

- systematic collation of all of the data gathered during previous work;
- geophysical characterisation of Quaternary sediments along the coastal strip and between the facility and the sea;
- geological characterisation of the barrier spit and other coastal features, linked to an estimate of sediment budgets;
- modelling to address aspects of the evolution of the Ravenglass Estuary, longshore processes and coastal erosion;
- production of an updated conceptual model, including review of the scenarios for climate change and coastal erosion as an appropriate basis for the 2011 ESC.

As part of the 2011 ESC, we will review and comment on what further research and development might be required in future.

TABLE OF CONTENTS

LLW Repository Ltd

1. INTRODUCTION

This report provides a summary of the research and development (R & D) undertaken over the past year by the Low Level Waste Repository Ltd. (LLWR) in the areas of repository post-closure and operational environmental safety.

It also summarises the process used to define the programme of research and development (see Section 2). The report has been produced to satisfy Requirement 4 of Schedule 9 of the LLWR's Authorisation to dispose of radioactive waste (Environment Agency, 2006). Requirement 4 sets out the need to '… *establish and carry out a programme of research and development in support of Items 1, 2 and 3…'* and to provide a programme and reports to the Environment Agency.

Items 1, 2 and 3 of Schedule 9 are respectively:

Item 1:

> *'The Operator shall provide the Agency with a full report of a comprehensive review of whether the current disposal practices for waste generated on the site continue to represent the best practicable environmental option, together with a programme for carrying out any necessary changes identified by the review.'*

Item 2:

> *'The Operator shall provide the Agency with a full report of a comprehensive review of national and international developments in best practice for minimising the impacts from all waste disposals on the site. This shall include a comprehensive review of options for reducing the peak risks from deposit of solid waste on the site, where those risks arise from potential site termination events (e.g. coastal erosion and glaciation) and potential future human action.'*

Item 3:

> *'The Operator shall provide the Agency with a full report of a comprehensive review of the means used to assess the activity of radionuclides in disposals and to determine compliance with this Authorisation including consideration of national and international developments in best practice.'*

A systematic process was pursued to develop an initial programme of R & D to address the requirements of Item 4. This included an analysis of gaps in understanding (Grimwood and Paulley, 2006). The review concluded that no R & D was required in support of Items 1 and 3 of Schedule 9, as the relevant methodologies and approaches are relatively well established. For Schedule 9, Item 2, however, a number of R & D projects were taken forward. The initial R & D programme comprised eight areas:

- climate change and site evolution;
- engineering material studies;
- evolution of vault waste form;
- trench waste colloid and organic complexation;
- near-field sorption of radionuclides;
- effects of seawater incursion into the near-field;
- hydrogeological tracer tests; and
- geosphere sorption.

In addition to these initial areas, five areas for further review were identified. It was anticipated that these reviews would be likely to recommend further R & D. These areas were:

- non-radioactive contaminant transport factors;
- use of alternative safety indicators;
- characterisation of the present day biosphere;
- upscaling of meteorological data to determine future climate and landscape change behaviour; and
- biosphere data for impacts assessments.

An interim review of the initial R & D programme was carried out in February 2007 (Grimwood, 2007). This review took account of:

- work undertaken over the previous six months;
- input from a full review of the Agency's Issue Assessment Forms (IAFs) (Grimwood, 2006); and
- feedback from the Agency on the initial R & D programme.

Further updates on the R & D programme were provided in May 2007 (Wareing, 2007), July 2008 (Baker, 2008a) and July 2009 (Baker, 2009).

In May 2008, the LLWR submitted documentation against Requirement 2 of Schedule 9 (see above). Given the completion of work against Item 2, no further supporting R & D is required to address that requirement. However, the technical issues that have been addressed in the R & D programme continue to be important in developing and supporting the LLWR's Environmental Safety Case (ESC). The ESC is required under Item 6 of Schedule 9 and will be submitted by May 2011. Accordingly, this document discusses R & D in support of the 2011 ESC.

