



Review of LLW Repository Ltd's 2011 environmental safety case: Assessments

Issue 1, 15 May 2015

We are the Environment Agency. We protect and improve the environment and make it a better place for people and wildlife.

We operate at the place where environmental change has its greatest impact on people's lives. We reduce the risks to people and properties from flooding; make sure there is enough water for people and wildlife; protect and improve air, land and water quality and apply the environmental standards within which industry can operate.

Acting to reduce climate change and helping people and wildlife adapt to its consequences are at the heart of all that we do.

We cannot do this alone. We work closely with a wide range of partners including government, business, local authorities, other agencies, civil society groups and the communities we serve.

Published by:

Environment Agency
Horizon House, Deanery Road,
Bristol BS1 5AH
Email: enquiries@environment-agency.gov.uk
www.gov.uk/environment-agency

Further copies of this report are available from our publications catalogue:

www.gov.uk/government/publications

or our National Customer Contact Centre:
T: 03708 506506

Email: enquiries@environment-agency.gov.uk.

© Environment Agency 2015

All rights reserved. This document may be reproduced with prior permission of the Environment Agency.

Executive summary

The Environment Agency is responsible for regulating the disposal of radioactive waste in England under the terms of the Environmental Permitting (England and Wales) Regulations 2010 (EPR10). As part of its current environmental permit we required LLW Repository Ltd to submit an Environmental Safety Case (ESC) for the Low Level Waste Repository (LLWR) in West Cumbria to the Environment Agency by 1 May 2011 (2011 ESC).

Our review of the 2011 ESC is documented in a series of reports. This report covers our review of the radiological and non-radiological assessments presented in the 2011 ESC. In our review, we have considered whether the 2011 ESC meets the principles and requirements set out in our guidance on requirements for authorisation of near-surface disposal facilities for solid radioactive waste (GRA). This guidance sets out what we would expect to see in an ESC.

We consider that the overall quality of the 2011 ESC assessment is of a high standard. The structure of the ESC and clarity of the arguments is generally clear and coherent with good referencing of associated and underpinning reports.

Overall we consider that the GRA requirements relating to assessment areas have been met, with LLW Repository Ltd's assessment demonstrating that the radiological doses and risks are acceptable.

We have no reason to think that LLW Repository Ltd's radiological assessments have significantly underestimated potential doses and risks. Generally, a range of cautious and conservative assumptions have been made about future events, processes, scenarios, human habits and behaviour.

We consider that more could be done to better manage uncertainties in a systematic manner. Some of the assessment results depend on the validity of the framing assumptions but these assumptions may be unclear in the ensuing assessment. The framing assumptions are potentially candidate 'uncertainties' to be captured in a register.

Assessed doses during the period of authorisation of the LLWR are below the legal constraints on radiation doses to members of the public set out in EPR10¹.

We reviewed LLW Repository Ltd's assessment of risks and doses following the 'coastal erosion' scenario in relation to possible encounters with small radioactive particles. This led to a range of additional assessments regarding possible doses incurred. Our assessment criteria after the period of authorisation of the LLWR are generally defined in terms of 'annual risk' to an individual. On this basis, we consider the risks of encountering these particles are acceptable (that is less than 1.0×10^{-6} per year). However, LLW Repository Ltd has introduced new Waste Acceptance Criteria for future consignments containing long-lived particles and discrete items. The company has also introduced a waste emplacement strategy for radium-bearing waste that will reduce potential exposures associated with radon gas.

A dose roughly equivalent to the dose constraint recommended by Public Health England for new nuclear power stations and waste disposal facilities (0.15 mSv annual dose), which has no legal force, could be received from direct radiation by a person hypothetically living adjacent to Vault 13. However, this location is currently uninhabited. In future, direct radiation exposures will be monitored and managed by an appropriate waste emplacement strategy. The Office for Nuclear Regulation also has powers to ensure that off-site direct radiation doses, during site operations, are as low as reasonably practicable.

LLW Repository Ltd supplies us with an annual report on its environmental monitoring activities and similar reporting will continue. Proposals for control, after the completion of disposals (for the

¹ 0.3 mSv annual dose in total from any source from which radioactive discharges are first made on or after 13 May 2000, and 0.5 mSv annual dose from the discharges from any single site.

period of active institutional control), will be finalised in consultation with stakeholders as site development and operation proceed.

Currently, there are no wells utilised for the abstraction of drinking water from the area between the LLWR and the coast. We consider it unlikely that a well will be drilled before the end of the operational phase. LLW Repository Ltd assesses the expectation value of dose to someone drinking groundwater from a hypothetical well sunk into the discharge plume at 3 μSv per year.

For the groundwater well pathway in the post-closure period, LLW Repository Ltd presents its assessment of peak risk to an individual at 4.0×10^{-8} per year (occurring at about 2250 AD, that is about 170 years after completion of the final cap); the key radionuclides are chlorine-36, carbon-14 and iodine-129.

Requirement R7 of our GRA requests the operator to show that dose thresholds for 'severe deterministic injury' to individual body tissues are unlikely to be exceeded as a result of human intrusion into the facility. We consider that LLW Repository Ltd has shown this to be so.

The non-radioactive component of the LLWR disposal inventory is subject to considerable uncertainty as non-radioactive contaminants in waste streams are not generally as well characterised as the radiological components. The material content of many waste streams included in the inventory is listed as 'unknown', but deposits are known to contain a range of hazardous substances and non-hazardous pollutants such as mercury, cadmium, tributyl phosphate and cyanide.

We understand that LLW Repository Ltd is working with consignors to provide a more accurate assessment of the hazardous and non-hazardous components of future disposals. The results of LLW Repository Ltd's current assessment indicate that, during the period of authorisation, projected future concentrations of all hazardous substances and non-hazardous pollutants are below the relevant assessment standards in the regional aquifer underlying the LLWR. During the period of authorisation, discharges to groundwater from the LLWR vaults are zero due to an assumed 100% effectiveness of the leachate management system.

After withdrawal of active institutional control, LLW Repository Ltd assesses concentrations of organic hazardous substances in groundwater underlying the site to be zero or close to zero. However, it assesses concentrations of chromium, lead, nickel, molybdenum and zinc to exceed the assessment standards in groundwater under the trenches after several hundred years beyond withdrawal of active institutional control.

To ensure continued demonstration of protection of groundwater we will require LLW Repository Ltd to produce an updated non-radiological hydrogeological risk assessment before the end of 2017. This updated assessment should have full regard to requirements of the GRA and Environment Agency guidance on hydrogeological risk assessments for landfills. We will also expect to see a better underpinned non-radiological source term used in this assessment as far as is practicable.

While we judge that LLW Repository Ltd has met the GRA requirements for radiological and non-radiological assessment, we emphasise that our considerations here do not address all potential environmental detriments, for example visual impacts, which might result from the long-term evolution of the site after the withdrawal of active institutional control and in particular following coastal erosion. Other environmental impacts are addressed to the extent required by relevant legislation within our decision document on permitting and also by the local planning authority as part of the planning permission process.

In summary, we consider that, for the purpose of determining a variation to the LLWR environmental permit for the continued disposal of radioactive waste, LLW Repository Ltd has adequately addressed those parts of the GRA relevant to the radiological and non-radiological assessments. Relevant requirements within the GRA, such as dose and risk guidance levels, have been shown to be met. However, we identified a number of areas where further improvements need to be made in the future, to make sure that the ESC continues to improve and meet the requirements of the GRA.