In annual R & D reports previous to July 2008, we have reported R & D that fell within a particular budget area, but excluded work that could be argued to be R & D, but which was funded within other budget areas. In this section and in future reports, a broader definition of R & D is adopted. We cover all technical work that is undertaken in support of the programme of environmental assessments except:

- the development of assessment methodologies and tools for safety assessment and actually carrying out the safety assessments;
- work in non-technical areas, for example the maintenance of databases and the management of Issue Assessment Forms;
- any work associated with monitoring;
- programmes of work associated with optimisation and the assessment of waste management innovations;
- Safety Case development work.

In Section 2, the process by which the programme has been developed is summarised. A key consideration is whether studies are addressing some issue or uncertainty that has the potential to have a significant affect on calculated environmental impacts or are able to build further confidence in current estimates of those impacts. Work that does not fulfil these requirements will normally have been screened out. In Section 3, the content of the R & D programme is described.

2. DEVELOPMENT OF THE R & D PROGRAMME

During the year to July 2010, the focus has been on delivering a programme of work that had been identified prior to the start of the year. In this section, the basis for the content of that programme is set out.

In identifying areas of work, our objective is to focus on those issues and uncertainties that might have some impact on the management or environmental performance of the site. Thus, we would not usually plan to undertake work to address an uncertainty that we do not believe impacts significantly on performance. This requires consideration of the results of recent assessments, most recently the update undertaken as part of our response to the Environment Agency's Requirement 2. Overall, this requires an iterative approach in which the results of successive safety assessments are used as an input to subsequent R & D.

In developing the plan for future R & D, the following inputs have been considered:

Results from the work undertaken in support of the submission of Requirement 2
Our submission in support of Requirement 2 (Baker, 2008b) identified a number of issues that require further work and which have been captured in the forward plan.

IAFs and Environment Agency comments
We have reviewed the issues raised in the Environment Agency's IAFs (Grimwood, 2006; Lean, 2007) and set out in the Environment Agency's review of the 2002 PCSC (Environment Agency, 2005). We have also considered other Environment Agency comments, including those received in relation to the Requirement 2 submission (Environment Agency, 2010a-e).

Recommendations arising from Previous R & D
A number of activities in the previous R & D programme resulted in recommendations for further work.

Due diligence
As part of the due diligence review undertaken by UK Waste Management Ltd., a technical review was undertaken of the post-closure safety case work. As a result, a number of issues and risks were identified and are addressed in our programme of work.

Workshops
As an input to the development of the ESC Lifetime Plan, 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;
- optimisation;
- Operational Environmental Safety Case.

Some of the workshops were attended only by LLWR staff. In other cases, staff from contractors and/or from Serco Ltd. (Serco are a member of the UKNWM Ltd. consortium and played a leading role in the due diligence review) attended. The purpose was not to agree or define the future work programme, but to seek opinions and ideas on the technical programme. Each workshop was documented using a flip chart approach – the output was then available for consideration in the development or review of the Lifetime Plan.

Peer review recommendations and comments
During peer review of the deliverables associated with Requirement 2 and subsequent work, a number of comments were received that need to be considered in defining future work (Bennett et al., 2008).

The above inputs were used by the ESC Project Team to define the programme of work set out in the current Lifetime Plan (LTP) for the LLWR's ESC Project. The programme was reviewed for gaps and coherence before submission to and agreement by the NDA. The programme is now refined and kept under technical review through a range of technical meetings, involving LLWR staff and subcontractors. Modifications to the LTP are subject to change control.

3. R & D TO SUPPORT THE 2011 ESC

3.1. Near Field

3.1.1. Inventory

As a basis for the Requirement 2 submission, two reports were prepared on the inventory and its spatial heterogeneity (Lennon et al, 2008; Wareing et al., 2008). Subsequently a further programme of work was put in place to improve and build confidence in the inventory. Interviews have been held with former operational staff at the LLWR, Sellafield and Windscale to determine disposal practices and the potential for any disposals that might not be consistent with the Conditions for Acceptance. A programme of work has also been pursued focusing on key radionuclides and waste streams. Two reports have been produced as an output from this work programme (Wareing 2009a; Wareing, 2009b).

During the year to July 2010, we have undertaken the following work:

- Undertaken a review of the non-radioactive inventory;
- Developed an improved inventory for future disposals (and disposals since April 2008 to Vault 8) based initially on data from WIDRAM08 and subsequently on data from WIDRAM09;
- Considered information from the interviews with operational staff to determine any implications; and
- Reviewed the details of the C-14 and Cl-36 inventories and the geometries of steel components containing these radionuclides.

These activities are addressed in turn in the following paragraphs.

Noting that it is not clear that the national inventory contains data on all of the potential chemotoxic materials that might result in groundwater contamination, a review of non-radiological inventory data was undertaken (Dickinson and Kelly, 2009). This identified a small number of substances that might be analysed for in leachate (since no relevant inventory data are available). As a result of the review, it was decided to undertake a comprehensive analysis of leachate in the Marine Holding Tanks for a range of potential contaminants. Following this analysis, no additional contaminants were identified that need evaluation within the assessment.

A simple Excel-based tool has been developed to process inventory data to produce four inventories (each derived on the basis of different assumptions about future waste management) on a vault-by-vault basis (Serco, 2010a). This tool takes account of waste processing and grouting and packing factors. Most recently the tool has been applied to derive a new assessment inventory based on the WIDRAM09 database (see Serco 2010b; Serco 2010c).

Information available from interviews from operational staff has been analysed. It has been concluded that there are no significant implications for the overall inventory of the trenches. Reporting of this work is in progress.

Considerable effort has been expended in understanding the inventories of C-14 and Cl-36 and their materials associations. Expert group meetings have been held for each radionuclide to determine the uncertainty in their future disposal inventories. A range of arguments has been considered related to the provenance and behaviour of these radionuclides in operating reactors. Resulting probability density functions will be used in the assessment calculations.

3.1.2. Near Field Understanding

A substantial programme of work on the near field was completed prior to the submission of the LLWR's response to Requirement 2 (summarised in Randall (2008)). The current focus is on developing assessment models, an area of work not described in this document. However, supporting work has also been completed or is underway to:

- revise the model of coupled transport and chemical reaction in the LLWR, developed previously using the GRM software and use it to evaluate the evolution of chemical conditions in the near field;

- develop a better understanding of the effect of heterogeneities in the near field; and
- develop an updated conceptual model for the near field.

These are discussed in turn.

In the 2002 PCSC, a coupled model of transport and chemical reaction was developed using the GRM software. The model was used directly within the assessment calculations (BNFL, 2002). Our strategy for the 2011 ESC is not to use the GRM model directly within the assessment calculations, but rather to use it as a supporting tool, for example to estimate pH and Eh variations with time and to estimate the generation rates of different gases and concentrations of C-14 in pore water. The GRM model has been revised. This includes developing a revised grid to represent the current design, reviewing and adding to the available thermodynamic data and using a groundwater flow field consistent based on calculations undertaken with a 3-D groundwater flow model.

On the basis of a preliminary GRM reference case, the following processes are believed to be important (Small et al., 2010a):

- Degradation of cellulose waste in the trenches, leading to mildly acidic and sulphate reducing conditions for periods lasting from several hundred years to over 1,000 years;
- A phase of trench re-oxidation when redox potential and pH return to that of the local groundwater; and
- Degradation and leaching of the vault wastes, leading to the establishment of alkaline and strongly reducing conditions where methanogenesis becomes established.

GRM is now being revised to incorporate the final repository design and groundwater flow field.

Conceptual models have been developed to address the effects of physical and chemical heterogeneity on the container scale (Small et al., 2010b). Conceptual models were developed for four distinct cases:

- directly consigned loose metal wastes encapsulated in cement grout;
- directly consigned soil and rubble materials, with grout;
- other directly consigned loose wastes including non-compacted organic wastes with grout;
- a mild steel compacted puck encased in cement grout.

The processes leading to the release of key radionuclides have been considered.

An updated conceptual model is being developed for the near field of the LLWR. Where appropriate, the model will be supported by calculations relating to the chemical and physical evolution of the system and/or the effects of heterogeneity. A report on the near-field conceptual model is in preparation.

3.1.3. Physical Form of Uranium

In the recent assessment carried out in support of the Requirement 2 submission (Baker, 2008b), an effective solubility limit was used to represent the effects of rate-limited dissolution of the Springfields fluoride wasteform with which much of the trench uranium inventory is associated. It is considered that uranium is present as discrete inclusions within the fluoride wasteform (Small et al., 2008). A programme of work has been completed to determine 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. SEM has confirmed the presence of spherical and angular uranium inclusions up to 30 μm in size. XRD 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.