Contents

Executive summary	3
1. Introduction.....	7
1.1. Introduction.....	7
1.2. The 2011 ESC submission	7
1.3. The review process	8
1.4. ESC review deliverables.....	10
2. Our review	12
2.1. Overview	12
2.2. Period of authorisation assessment.....	12
2.2.1. Requirement R5: Dose constraints during the period of authorisation.....	12
2.2.2. Integration between the period of authorisation and post-closure assessments.....	14
2.3. Assessment of long-term radiological impacts	15
2.3.1. National inventory update.....	16
2.3.2. Groundwater pathway	17
2.3.3. Gas pathway.....	26
2.3.4. Natural disruption and dispersion pathway - coastal erosion.....	28
2.3.5. Delayed coastal erosion / no erosion scenario	33
2.3.6. Human intrusion	34
2.3.7. Waste and borehole fire scenario.....	37
2.3.8. Assessment of criticality	37
2.3.9. Management of uncertainty	38
2.3.10. Model code quality assurance and documentation.....	40
2.3.11. Environmental safety indicators.....	41
2.3.12. Non-human biota assessment.....	41
2.4. Radiological limits in the waste acceptance criteria	43
2.4.1. Groundwater pathway assessment	44
2.4.2. Gas pathway assessments.....	46
2.4.3. Coastal erosion and human intrusion assessments	46
2.4.4. Use of risk guidance levels as a basis for WAC	47
2.4.5. Development of WAC	47
2.5. Non-radiological assessment.....	48
2.5.1. Non-radioactive inventory.....	48
2.5.2. Asbestos.....	50
2.5.3. Non-radiological groundwater pathway assessment	50
2.5.4. Surface water discharges	53
2.5.5. Coastal erosion.....	53
2.5.6. Human intrusion	55
2.5.7. Gas pathway.....	56
2.5.8. WAC for non-radiological substances.....	56
2.6. Extended Disposal Area assessment	57
3. Meeting our requirements	59
3.1. Requirements R5, R6 and R7: protection of human health against radiological hazards	59

3.2. Requirement R9: Environmental radioactivity	60
3.3. Requirement R10: Protection against non-radiological hazards.....	60
3.4. Requirement R13: Waste acceptance criteria.....	61
3.5. Summary.....	61
4. Conclusions	62
5. References	63
6. Appendix 1 - Issue Resolution Forms	69
6.1. Introduction.....	69
6.2. Assessments Issue Resolution Forms	69
7. Appendix 2 - Recommendations.....	74
7.1. Introduction.....	74
7.2. Assessments recommendations	74
8. Appendix 3 - Forward Issues	78
8.1. Introduction.....	78
8.2. Assessment Forward Issues.....	79
List of abbreviations.....	81
Glossary	84

1. Introduction

1.1. Introduction

The Environment Agency is responsible for regulating the disposal of radioactive waste in England under the terms of the Environmental Permitting (England and Wales) Regulations 2010 (EPR10) as amended (and before that was responsible under the terms of the Radioactive Substances Act 1993 (RSA 93) as amended). In accordance with government policy, we periodically review environmental permits for the disposal of radioactive waste. During this process we consider a wide range of information, including the conclusions from our reviews of the Environmental Safety Case (ESC) produced by the operator of the disposal facility concerned.

The Low Level Waste Repository (LLWR) near Drigg, Cumbria is the UK's primary facility for the disposal of solid low level radioactive waste (LLW). As a result of a major review of the LLWR ESC undertaken between 2002 and 2005, we included a requirement in the current LLWR environmental permit for the operator, LLW Repository Ltd, to 'update the Environmental Safety Case(s) for the site covering the period up to withdrawal of control and thereafter' (Schedule 9 Requirement 6). We received the updated ESC on 1 May 2011 (the 2011 ESC). We have subjected this ESC to a rigorous technical review using suitably qualified and experienced personnel.

The aims of the review were:

- to determine the adequacy of the 2011 ESC as a submission against Schedule 9 Requirement 6 of the current LLWR environmental permit;
- to provide an Environment Agency view on the technical adequacy of the 2011 ESC;
- to use as a major input to a forthcoming regulatory decision on permitting the LLWR for further disposal of radioactive waste; and
- to provide a forward programme for areas of improvement to the 2011 ESC, to guide LLW Repository Ltd.

In our review, we have considered whether the 2011 ESC is based on sound science and engineering and meets the principles and requirements set out in the most recent environment agencies' guidance on requirements for authorisation (GRA) of near surface disposal facilities (Environment Agency et al. 2009). The GRA explains the requirements that we expect an operator to fulfil in applying to us for a permit to operate such a facility. It includes our radiological protection requirements and provides guidance on the nature of the ESC we would expect to see.

On 28 October 2013 LLW Repository Ltd made an application to the Environment Agency to vary the existing environmental permit under the EPR10 to dispose of further waste at the repository. This application covered an extended disposal area, which would allow sufficient capacity for the LLWR to accept a significant proportion of the UK's LLW predicted to be generated out to around 2130 (excluding lower activity LLW that could be diverted to other facilities). The application is in line with the proposals set out in the 2011 ESC, incorporating any subsequent modifications since the ESC submission. The proposal is to design, operate and close the facility in accordance with the 2011 ESC and subsequent changes described within the environmental permit application.

Our review of the ESC is intended to provide technical underpinning of our decision on LLW Repository Ltd's permit variation application. We will only permit further disposals at the LLWR if we are convinced, through the ESC, that these disposals will not present an unacceptable risk to people and the environment. That is, the ESC needs to demonstrate that the short-term and long-term environmental impacts from past and proposed future disposals, taken together, will be acceptable.

1.2. The 2011 ESC submission

LLW Repository Ltd submitted the 2011 LLWR ESC to the Environment Agency on 1 May 2011. The ESC comprised the following hierarchy of documents:

- Level 0 - A non-technical summary, not aimed at regulators
- Level 1 - A single top level main report (143 pp) summarising the main arguments and the broad lines of evidence supporting them
- Level 2 - 16 topic reports (of 50–250 pp each) setting out in more detail the evidence to support the main arguments
- Key Level 3 - 95 underpinning reports (mostly 50–200 pp) identified by LLW Repository Ltd as being 'key'
- Other Level 3 - Several hundred other references referred to in the above documentation but not identified as 'key'

The Level 1 and 2 documents form the core of the 2011 ESC, with additional detailed information contained in Level 3 documents. During our review, we needed to extensively scrutinise many of the Level 3 documents in order to understand the safety arguments. The Level 0, 1 and 2 documents plus the 'key' Level 3 documents are available from relevant public registers and, at the time of writing and during our consultation period, from the LLW Repository Ltd internet site at: <http://llwrsite.com/national-repository/key-activities/esc/esc-documentation/>

LLW Repository Ltd has informed us that it is continuing to investigate potential options for the future design, operation and long-term management of the LLWR. We are also aware that the Nuclear Decommissioning Authority (NDA) and Site License Companies (SLCs) have been reviewing their procedures for estimating and reporting future LLW arisings to improve the accuracy of future inventory data. However, the scope of our review has comprised only the 2011 ESC as submitted, together with supporting documentation and further information provided up to and including the date of the environmental permit variation application made in October 2013. Any subsequent proposals to change the basis of the ESC will be addressed separately.

1.3. The review process

We have carried out a detailed technical review of the 2011 ESC. The review comprised an assessment of whether the ESC arguments, outlined in the Level 1 report, adequately address the requirements of the GRA and whether the evidence provided supports the arguments.

We have reviewed lines of evidence and underpinning information, judged by our suitably qualified and experienced reviewers to be of importance to the ESC to the depth considered necessary to determine their validity, including tracing data and assumptions back to original empirical evidence. We have pursued other lines of evidence and underpinning information considered to be of less importance in less depth. We have carried out a detailed review of the Level 1, Level 2 and important Level 3 documentation, also referring to other Level 3 documents to the extent that they underpin the ESC.

Environment Agency (2015a) provides further information on our approach to the review and the process we have used.

The primary test of the acceptability of the 2011 ESC as a whole, or of an individual document, was whether it meets Schedule 9 Requirement 6 of the current site permit and satisfies the relevant principles, requirements and guidance in the GRA. Where potential deficiencies or other issues were identified during our review, they were categorised as follows:

- A Regulatory Issue (RI) is a deficiency sufficiently serious that, unless or until it is resolved, we will either: (a) not grant a permit; or (b) grant a permit constrained by major limiting conditions (as distinct from information or improvement conditions) defined by us to mitigate the consequences of the RI.
- A Regulatory Observation (RO) is a deficiency not sufficiently serious to prevent our issuing a permit but sufficiently serious that, unless or until it is resolved, we will include an improvement or information condition in the permit requiring defined actions on defined timescales to resolve it (or to demonstrate suitable and sufficient progress towards resolving it). Related ROs may be grouped into a single improvement or information requirement. (We may also apply minor limiting conditions in the permit until it has been resolved.) An RO can become an RI if the condition is not met.

- A Technical Query (TQ) is a deficiency not sufficiently serious for us to require defined action by LLW Repository Ltd but sufficiently significant for us to request action. An individual TQ is unlikely to become an RO even if not addressed, but a number of unresolved TQs may accumulate into an RO.
- Any other further information or points of clarity considered to be worth requesting of LLW Repository Ltd are designated as Minor Comments. LLW Repository Ltd were requested, but not required, to provide responses to these to enable us to conclude our review of the 2011 ESC. However, LLW Repository Ltd did provide responses whenever requests for further information were made.

For each RI, RO and TQ we have generated an Issue Resolution Form (IRF), which records and tracks the issue and its resolution. IRFs are detailed records of concerns raised as part of our review of the 2011 ESC. Each IRF defines one or more actions. We have expected LLW Repository Ltd to provide a substantive response to the action(s) specified on the IRF by a specified date(s).

The IRFs form a substantial element of our review output. LLW Repository Ltd has provided responses on each IRF; where appropriate this may be a summary of the response, referring to more detailed information in supporting documentation. Each IRF also records our evaluation of the response. An issue has only been closed out when we have determined that the response from LLW Repository Ltd adequately addresses it. Where appropriate, we raised further actions or queries so we could close the IRF. All IRFs have now been closed.

We recognise that the 2011 ESC is a complex submission involving a wide range of technical assessments that will evolve and improve in the future as technology and understanding advances. Certain details will also be developed further as the site advances, for example towards construction of the final engineered cap over the waste. Within our review we therefore identify important areas which we believe will benefit from further work, development or clarification in the future. These areas are identified as Forward Issues (FIs). These represent areas of work that we believe it is important for LLW Repository Ltd to progress as part of its forward improvement plan. FIs address areas where we expect continued improvement in the ESC and its implementation. We will require LLW Repository Ltd to engage with us on these FIs, to put in place formal mechanisms to track and address them and, as necessary, incorporate work to address them in its forward programmes of work and report to us on progress and when it believes the FIs have been fully addressed. We will expect the outcome of FIs to be considered within any subsequent updates to the ESC.

Throughout the review, we also made a number of specific recommendations to LLW Repository Ltd. Recommendations represent areas where we see scope for possible improvement or development, but which are relatively minor in nature relative to FIs. These recommendations are numbered and highlighted in this document. As a matter of good practice we expect LLW Repository Ltd to address these recommendations and will expect a mechanism to be put in place to track them.

It is important to note that these FIs and recommendations do not represent the only areas of work that we will expect LLW Repository Ltd to progress and are not intended to represent a comprehensive scope for forward work. We will require the company to develop its own forward programme of work as necessary to maintain and improve the ESC; our FIs and recommendations should only form part of that programme. LLW Repository Ltd's forward programme of work must be informed by a wide range of inputs, for example monitoring data, research and development, improvements in technology and continuous improvement.

This report is necessarily focused on the negative, bringing out areas where we have raised concerns, or have remaining concerns, or expect further action or permitting requirements. We do not necessarily comment on areas we are content with and we do not list everything we have reviewed. The length of discussion on any particular topic may depend on the degree of interaction between us and LLW Repository Ltd and does not necessarily reflect the significance of the issue. However, we have made positive comments where we believe that the treatment of issues represents good practice.

1.4. ESC review deliverables

The output from our review of the ESC is a series of review reports that will provide technical underpinning to future permitting decisions. The document hierarchy is illustrated in Figure 1.

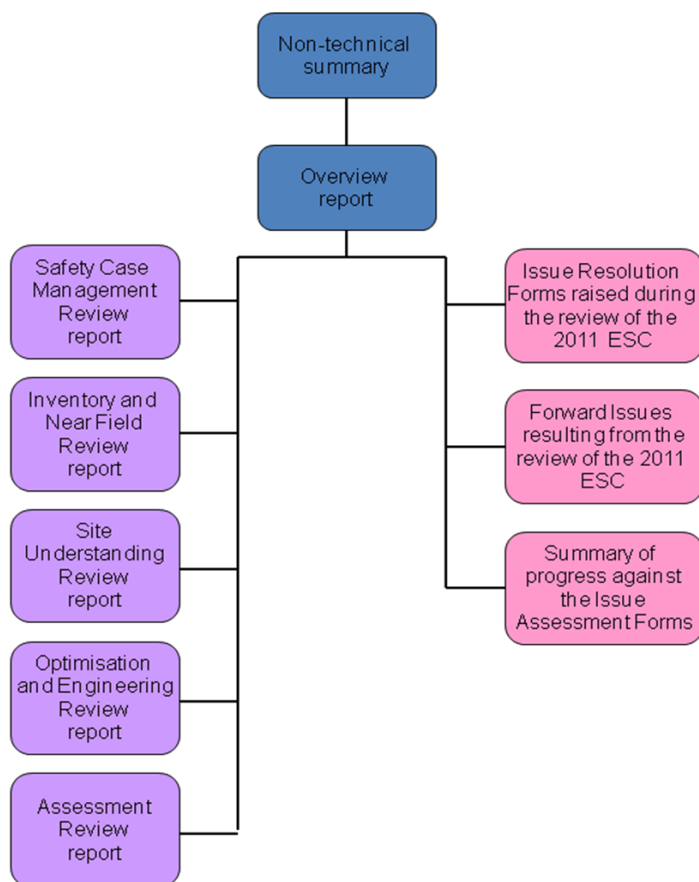


Figure 1 Hierarchy of documents supporting the Environment Agency review of the 2011 ESC

The main document is the overview report of the technical review (Environment Agency 2015a). It provides our conclusions on the extent to which LLW Repository Ltd's 2011 ESC demonstrates to our satisfaction that existing and proposed future disposals meet the requirements set out in the GRA, as well as whether Schedule 9 Requirement 6 has been met satisfactorily. The overview report includes background information on the history of the LLWR and regulatory requirements. It also describes our review process in greater detail.

The overview report is supported by 5 technical review reports, which provide more detailed conclusions on the technical adequacy of the 2011 ESC as a basis for permitting future disposals. These reports cover the following topic areas: Safety Case Management (Environment Agency 2015b); Inventory and Near Field (Environment Agency 2015c); Site Understanding (Environment Agency 2015d); Optimisation and Engineering (Environment Agency 2015e); and Assessments (this report). The IRFs resulting from each of the topic area reports are collated in a standalone report (Environment Agency 2015f).

Forward Issues that are raised as a result of our review of the 2011 ESC are also collated in a separate report (referenced as ESC-FI-xx) (Environment Agency 2015g). We will agree with LLW Repository Ltd when and how it addresses these issues through our normal regulatory interactions and will track progress made to resolve them.

We documented concerns from our review of the previous LLWR Operational Environmental and Post-Closure Safety Cases (the 2002 ESCs; British Nuclear Fuels Ltd (BNFL) 2002a,b) on Issue Assessment Forms (IAFs), which are similar to the IRFs. We report our review of LLW Repository

Ltd's progress in addressing actions raised in the IAFs in Environment Agency (2015h). Any actions that we consider have not been fully addressed in the 2011 ESC are taken forward in our FIs or recommendations.

We have also prepared a non-technical summary of our review of the 2011 ESC (Environment Agency 2015i).

Together the documents describing the review of the 2011 ESC summarise the findings of our review and provide information to support consultation on our draft decision about the future permit for the LLWR.

We welcome any comments on our review findings. These comments could be provided in response to our forthcoming consultation on permitting the LLWR.

2. Our review

2.1. Overview

This report is one of 5 technical assessment reports that support the overview report of our review of the 2011 ESC and cover the main topic areas of the ESC in more detail. It covers LLW Repository Ltd's assessment work and addresses the adequacy of the methods and models used to assess the standard of protection achieved for people and the environment in the future, including radiological doses and risks and non-radiological health effects.

The 2011 ESC assessments include separate radiological safety assessments for the period of authorisation and the subsequent period. This division reflects the different assessment standards set out in the GRA for these two periods.

In the 2011 ESC, the assessment results are compared to the GRA's dose constraint (for the period of authorisation) and to the risk guidance level (for the subsequent period). The respective GRA requirements are explained in the sections below.

The assessment for the period after the period of authorisation is more extensive than for the period of authorisation, because the timescale extends out to thousands of years. Our review of the period after the period of authorisation broadly follows the structure of LLW Repository Ltd's assessment, which divides the assessment according to the different pathways by which contaminants can come into contact with people. Our review centres on the arguments presented in the 2011 ESC Level 1 and 2 assessment reports. Where there was a need to examine further evidence than that presented in the Level 2 documents we reviewed the Level 3 documents, which are largely specialist contractor reports.

We raised a series of IRFs as part of our assessment. This was to challenge, clarify or seek further evidence in areas where we considered the case submitted fell short, for example, where we considered that the requirements of the GRA were not fully addressed, or where we took the view that technical arguments or conclusions required further evidence to support them. The IRFs are summarised in Appendix 1 of this report and presented in full in a separate report (Environment Agency 2015f).