3.1.4 Sorption

Work has been undertaken to address the sorption of uranium(IV) and uranium (VI) to a range of near-field substrates: soil, cement, concrete and corrosion (Clacher, 2010). A number of experiments have been completed covering:

- conditions appropriate to uranium (IV) and uranium (VI);
- sorption to soil, concrete, grout and corrosion products;
- for cement and concrete, sorption at a single appropriate pH and, for soil and corrosion products, under appropriate neutral and high pHs.

Uranium was selected for study because uranium series radionuclides were considered likely to be key contributors to radiological impact for releases to groundwater.

The determined R_d values for the uranium sorption onto the LLWR soil were low, with little variation between uranium (IV) and uranium (VI) sorption. These low values may be explained by the sandy nature of the soil sample provided by LLWR, with weak uranium sorption to the silicaceous matrix. Sorption is stronger in the case of OPC than for the LLWR grout, which may be explained by the higher Si:Ca ratio in LLWR grout compared with OPC alone. It has been shown in this study that sorption is stronger for uranium (IV) onto magnetite than for uranium (VI) onto haematite under the same pH conditions, particularly at near-neutral pH. Sorption was strongest for haematite under the higher pH conditions, whereas for magnetite the sorption was strongest at the near-neutral pH. It was expected that uranium (IV) would be more strongly sorbed than uranium (VI), at least in the case of geological materials. The results obtained, however, show little variation in the R_d values between uranium (IV) and uranium (VI) for the same substrate under the same pH conditions. A repeat experiment is being undertaken to clarify one result before reporting is finalised.

3.1.4. LTVE and LTTE

Long-term experiments appropriate to vault and trench conditions had been underway, but maintenance and monitoring had lapsed for a number of years. The experiments were designed to increase understanding of near field evolution and support appropriate treatments in assessment models. The Long-term Vault and Trench Experiments (LTVE and LTTE) have been examined and it was decided that continued monitoring is feasible. Accordingly, maintenance activities have been carried out and data are being collected again from these experiments. This continued throughout the year to July 2010. Data will be interpreted and used as appropriate to support the treatment of the near field in safety assessment calculations. If the experiments proceed according to plan, it is envisaged that destructive analysis of one or more of the experiments will eventually be undertaken.

3.2. Site Understanding

3.2.1. 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 (EM) Conductivity and Seismic Refraction. In front of the LLWR and on the Drigg Spit, eight profiles, totalling approximately fourteen line kilometres in length, were surveyed using resistivity and two GPR methods. Approximately 640m of seismic refraction data were also collected on the beach. The resulting data were generally of a high quality. 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.

3.2.2. Geological Model

A revised geological interpretation has been produced and documented in a key supporting report (Michie et al, 2010). In previous work, we have subdivided the sedimentary deposits into lithofacies units composed of similar material types. In 2008 and 2009, two phases of additional borehole drilling were completed. Geophysical surveying and other scientific studies were also conducted. The lithology logs from the recent boreholes provide new information, which supports the lithofacies model as a valid characterisation of the LLWR site. 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 itself and the surrounding region.

A new 3-D model has been developed using the geophysics and other new data, using the program GIS3D. This model has been used to provide surfaces for use in 3-D hydrogeological modelling.

We are currently reviewing the status of the 3-D model and comparing cross sections from the geological interpretation report with those produced by the 3-D model to determine how well the 3-D model reflects the interpretation in key areas of interest. This may lead to some update of the 3-D model in the near future.