LLW Repository Ltd satisfactorily addressed all the IRFs raised in the assessments area during the course of our review and we have closed them. Nevertheless we have identified a series of recommendations and FIs where we consider there is scope for LLW Repository Ltd to make further improvements or pursue developments to the ESC in the future. Whether we made a recommendation or raised a FI depends on the environmental consequences in the absence of any further work. Tables summarising the recommendations and FIs are respectively presented in Appendix 2 and Appendix 3 of this report. We also assessed whether the information presented was sufficient to address technical issues that we raised previously in our assessment of the 2002 ESCs (Environment Agency 2005a). A summary of how LLW Repository Ltd has addressed these issues can be found in a separate report (Environment Agency 2015h).

The following sections detail our review, focussing on those areas we deemed important to the 2011 ESC. Our review focuses on the assessment work covering the LLWR Reference Disposal Area (RDA), which comprises the trenches and Vaults 8 to 14. A separate section is provided addressing the assessment of the impacts associated with an Extended Disposal Area (EDA), which comprises the RDA plus additional Vaults 15 to 20. We highlight why we raised certain issues based largely on GRA requirements and indicate whether we consider relevant requirements or issues have been adequately addressed.

2.2. Period of authorisation assessment

2.2.1. Requirement R5: Dose constraints during the period of authorisation

The period of authorisation includes the operational period, which LLW Repository assumes will continue up to 2080 AD in the case of the RDA or 2130 AD in the case of the EDA, and a subsequent period of active institutional control. Active institutional control is anticipated to last for

a minimum of 100 years following completion of disposals (and a maximum of 300 years) and include management of the site and monitoring.

GRA Requirement R5 states that, 'During the period of authorisation of a disposal facility for solid radioactive waste, the effective dose from the facility to a representative member of the critical group should not exceed a source-related dose constraint and a site-related dose constraint'.

As outlined in GRA paragraph 6.3.2, the following dose constraints are defined:

- 0.3 mSv y⁻¹ from any source from which radioactive discharges are made
- 0.5 mSv y⁻¹ from the discharges from any single site

In addition, supplementary guidance to the GRA related to the implementation of the Groundwater Directive states that the dose to members of the public through the groundwater pathway during the period of authorisation of the facility should be consistent with, or lower than, a dose guidance level of 20 µSv y⁻¹ (Environment Agency 2013).

LLW Repository Ltd has used its measured discharges and environmental concentrations to provide evidence that the dose constraints have been met in the past (LLW Repository Ltd 2011a). Consideration of likely future discharges during the period of authorisation coupled with assessments show that future radiological impacts will be below the dose constraints, even when cautious assumptions are made.

LLW Repository Ltd (2011a) summarises the assessment of peak annual doses to potentially exposed individuals for each possible exposure pathway. Estimated doses are below the source dose constraint even if the peak assessed annual doses are summed (and different exposure pathways lead to peak doses in different locations at different times).

To compare against the source-related dose constraint of 0.3 mSv y⁻¹, LLW Repository Ltd has provided assessments of dose from direct radiation and from discharges.

We raised an IRF requesting LLW Repository Ltd to consider the National Dose Assessment Working Group (NDAWG) and Environment Agency guidance on prospective dose assessments (ESC-RI-ASO-014). We queried the adequacy of the summation of doses between exposure pathways and the evolution of doses throughout the period of authorisation to illustrate the trend in doses up to the end of that period and into the beginning of the subsequent period.

In response, LLW Repository Ltd has confirmed that (Sumerling and Jackson 2013):

- The critical group for the present day can be considered as the population dwelling to the north-east of the disposal area. The exposure of this group is primarily from inhalation of radon daughters, assumed consumption of local foodstuffs (mainly milk and milk products) and direct radiation (workers at the coal yard and site perimeter walkers); other pathways make trivial additions.
- A reasonable estimate of the annual effective dose to adults in this group is about 70 µSv. Children and infants could receive higher doses than adults via consumption of milk and milk products (plus 20% and times 3 respectively), but their exposure via direct radiation will be much lower, so that children and infants are unlikely to receive a total annual dose greater than the adults considered.
- To assess the evolution of doses over the period of authorisation, LLW Repository Ltd considered 2 potentially exposed groups: the north-east resident group (see above) plus a hypothetical group that does not exist at present, making use of a drinking water well to the south-west of the disposal area and also exposed through other pathways. The assessed total annual dose to both groups decreases to about 1 µSv at the assumed end of active control of the site (end of the period of authorisation). That is, comfortably below the value of 20 µSv y⁻¹ that corresponds to the risk guidance level after the period of authorisation for a situation that is assumed to occur.
- The largest contribution to the assessed annual dose for both groups is from radon gas. This decreases as capping proceeds.
- The dose from the groundwater pathway, considered separately, remains below the 20 µSv y⁻¹ dose guidance level at all times.

- Releases of tritium to groundwater do not contribute significantly to radiation dose at present. Furthermore, the land between the disposal area and the coast is currently a Site of Special Scientific Interest (SSSI), so that there is unlikely to be any development that would include a well that might abstract tritium contaminated groundwater. Nevertheless, the possibility that tritium contaminated groundwater could be abstracted from an offsite borehole (assumed to be located between the site and the coast) has been examined indicating a potential dose from tritium (via the well abstraction pathway) of a maximum of $3 \mu\text{Sv y}^{-1}$ (falling by more than an order of magnitude by 2050).

We reviewed the 2011 ESC assessment and the response to our IRF (Sumerling and Jackson 2013) and accept LLW Repository Ltd's approach, reasoning and conclusions. However, given the limitations inherent in all environmental modelling projections, it would not be appropriate to rely entirely on this assessment. Instead, we require site monitoring to be able to identify any significant changes to existing contamination levels. Our review of the current and forward monitoring programmes confirms that sufficient monitoring capability is in place (Environment Agency 2015d).

In June 2013, LLW Repository Ltd notified us of an error it had identified in the assessments of direct radiation and dust inhalation dose rates in the 2011 ESC reports for the period of authorisation. The error related to radionuclide inventories assumed for the future, taking into account radioactive decay. For dust inhalation, revised assessments show that the maximum effect of the error is for the EDA vaults, where the assessed annual dose increases from 0.35 to $0.41 \mu\text{Sv}$ (Penfold 2013a). For direct radiation, there is a more significant increase in assessed radiation doses. Maximum annual doses were previously assessed for Vault 9 ($7 \mu\text{Sv}$ for the dog walker, $72 \mu\text{Sv}$ for the coal worker and $145 \mu\text{Sv}$ for the resident) (LLW Repository Ltd 2011a). For the revised assumption concerning decay, maximum annual doses from direct radiation are assessed for Vault 13 ($30 \mu\text{Sv}$ for the dog walker, $300 \mu\text{Sv}$ for the coal worker and $600 \mu\text{Sv}$ for the resident) (Penfold 2013b). This is approximately a four-fold increase over the earlier dose that results in assessed total annual doses in excess of the source related dose constraint of $300 \mu\text{Sv y}^{-1}$.

LLW Repository Ltd claims that these revised doses are overestimates of annual direct radiation because existing houses are located some distance from the site boundary and houses would not be developed on the SSSI, so that the doses estimated for this pathway would not arise. Similarly, a coal yard would not be developed on the SSSI and dose contributions from Vaults 9 onwards are not significant for the existing coal yard. We agree that the conservatisms used in the revised assessment mean that the dose constraint is unlikely to be exceeded in practice. Assuming continued regulation of the site equivalent to today's standards, these exposure scenarios would not be permitted without further mitigation measures to reduce off-site radiation doses. Given that the LLWR is a nuclear licensed site, the Office for Nuclear Regulation would also need to be satisfied that direct radiation doses during future site operations are kept as low as reasonably practicable.

In summary, we consider that LLW Repository Ltd has demonstrated through monitoring and assessment that the dose constraints have been met in the past and that future radiological impacts will be below the dose constraints throughout the period of authorisation. We consider the assessment methods to be appropriate and consistent with the GRA. However, we recommend that future period of authorisation assessments should include a more thorough assessment of scenario, conceptual and parameter uncertainties (**Recommendation ASS1**).

2.2.2. Integration between the period of authorisation and post-closure assessments

The 2011 ESC presented separate models of groundwater impact for the period of authorisation and the subsequent period. We questioned the consistency of this approach, given that the models were developed using different assumptions (for example, the period of authorisation model takes into account the sequential nature of disposals but omits the effects of engineering activities at closure, whilst the model for the period after the period of authorisation begins at 2080 AD, when it is assumed that all disposals and the final cap are in place) and there is a 100 year overlap for both the radiological and non-radiological assessments (ESC-TQ-ASO-008). In particular, the models for the period after the period of authorisation do not make allowance for discharges to

groundwater that occurred previously (that is before 2080). This is not an issue for the vaults, as it is assumed that leakage is minimal throughout the period of authorisation. However, discharges to groundwater from the trenches have occurred from the beginning of operations as evidenced by the current tritium plume in groundwater down gradient of the trenches.

In response, LLW Repository Ltd has presented combined graphs of impact throughout the entire assessment period for both radiological risk and environmental concentrations of non-radioactive contaminants. LLW Repository Ltd has provided 2 cases for the period of authorisation based on a 50 mm y^{-1} infiltration rate through the interim trench cap (as considered in the 2011 ESC) and a 300 mm y^{-1} infiltration rate (a more realistic rate based on the results of recent cap performance assessment outputs and trench cap observations (Environment Agency 2015e)).

There is reasonable correlation in total radiological risk between the results at the end of the period of authorisation assessment and the start of the post-closure assessment (50 and 300 mm y^{-1} infiltration rate scenarios). Earlier breakthrough of radionuclides such as neptunium-237 (Np-237) and lead-210 (Pb-210) is seen in the period of authorisation model. However, overall risks are significantly below the risk guidance level. The correlation between the models is poorer for the non-radioactive contaminant assessment; this is discussed further in Section 2.5.3. The presentation of discharges and impacts from the assessments for the period of authorisation and for the subsequent period as a single output would assist LLW Repository Ltd in communicating the nature and significance of environmental impacts. We recommend that future versions of the ESC seek to fully integrate the assessments for the period of authorisation and for the subsequent period (**Recommendation ASS2**).

2.3. Assessment of long-term radiological impacts

LLW Repository Ltd's objective for its long-term radiological assessment is to assess the radiological impacts to humans that may happen in the long-term as a result of disposal of solid radioactive waste at the LLWR while the facility continues to operate. 'Long-term' means at all times after the completion of disposal and the end of active institutional control of the site (currently anticipated to be 2230 AD for the EDA).

LLW Repository Ltd assesses the radiological performance of the LLWR in terms of the potential mechanisms by which contaminants may be released, migrate or give rise to either exposure to humans or the presence of contaminants in the biosphere. Four exposure pathways are considered: groundwater, gas, coastal erosion and human intrusion. Future 'Potentially Exposed Groups' (PEGs) could receive external exposure, inhale or ingest contaminated dust, ingest particles and consume contaminated substances, for example drinking water, garden produce, marine foodstuffs and animal products.

LLW Repository Ltd's primary goal is to show that, accounting for a range of uncertainties, the assessed radiological impacts are consistent with GRA Requirements R6 and R7:

- Requirement R6 of the GRA (Environment Agency et al. 2009) states that 'After the period of authorisation, the assessed radiological risk from a disposal facility to a person representative of those at greatest risk should be consistent with a risk guidance level of 10^{-6} per year (that is 1 in a million per year).' (GRA Paragraph 6.3.10)
- Requirement R7 of the GRA (Environment Agency et al. 2009) states that 'The developer/operator of a near-surface disposal facility should assess the potential consequences of human intrusion into the facility after the period of authorisation on the basis that it is likely to occur. The developer/operator should, however, consider and implement any practical measures that might reduce the chance of its happening. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv/year to around 20 mSv/year. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short-term (transitory exposures)' (GRA Paragraph 6.3.36)

LLW Repository Ltd's current radiological assessment builds on earlier assessments carried out by the previous site operators, BNFL and British Nuclear Group Sellafield Ltd. The 2011 ESC assessment takes account of our review of the previous ESCs (the 2002 Operational

Environmental Safety Case, or OESC, and Post-Closure Safety Case, or PCSC; BNFL 2002a; 2002b), our review of LLW Repository Ltd's 2008 response to Schedule 9, Requirement 2 of the LLWR environmental permit, which provided an update on LLW Repository Ltd's performance assessment and its strategy for optimisation at the LLWR (Environment Agency 2009a) and our queries subsequently raised during ongoing dialogue with LLW Repository Ltd in the intervening period before the 2011 ESC was produced.

LLW Repository Ltd has assessed radiation doses and risks for the 4 exposure pathways. The assessments include migration of radionuclides from the LLWR (for example, via the groundwater or gas pathways) to the biosphere and transport within the biosphere. The assessments cover the expected evolution of the repository and its environment, taking account of a range of uncertainties, and consider a range of cautiously defined PEGs, so as to identify persons representative of those at greatest risk (or who could receive the radiation doses in the event of human intrusion scenarios). This approach is consistent with the GRA. The assessment results are presented in LLW Repository Ltd (2011b; 2011c), in some cases superseded by later supplementary technical memos as described in LLW Repository Ltd (2013c).

A prospective radiological assessment requires the use of conceptual and mathematical models (implemented via computer codes) and the results depend on the models used. All models have their limitations and uncertainties but the usual approach to mitigating these aspects, where data or evidence of physical process or knowledge about what people may do in the future is lacking, is to employ cautious or bounding assumptions and scenarios. This approach, adopted by LLW Repository Ltd, seeks to make sure that doses and risks are not underestimated, without being grossly overestimated. In practice, this means that assessed doses and risks tend to converge at or just below the relevant safety criteria. This is not by accident, but is part of the modelling process whereby modellers are as cautious as they need to be in their framing assumptions and choice of data, while avoiding excessive caution. This is a normal part of the assessment process but care is required to make sure that, when reducing pessimisms, revised assumptions and data are 'realistic', in as far as this can be established, or demonstrably not optimistic. Our review of LLW Repository Ltd's assessments has focused on the reasonableness of the modelling assumptions, and choice of modelling scenarios and data, as well as on whether the numerical criteria have been met. As part of our review, we audited the quality framework in which the 2011 ESC groundwater models were developed and used (Fairhurst 2013).

To support and build confidence in the models used and the outcomes of the assessments presented in the 2011 ESC, we will require LLW Repository Ltd to undertake continued monitoring of the site and the facility throughout the period of authorisation. Monitoring will also provide reassurance that there are no unexpected or step-change increases of radioactivity into the environment. We reviewed the current monitoring arrangements and forward plan and concluded that they are fit for purpose (Environment Agency 2015d).

In evaluating the long-term assessment case, we refer here to results presented in the 2011 ESC. Several supplementary memos have been submitted to us since May 2011, some of which update these results. LLW Repository Ltd issued an updated summary of the assessment results in December 2013, which clarifies where the results presented in the 2011 ESC have been superseded (Cummings 2013).

2.3.1. National inventory update

The 2011 ESC is based on inventory data reported in the 2007 United Kingdom Radioactive Waste Inventory (UKRWI). The UKRWI was updated in 2010 after the data freeze for the 2011 ESC assessment calculations (NDA 2010). We requested an assessment of the effect on the 2011 ESC results of using data from the 2010 UKRWI (ESC-RI-INF-001).

LLW Repository Ltd has provided a reassessment of doses and risks using data reported in the 2010 UKRWI (LLW Repository Ltd 2012a). The 2010 inventory primarily updated the volumes reported in the 2007 inventory. LLW Repository Ltd has also carried out revised assessments based on the 2010 UKRWI, but has identified no significant implications for the 2011 ESC. For most key radionuclides, with the exception of chlorine-36 (Cl-36) and americium-241 (Am-241), the total inventory projected for the EDA vaults (that is, Vaults 8 to 20) is less using the 2010 inventory data than the inventory assumed in the 2011 ESC. Risks from releases to groundwater are

increased by adoption of the 2010 inventory. For the PEG abstracting water from a well (the most restrictive case), the risk increases from $3.9 \times 10^{-8} \text{ y}^{-1}$ for the 2011 ESC inventory to $7.8 \times 10^{-8} \text{ y}^{-1}$ for the 2010 inventory. These changes in risk are caused primarily by changes to the inventories of carbon-14 (C-14) and Cl-36, the timing of disposals of these radionuclides and changes in the materials inventories in individual vaults. For C-14, these aspects affect the fraction of the inventory that is partitioned into the aqueous phase. In all cases and for all risk pathways, the impact does not challenge the risk guidance level of 1×10^{-6} .

The UKRWI is regularly updated, with the 2013 version published in February 2014 (NDA 2014). While there are no significant changes to the 2011 ESC as a result of the review against the 2010 UKRWI, we expect LLW Repository Ltd to undertake a similar reassessment of doses and risks against the most recent version of the UKRWI as part of LLW Repository Ltd's submission for the next major ESC update (**Recommendation ASS3**).