3.2.3. Development of Hydrogeological Models

A programme of work has been substantially completed to develop an updated model of groundwater flow, suitable as a basis for the 2011 ESC. This covers a domain somewhat larger than that of the existing Site-Scale model (Arthur et al., 2008). The model has been developed within the CONNECTFLOW software. 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 optimisation studies and as the basis for a flow network model for use in the assessment. Transient data 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 (Hartley et al., 2010). Upscaling[1] calculations were carried out to derive the distributions of the effective hydraulic conductivities of blocks of different lithofacies packages with lateral dimensions of order a hundred metres, which is of the order of the size of the finite elements in the site-scale flow model. If hydrogeological units in the 3–D groundwater flow model of the site are assigned central values from the distributions of heterogeneous upscaled properties, the match to observations (of head and other parameters) is acceptable. A series of calculations have been undertaken to compare the results of models in which the heterogeneity is explicitly represented with those in which units are assigned homogeneous properties. Broadly, the results for the heterogeneous realisations are similar to those for homogeneous models, although there are some differences. As part of the study, the implications for performance assessment were discussed. Overall, the study demonstrated that heterogeneity can be taken into account, and its implications considered in performance assessments.

As part of the supporting material for the 2011 ESC, a revised hydrogeological conceptual model will be documented, building on that documented by Henderson (2008).

3.2.4. Tritium Data

Some activities have been pursued in relation to interpreting data on concentrations of tritium in groundwater. An estimate of the quantity of tritium that has been released from the facility has been made based on monitoring data (Henderson, 2010). The estimate suggests that of order ten percent of disposed tritium has been released from the facility since wastes were disposed.

The latest data on tritium data in groundwater from 2009/2010 have been mapped based on monitoring data (Henderson and Smith, 2009). Upper Groundwater[2] tritium activity concentrations are much less than they were 2005. Recent data confirm the existence of the previously recognised tritium plumes in the Regional Groundwater[2]. Recent data have been added to existing breakthrough curves. In most boreholes, concentrations continue to fall. However, in three cases, rises in tritium concentrations have been observed. Overall the data reflect the reductions in tritium concentration associated with the construction of the trench cap and cut-off walls.

---

[1] Upscaling is the process whereby various measurements on small lengthscales are processed to derive estimates of properties on longer lengthscales.

[2] See Henderson (2008) for more information on the distribution of Upper and Regional Groundwater.

3.2.5. Long-term Monitoring

A review has been carried out of the requirements for long-term monitoring (Entec, 2010). This has provided a detailed review of parameters that might require monitoring, based on the requirements of different parts of the LLWR's programme.

3.2.6. Coastal Erosion

A number of activities have been completed or are almost complete in terms of characterising the future evolution of the coast:

- systematic collation of all of the data gathered during previous work (Halcrow, 2009);
- geophysical characterisation of Quaternary sediments along the coastal strip and between the facility and the sea (see subsection 3.2.1);
- geological characterisation of the barrier spit and other coastal features, linked to an estimate of sediment budgets;
- modelling to address aspects of the evolution of the Ravenglass Estuary, longshore processes and coastal erosion;
- production of an updated conceptual model, including review of the scenarios for climate change and coastal erosion as an appropriate basis for the 2011 ESC.

Geological characterisation work is currently being reported. Initial indications from the results of C-14 dating studies are that the spit is an old feature.

The computer program SCAPE has been used to model the erosion of the coastline (Walkden, 2010). This model was run from 11,000 years ago to the present day, to explore the historic evolution of the coast to its present form. Considerable uncertainty remains about the historic morphology, but the model was able to reproduce much of the current profile form, and was found to be quite robust to parameter settings, both in terms of emergent profile shape and recession rate.
The model was then used to make projections of future shore profile change, recession rate, and time to encroachment of the LLWR through shore recession. Uncertainty in input scenarios of sea level rise, beach volume, and surge climate were represented through various sensitivity tests.
Model calculations suggested that encroachment of the LLWR by the sea might occur between around 370 years and 860 years from the present.

An updated conceptual model has been produced incorporating results from the detailed studies (Fish et al, 2010). Future coastal evolution mechanisms have been derived from the combined outputs of an empirically-based cliff recession model, a processed-based cliff recession model, and an estuary evolution model. These inform the time required for initial encroachment of the sea on the LLWR, and the mechanisms by which the site would be disrupted. Key aspects of the conceptual model can be summarised:

- The combination of significant projected sea level rise and a regime in which sediment and other material is unlikely to accumulate on beaches to form natural shoreline defences mean that coastal recession will progress inland and at some point in time breach the LLWR.
- Based on the range of sea level rise projections and the available evidence concerning natural coastal change processes on the west Cumbrian coast, the LLWR is liable to be disrupted by cliff instability and erosion within a time frame of a few hundreds to thousands of years.
- The most likely outcome is that disruption of the LLWR will occur by undercutting of the engineered structures. Once undercutting has begun, the vaults will rapidly collapse and wastes will disperse onto the beach and foreshore.