We note that LLW Repository Ltd undertook no revision of the non-radiological inventory for the review of the 2011 ESC against the 2010 UKRWI. We understand that NDA has been improving the accuracy and scope of the non-radiological national inventory since the 2010 UKRWI was published. We recommend that LLW Repository Ltd assesses the implications of changes to the non-radiological component of the 2013 UK national inventory on the 2011 ESC (**Recommendation ASS4**). Elsewhere in our review we state that we will work with LLW Repository Ltd, NDA and waste consignors to ensure that future updates of the UKRWI better address the non-radiological components to support future non-radiological assessments within the ESC (Environment Agency 2015c).

2.3.2. Groundwater pathway

One pathway whereby radionuclides could return to the surface environment is via mobilisation of radionuclides from the waste and their subsequent migration in groundwater.

As part of a groundwater pathway assessment, we would expect an ESC to model the circumstances in which radionuclides may be released from the disposal facility, migrate within groundwater and expose humans to radiation. These scenarios need to be assessed and reported in a manner proportionate to the significance of their potential impacts. An important part of building confidence in an ESC is provided by including an adequate consideration of the range of scenarios that could arise and the effect of uncertainties in the assessments.

Our review of the groundwater pathway included the characterisation of the LLWR near field (Environment Agency 2015c), geological environment, hydrogeological behaviour (Environment Agency 2015d) and the quality framework in which the assessment was carried out (Environment Agency 2015b). We were able to conclude from these reviews that the groundwater assessment has been appropriately informed.

Exposure pathways to contaminated groundwater

The long-term groundwater radiological assessment considers potential exposures arising from the following 4 biosphere pathways:

- abstraction of water from a well located between the disposal facility and the coast (referred to as the 'well pathway')
- discharges of groundwater to the intertidal area of Drigg Beach (referred to as the 'marine pathway')
- discharges of groundwater to the East-West and Drigg Streams via a near-surface route (referred to as the 'stream pathway') as a result of repository over-topping
- discharges of groundwater to Ravenglass Estuary (referred to as the 'estuary pathway')

Table 1 below summarises the results from those calculations carried out within the long-term radiological assessment that considered exposures via contaminated groundwater for those biosphere pathways detailed above. The calculations considered the reference disposal area and are those submitted in 2013 to support the application for a permit variation (Cummings 2013), with the exception of the probabilistic calculation for the well pathway where the 2011 ESC calculation is reported.

Table 1: Results from the long-term radiological assessment groundwater pathway for the reference disposal area

Calculation case	Risk, y^{-1}	Year (and years post vault closure)	Key radionuclides
Well - probabilistic case	1×10^{-7}	2230 (150)	C-14 / Cl-36
Well - deterministic case	4×10^{-8}	2252 (172)	C-14
Marine release	2×10^{-9}	2226 (146)	C-14
Estuary release	2×10^{-9}	2226 (146)	C-14
Stream release	6×10^{-8}	3180 (1100)	C-14
Results reported above for well – deterministic case, marine release, estuary release and stream release are based on calculations reported in Kelly and Berry (2013), which update those reported in the 2011 ESC (LLW Repository Ltd 2011c).			

Based on a probabilistic calculation, LLW Repository Ltd assesses a peak risk from the well pathway of about $1 \times 10^{-7} y^{-1}$ at around 2230 AD. This is dominated by the contributions from C-14 and Cl-36. Based on a deterministic approach (the reference case), LLW Repository Ltd assesses a peak risk from the well pathway of about $4 \times 10^{-8} y^{-1}$ at around 2250 AD (that is about 170 years after completion of the final cap); the key radionuclide is C-14. Peak risks via other biosphere paths are lower, with C-14 as the key radionuclide. All these peak risks are below our risk guidance level.

Additional cases have also been presented by LLW Repository Ltd (for example, delayed coastal erosion, different inventories and different near field models), all of which show peak risks below the risk guidance level, except for a calculation in which sorption within the near field² is not included. We consider that the omission of sorption in the near field is a very conservative assumption, and hence this risk projection does not give us cause for concern.

As part of a proportionate regulatory review, we undertook an increased level of scrutiny of the well pathway calculations, as this part of the assessment gives rise to the highest estimated peak risks in the 2011 ESC, and is used to derive the limits for radiological capacity.

Modelling approach

LLW Repository Ltd's long-term radiological assessment of the LLWR and its environs took into account the expected evolution of the local landscape, including coastal erosion, in response to climatic conditions, together with the likely long-term performance of the waste and engineering components. LLW Repository Ltd's aim was to adopt a 'cautiously realistic' modelling approach.

To support the assessment, LLW Repository Ltd developed numerical hydrogeological models using the ConnectFlow software to establish a quantitative understanding of groundwater flow (Hartley et al. 2011). Outputs from ConnectFlow informed the development of a compartmental flow model, which provided groundwater flows for use in the 2011 ESC assessments. The compartmental flow model and assessment models were developed within GoldSim. Additionally, LLW Repository Ltd used a biogeochemical model to understand the potential evolution of the waste disposed of and to assist in the parameterisation of GoldSim (Small et al. 2011). The GoldSim assessment model calculates the release of radionuclides from the near field, migration through the geosphere and transport and uptake in the biosphere. Both ConnectFlow and GoldSim have been used by other radioactive waste management organisations. Our review of the

² The 'near field' means the engineered features of the repository, all the materials contained within the repository including the wastes, and any associated soils and sediments within the envelope of the facility.

appropriateness of the supporting models used in the groundwater assessment can be found in (Environment Agency 2015c).

The assessment model used a number of GoldSim compartments and pipes³ to represent the disposal system including the adjacent geological bodies, to assess the release and migration of radionuclides from the waste. The complexity of the model used to represent the disposal facility components is an important consideration in any model development. A less complex model, for example one with fewer compartments, provides a poorer representation of a system compared to a more complex model⁴. In the 2011 ESC, the trenches and the vaults used 2 separate vertical compartments to enable saturated and unsaturated areas to be distinguished. Trenches 1- 6 were further subdivided into 2 longitudinally and the vault disposal area was similarly divided into 7. This is important because in compartmental models the contaminants present are assumed to be evenly dispersed within a compartment. Consequently, the 2011 ESC cannot represent the emplaced inventory in any greater level of detail than this. Thus, if there are instances of higher radionuclide concentrations in a particular part of a trench or vault (for example arising from inventory heterogeneity or the disposal of discrete items), this scale of heterogeneity cannot be represented in the model.

Furthermore, further averaging of concentrations may have been introduced into the 2011 ESC as a result of the representation of the regional groundwater below each trench by a single geosphere pipe, rather than by the multiple pipes used underneath each vault and between the vaults and the coast. The 2011 ESC does not investigate whether these aspects of model configuration may affect the assessment results. We recommend that LLW Repository Ltd considers a sensitivity study of the effects of inventory heterogeneity and configuration of the groundwater model on the assessment results in future assessments (**Recommendation ASS5**).

Within the marine pathway the discharge of groundwater is conceptualised to be 'into the intertidal region on the beach' (Kelly et al. 2011) as this is where the outcrop of lithofacies B3 occurs, in which the regional groundwater flows. From here it is assumed that radionuclides carried in the groundwater will be mixed and dispersed in local coastal waters and that exposures to humans could arise from contact with the beach sediments and flora and fauna in the local coastal waters. The beach and intertidal zone are not separated in the assessment model, which is configured such that radionuclides are directly input to local coastal waters and sediments. The approach used for the estuary pathway adopts a greater resolution of compartments than that for the marine pathway.

The 2011 ESC does not provide a description of how the geosphere-biosphere interface for the marine pathway is configured. The beach compartment is stated to represent an area of 840,000 m² (about twice the present day area between the site and the sea) but the relationship between the beach compartment area and the area of groundwater discharge is not discussed. Furthermore, the groundwater particle tracks presented apparently converge on an area about 200 m in length north of Barn Scar at early times and at later times the area appears around 800 m in length. LLW Repository Ltd does not discuss the reasons for the apparent increase in discharge area over time shown in the particle tracking or the implications on modelled concentrations in the beach area.

LLW Repository Ltd present 2 assessment scenarios in which cliff recession happens, each ultimately resulting in disruption of the site. In the assessment model the distance groundwater travels between the site and the intertidal zone is fixed throughout the assessment period at 500 m, but a variant assessment is also presented that considers a shorter 10 m groundwater pathway. For this shorter pathway variant, the geosphere-biosphere interface appears still to be configured to discharge into the intertidal zone as opposed to discharging to the beach as seepages from a receding cliff line.

³ The GoldSim model represents groundwater flow processes using a series of 'pipes'.

⁴ However, a model with a large number of model compartments (processes) is more demanding in terms of data requirements and model execution and interpretation.

We expect LLW Repository Ltd to further explore the effect of cliff recession on the geosphere-biosphere interface in future ESCs. This should take into account the uncertainty associated with projected groundwater flow pathways in terms of pathway length, spatial variability and location of discharge to the beach (**Recommendation ASS6**).

The assessment approach adopted in the 2011 ESC uses a series of 'snapshots' to represent future environmental states for radiological assessment. We consider this approach to be appropriate.

Within the stream pathway, radionuclide discharge to the stream was conceptualised as occurring only when repository leachate levels substantially increase, following the degradation of the engineered capping system. Overtopping of the disposal facility could then occur, resulting in near-surface releases towards the stream. For the purposes of the assessment calculations it is cautiously assumed that the leachate which overtops under these circumstances discharges directly into the stream. The 2011 ESC design includes a number of engineering design features which are designed to act together to minimise the contact between infiltrating water and the waste and to divert the leachate into the shallow groundwater environment. In our review of the 2011 ESC engineering design, we identified uncertainties in the timing, location and extent of surface discharges resulting from overtopping. We set out our expectations for a forward programme designed to improve the understanding of the overtopping sequence in ESC-FI-023. However, we are satisfied that, despite the remaining uncertainty, LLW Repository Ltd's cautious assumption that overtopping leachate directly discharges to the stream means that it is unlikely to have underestimated potential exposures associated with discharges via the stream pathway (Shevelan 2012).

LLW Repository Ltd uses a GoldSim compartmental model to project transfer of radionuclides within the biosphere and uptake by PEGs. We consider that this approach is consistent with good practice and has been implemented appropriately. Substantiation of parameters used to define the biosphere and PEG habits and associated uncertainties is provided by Thorne (2009). However, there are places where it is not evident which data have been carried through to assessment calculations (for example, typical or high foodstuff consumption rates). We recommend that PEG habits for each pathway, and associated uncertainties, are more transparently documented in future ESCs (**Recommendation ASS7**).

We note that the 2011 ESC does not include an assessment of the sensitivity of assessment calculations to the assumptions and parameters in the biosphere, which is considered for other parts of the system. For example, LLW Repository Ltd explores uncertainty in sorption coefficients in the near field and geosphere but not the biosphere. We recommend that this is considered in future ESC updates (**Recommendation ASS8**).

To build confidence that the configuration of the assessment models is appropriate, we would expect an assessment of the effects of choices made when developing and configuring models on the results calculated. We note that this has not been carried out in some areas for the 2011 ESC. We expect these matters to be explored during any further model development and configuration, and reported as part of future updates of the ESC. LLW Repository Ltd should build confidence in its future ESCs by assessing the effects on calculated results of the choices made when developing and configuring models (**Recommendation ASS9**).

In documenting the results of the groundwater pathway assessment, LLW Repository Ltd tabulates only headline risks. We consider that dose is also useful to see, particularly for scenarios with a likelihood that is less than 1. We recommend that the presentation of risks should be accompanied by a clearer indication of the likelihood associated with the potential exposure in future versions of the ESC, to enable its context to be more readily understood (**Recommendation ASS10**).

Assessment of impacts of uncertainty

After the period of authorisation, the evolution of the disposal system becomes increasingly uncertain over time. Uncertainties may arise from a variety of sources and could include, for example, inherent difficulties in characterising spatial variability (for example, of geological and environmental media) and uncertainties in the evolution of the environment. Simplifications made in developing conceptual and numerical models will also add uncertainty. It is important that an

ESC recognises this fact and includes a structured analysis of the effects of important uncertainties on the potential impacts that could arise from the disposal facility. A structured analysis should identify and rank relevant sources of uncertainty so that a prioritised list of uncertainties can be developed and the impacts of uncertainties on potential exposures can be quantified.

The deterministic cases presented in the 2011 ESC (LLW Repository Ltd 2011c; Kelly et al. 2011) are based on 2 environmental evolution scenarios (the Expected Natural Evolution Scenario and the Delayed Coastal Erosion Scenario), 4 inventory cases and 2 near field models. The Expected Natural Evolution Scenario assumes that coastal erosion of the facility begins at 3180 AD (that is 1000 years after the assumed date of closure of the facility). The Delayed Coastal Erosion Scenario assumes that the onset of coastal erosion of the facility is delayed until 5,000 years after the present date. In each case the assessments are terminated when gross disruption is assumed to begin. Separate assessments are carried out to consider the potential impacts of gross disruption of the repository (coastal erosion scenario; see Section 2.3.4). Conditional risks are estimated within the deterministic assessments. The risks are conditional on the assumption that the scenario occurs, that is, has a probability of 1.

LLW Repository Ltd presented a 'reference case' assessment based on the Expected Natural Evolution Scenario and a near field model in which radionuclides in saturated regions of the trenches and vaults are assumed to be immediately available for dissolution (except for C-14, which is given a more realistic treatment). As discussed in the previous section, the length of the path along which contaminants released from the site travel is fixed at 500 m for all the assessments. The calculation was configured using best estimate parameter values.

Several deterministic variant cases are also presented to investigate parameter uncertainty. For example, LLW Repository Ltd assessed uncertainty in the near field modelling by considering 2 different models of radionuclide release and behaviour, a reference case and 3 variant disposal inventories and exploring the effect of assuming that retardation via sorption does not happen. These calculations used alternative parameter values, which were sometimes values aimed at bounding the case under consideration. Whilst bounding values can be useful for identifying the limits on result sensitivities, they could also result in unrealistic calculations. For example, one variant calculation considered the case in which no sorption occurs in the near field. This calculation case gives rise to peak impacts that exceed the risk guidance level, however, as noted earlier; this does not give us cause for concern due to the conservative nature of the calculation.

LLW Repository Ltd carried out a number of studies to assess the effects of variability and uncertainty in the near field and hydrogeological models. The company used the outputs to inform the groundwater pathway assessment model. However, it did not define variant cases to consider the effects of this variability on the assessment. For example, the company considered the effects of spatial variability in hydrogeological behaviour using variant ConnectFlow calculations but it did not consider this variability in the assessment calculations. LLW Repository Ltd also noted the potential for changes in the chemical conditions for the trenches and vaults after a few thousand years, but did not consider these changes in, for example, the variant Delayed Coastal Erosion Scenario. In general, we consider that LLW Repository Ltd has assessed a reasonable range of variant cases for the groundwater pathway assessment. However, we recommend that it considers a consistent set of variant calculations to take account of conceptual model and parameter uncertainty in both detailed process-scale models and assessment models in future assessments, or explains why this has not been done (**Recommendation ASS11**). We also recommend that it should further investigate variability in the nature of the geosphere-biosphere interface (see Recommendation ASS6).

LLW Repository Ltd carried out a probabilistic assessment for the well pathway only. The company chose this pathway for probabilistic assessment '...because the groundwater well is the limiting biosphere release path for the groundwater pathway, the pathway is amenable to probabilistic analysis, and probability of a well is intrinsic to the analysis' (LLW Repository Ltd 2011c).

LLW Repository Ltd derived probability distribution functions for several input parameters. To derive time-dependent values of parameters for use in the assessments from elicited probability distributions, it used a linear interpolation scheme (Jackson et al. 2011). Parameters having elicited distributions include those representing engineered features, properties of the waste and

wasteform, and settlement. We understand from discussion with LLW Repository Ltd that the interpolation was performed on logarithms of values due to the way in which the elicitation was conducted. The 2011 ESC included a deterministic calculation case aimed at assessing rapid near field degradation that used 95th percentile values. However, application of the interpolation scheme results in consideration only of a relatively smooth transition in parameter values (and degradation of the near field barriers). The effect of abrupt changes in parameters, as could arise, for example, from rapid or sudden failure of a near field barrier or safety function, was not considered. We discuss our requirements for assessment of fault scenarios in future ESCs in Environment Agency (2015e) and raised an FI (ESC-FI-026) that seeks the development of a systematic approach to the identification and assessment of changes in engineering performance resulting from barrier failures.

We did not find it clear how the parameter ranges used in the deterministic calculations compare to probability distribution functions used in the probabilistic calculations and whether the purpose of the probabilistic case was to assess in combination those uncertainties considered in individual deterministic cases. Given that LLW Repository Ltd did not update the probabilistic groundwater pathway assessment after 2011 as it did the deterministic groundwater pathway assessment, we do not consider that this lack of clarity is a significant detriment to the overall 2011 ESC. However, we expect LLW Repository Ltd to provide a better explanation of how it identifies uncertainties and prioritises them for consideration in the deterministic and probabilistic assessments in future ESCs (**Recommendation ASS12**).