3.3. Radon

In the Requirement 2 submission to the Environment Agency (Baker, 2008b), we adopted an empirical approach to determine the relationship between radium concentrations in waste and concentrations that might potentially arise in dwellings. In order to improve the approach, we have conducted a programme of work 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). Extensive UK datasets for radon in dwellings and uranium in soil are held by the HPA and the BGS, resulting from over 20 years of work by the HPA and by BGS. Data were assembled on concentration of radon in soil gas, concentration of uranium in soil, estimated uranium (eU) from ground-based gamma-ray surveys, estimated uranium (eU) from 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.

4. REFERENCES

Appleton, J. D. and Miles, J.C.H., 2009. Empirical Relationships to Assist in the LLWR Assessment of Radon. British Geological Research Report CR/09/066.

Arthur, S.R., Sears, R.C. and Whitaker, D., 2008. LLWR Lifetime Project: Version 2 Site-Scale Groundwater Flow and Transport model. Nexia Solutions Report No. (07) 9272.

Baker, A.J., 2008a. Progress on Research and Development to July 2008, 10007 LLWR LTP Issue 1.

Baker, A.J., 2008b. LLWR Lifetime Plan. Managing Existing Liabilities and Future Disposals at the LLWR. Low Level Waste Repository Ltd. 10001 LLWR LTP Volume 1 Issue 01.

Baker, A.J., 2009. Progress on Research and Development to July 2009, LLWR/ESC/R(09)10014, Issue 1.

Bennett, D., Bath, A., Fleming, G., Garrard, G., Holton, D and Jones, S., 2008. Independent Peer Review of LLWR Response to Environment Agency Schedule 9 Requirement 2, Version 1.

BNFL, 2002, Drigg Post-closure Safety Case: Software Tools and Codes.

Cave, M.R., Appleton, J. and Miles, J.C.H., 2010. Regression Analysis to Assist in the LLWR Assessment of Radon, BGS Commissioned Report, CR/10/013.

Clacher, A., 2010. Sorption of Uranium(IV) and Uranium(VI) onto LLWR Near-Field Materials, Serco/TAS/003623/001, Draft.

Dickinson, M. and Kelly, M., 2009. Review of Non-radiological Inventory Data, Serco/TAS/E003756/001 Draft.

Entec, 2010, Long Term Environmental Monitoring Strategy, Draft Entec Report.

Environment Agency, 2005. The Environment Agency's Assessment of BNFL's 2002 Environmental Safety Cases for the Low-Level Radioactive Waste Repository at Drigg. Document NWAT/Drigg/05/001, Version 1.0.

Environment Agency, 2006. Certificate of Authorisation and Introductory Note, Disposal of Radioactive Waste from Nuclear Site British Nuclear group Sellafield Ltd., Low Level Waste Repository, Drigg, Cumbria, Authorisation Number BZ2508.

Environment Agency, 2010a. Review of LLW Repository Ltd's "Requirement 2" Submission: Technical review of Volume 1: Overview, Environment Agency Report NWAT/LLWR/09/001.

Environment Agency, 2010b. Review of LLW Repository Ltd's "Requirement 2" Submission: Technical review of Volume 2: Assessment of Options for Reducing Future Impacts from the LLWR, Environment Agency Report NWAT/LLWR/09/002.

Environment Agency, 2010c. Review of LLW Repository Ltd's "Requirement 2" Submission: Technical review of Volume 3: Inventory and Near Field, Environment Agency Report NWAT/LLWR/09/003.

Environment Agency, 2010d. Review of LLW Repository Ltd's "Requirement 2" Submission: Technical review of Volume 4: Site Understanding, Environment Agency Report NWAT/LLWR/09/004.

Environment Agency, 2010e. Review of LLW Repository Ltd's "Requirement 2" Submission: Technical review of Volume 5: Performance Update for the LLWR, Environment Agency Report NWAT/LLWR/09/005.

Fish, P., Thorne, M., Moore, R., Penfold, J., Richards, L., Lee, M. and Pethick, J., 2010. Forecasting the Development of the Cumbrian Coastline in the Vicinity of the LLWR Site, QRS-1443X-1, Draft.

Grimwood, P. and Paulley, A., 2006. LLWR Lifetime Project: Development of an Initial Research and Development Programme to Address Schedule 9, Item 4 of the Disposal Authorisation for the Low Level Waste Repository at Drigg, Cumbria. QRS-1354A-RD1.

Grimwood, P., 2006. Environment Agency's Issue Assessment Forms from the 2002 LLWR Environmental Safety Cases: Overview of Assessment. Quintessa Report QRS – 1354B-IAF1, Issue 1.

Grimwood, P.D. (Ed.), 2007. LLWR Lifetime Project: Interim Review of the Initial R & D Programme. Nexia Solutions Report (06) 8212. QRS-1354D-RD2. Issue 2.

Halcrow, 2009. Coastal Studies Forward Programme Data Compilation and Position Statement.

Halcrow, 2010. Drigg Coastal Erosion: Geophysical Report.

Hartley, L., Applegate, D., Couch, M. and Jackson, P, 2010. Hydrogeological Modelling for LLWR 2001 ESC Phase 2, Serco/TAS/003632/005, draft.

Henderson, E., 2008. Hydrogeological Conceptual Model. Nexia Solutions Report (08) 9711.

Henderson, E. and Smith, N., 2010, Utilisation of 2009/2010 Groundwater Level and Tritium Data, NNL(09)10587.

Henderson, E., 2010. Leachate Data Scoping, NNL(09)10766, Draft.

Lean C., 2007. LLWR Lifetime Project: Review of Progress Against the Environment Agency's Issue Assessment Forms – September 2007, Nexia Solutions (07) 8841 Issue 2, December 2007.

Lennon, C. P., Jones, A., Eden, L. and Ball, M.,2008. Heterogeneity in the Inventory of Past

and Potential Future Disposals in the LLWR. Nexia Solutions Report No 9126.

Michie, U., Hunter, J. and Towler, G., 2010, Geological Report, QRS-1443Y-R1, Draft.

Randall, M., 2008. Vol 3, Lifetime Plan: Inventory and Near Field, 10003 LLWR LTP Volume 3 Issue 01.

Serco, 2010a. User Guide for PIER V1.0: A Tool for Calculating the Forward Inventory of the LLWR, Serco 003756 03, 2010.

Serco, 2010b. Forward Inventory Cases for the 2011 ESC for the LLWR, SERCO/TAS/003756/009, Draft.

Serco 2010c, Improvements to the Disposal Inventory, SERCO/TAS/003756.04/003, Draft.

Small, J., Lennon, C., Kwong, S and Abrahamsen, L., 2010a. Preliminary GRM Modelling of the LLWR Near Field to Support the 2011 ESC, Draft.

Small, J., Randall, M. and Lennon, C., 2010b. Physical and Chemical Heterogeneity on the Container Scale, NNL(09)10694, Draft.

Thompson, O., Coppersthwaite, D., Weaver, W., May, S., Kent, C. and Small, J., 2010. Characterisation of Uranium in a Fluoride Wasteform, NNL(10)10816.

Walkden, 2010. Soft Cliff and Platform Erosion (SCAPE) Modelling of the Drigg Coast, Royal Haskoning Report 9V4698PR/R/303948/Exet, Draft.

Wareing, A. (Ed.) 2007. LLWR Lifetime Project: Annual Review of the Initial R & D Programme. Nexia Solutions (07) 8511. Issue 01.

Wareing, A. S., Eden, L., Jones, A. and Ball, M.,2008. LLWR Lifetime Project: The Inventory of

Past and Potential Future Disposals at the LLWR. Nexia Solutions Report 9124.

Wareing, A., 2009a. Assessment of Uncertainty in the LLWR ^{14}C Inventory, NNL Report NNL(08)10144.

Wareing, A., 2009b. Assessment of Uncertainty in the LLWR Inventory for Key Radionuclides, NNL Report NNL(08)10241.