We consider that LLW Repository Ltd should continue to develop its approach to reporting the configuration, implementation and interpretation of probabilistic environmental safety assessments as part of a progressive process of improvement, and to fully integrate these improvements into future ESCs. We expect that in future ESC updates LLW Repository Ltd should undertake a structured analysis of uncertainty that identifies and ranks relevant sources of uncertainty and develops a prioritised list of uncertainties for which the impacts of uncertainties on potential exposures are assessed. Additionally, LLW Repository Ltd should consider the use of probabilistic assessment as the main way of comparison against the risk guidance level where viable in future ESCs, supported by further deterministic calculations as appropriate, as part of a structured analysis of uncertainty. This should prioritise uncertainties for assessment and consider use of probabilistic assessment as the main way of comparing against the risk guidance level, where viable (**Recommendation ASS13**).

Further analysis of the well pathway assessment

As previously noted we undertook an increased level of scrutiny of the well pathway assessment, as this pathway gives rise to the highest estimated peak risks in the 2011 ESC.

In the 2011 ESC LLW Repository Ltd reported that 'the local context suggests that were a well to be constructed in the area of interest, it would be of low yield and would provide water to 1 or a few domestic dwellings, an agricultural building or a recreational facility such as a caravan park' (Kelly et al. 2011).

On this basis, LLW Repository Ltd identified the following principal PEGs as requiring consideration:

- a group meeting all their drinking water requirements from the contaminated well water
- a group (smallholders) meeting all their drinking water requirements from the contaminated well water and also using it to irrigate a garden or smallholding from which they produce all the vegetables they consume

In addition, LLW Repository Ltd identified the following, less likely, variant PEGs:

- smallholders who also use the contaminated well water as a drinking water supply for hens kept for egg production
- smallholders who also use the contaminated well water as a drinking water supply for goats kept for milk production
- smallholders who obtain all the milk, meat and offal that they consume from a herd of cattle whose sole drinking water supply is contaminated well water (Thorne et al. 2010)

In the cases included in the 2011 ESC radiological assessment, the third PEG above is considered 'in order to provide an indication of the magnitude of the radiological risks that could arise under 'reasonable' use of the abstracted well waters, but excluding behaviour that could be considered less likely, for example the grazing of a herd of cattle' (Kelly et al. 2013).

The probabilistic assessment of the well pathway uses elicited values of the likelihood that a well is located between the repository and the coast. In ESC-TQ-ASO-009 we queried why the assumed probability for the existence of a well used by the smallholder PEG appeared low compared with observed well densities on the Cumbrian coast. We also queried why only a smallholder had been considered because it is stated in several places in the 2011 ESC that the possibility of ephemeral site uses, such as caravan parks, cannot be ruled out and that, even for a caravan park or holiday homes, there could be 1 or more caravans or nearby dwellings occupied by permanent residents, such as a site manager, who might use water throughout the year from a borehole associated with the caravan park (see, for example, Jackson et al. (2011)). We thus queried why the well likelihoods used in the assessments are the lower values elicited for an isolated dwelling rather than the higher values elicited for a caravan/chalet park.

LLW Repository Ltd provided a response addressing our concerns relating to the probability of the smallholder PEG having a well. LLW Repository Ltd also provided deterministic assessments for caravan site manager and resident PEGs for the RDA vaults (Jackson and Kelly 2013). Peak risks for the caravan site manager PEG from a deterministic calculation are $2 \times 10^{-7} \text{ y}^{-1}$, approximately a factor of 5 greater than the peak risks associated with the reference case smallholder PEG⁵. Peak risks for the caravan site resident PEG are also greater than the smallholder PEG peak risks. A key reason for the increase in the assessed risk is that the probability of a well associated with a caravan site, based on the present-day coastline, is about a factor of 3 higher than the probability of a well for an isolated dwelling. The assumptions used in deriving these PEGs seem reasonable and, with these additional assessments, we consider that a suitable range of potential exposures associated with contaminated groundwater has been assessed. However, we queried LLW Repository Ltd's assumption that the smallholder PEG remains the reference PEG for the well pathway, since the reasons for selecting the smallholder PEG as against the caravan site manager PEG are not adequately substantiated (see Section 2.4 for further discussion).

LLW Repository Ltd elicited values for the likelihood of wells using information consistent with present day conditions at the site and its surroundings and configured a calculation based on consideration of a well being located in the area between the disposal facility and the discharge point assumed to be 500 m away at the location of the present coastline. The probability of a well supplying a dwelling will decrease as land is lost between the LLWR and the coast due to coastal erosion. The company undertook an alternate calculation in the 2011 ESC in which a 10 m groundwater pathway was assessed but did not include the well pathway in the calculation as it considered that this is insufficient land within which a borehole could be credibly located. The probability of a well supplying a caravan park will remain unchanged as land is lost between the LLWR and the coast as it is based on length of coastline as opposed to area. For wells supplying both caravan parks and dwellings there will be a critical distance between the site and coast below which the probability of a well being drilled is negligible due to lack of space or saline intrusion. It is assumed that the likelihood of a well existing will decrease as land is lost, whilst groundwater concentrations will increase due to the reduced distance to the well.

LLW Repository Ltd has not carried out an assessment of how sensitive estimated impacts arising from a well to either a dwelling or a caravan park are to the location of the coastline. The impact of saline intrusion is also not considered. These issues are not anticipated to have a significant

⁵ As reported previously, LLW Repository Ltd assesses a peak risk to the Smallholder PEG from the well pathway of about $1 \times 10^{-7} \text{ y}^{-1}$ from the probabilistic calculation. The corresponding value from the deterministic calculations is $4 \times 10^{-8} \text{ y}^{-1}$. If probabilistic calculations had been undertaken for the caravan site manager PEG we expect that this would have exceeded results from deterministic calculation. If a similar linear relationship exists for the caravan site manager PEG, then a probabilistic calculation may be expected to result in a peak risk of around $6 \times 10^{-7} \text{ y}^{-1}$.

impact on well pathway risks but should be considered in the refinement of any future assessment (**Recommendation ASS14**).

We queried whether the number of realisations carried out in the probabilistic assessment (a maximum of 500) was sufficient to obtain a stable output (ESC-TQ-ASO-009). LLW Repository Ltd presented the results from assessments carried out with 1000 and 2000 realisations that it stated provided confidence that a sufficient number of realisations had been used (Jackson and Kelly 2013). We note that the key radionuclides, C-14, Cl-36 and iodine-129 (I-129), are not strongly retarded and that this may in part explain why converged stable output is achieved in the probabilistic assessment using a relatively limited number of realisations.

We also raised a concern that the approach adopted by LLW Repository Ltd for averaging radionuclide concentrations in abstracted groundwater was unclear. Averaging is carried out over the entire area between the LLWR and the coast. We were uncertain whether this could result in concentrations being underestimated. This subject is discussed by Jackson and Kelly (2013) and Baker (2013b), in terms of the approach to assessing the impact of water abstraction wells. However, we were uncertain about the range of radionuclide concentrations that may be present in the plume (as represented by the various GoldSim pipes) in relation to the assessed average. We were also uncertain whether any differences could be significant in understanding the pattern of potential exposures. We raised a further query with LLW Repository Ltd on this (ESC-TQ-ASO-009a).

The assessment model calculations carried out with GoldSim assume that the geological strata are homogenous and thus also assume that the hydrogeological behaviour is homogeneous. However, LLW Repository Ltd recognises elsewhere in the 2011 ESC that the shallow geology around the site exhibits substantial heterogeneity. For example, LLW Repository Ltd has carried out ConnectFlow simulations that explore the effects of this spatial heterogeneity. In these simulations, particle tracking revealed areas of both preferential and reduced groundwater flow in response to variations generated in the realisations of hydraulic conductivity. We could not find any information in the 2011 ESC on the effects of variations in modelled groundwater concentration on the well pathway assessments, or a commentary on how these variations might compare with conditions expected at the site. Without further information, we could not judge the acceptability of LLW Repository Ltd's approach of using only the average radionuclide concentration in its assessments. We thus sought this information (ESC-TQ-ASO-009a).

LLW Repository Ltd responded to ESC-TQ-ASO-009a by providing further analysis that presented the range of potential exposures associated with the use of a well taking into account uncertainty and spatial variability (Applegate et al. 2013). LLW Repository Ltd also clarified the methodology used to estimate the average radionuclide concentrations within the expected plume area in response to our remaining uncertainties.

LLW Repository Ltd demonstrated the effect of parameter uncertainty by presenting the peak conditional doses and the mean value of the peak conditional doses for 1,000 realisations of the GoldSim calculation (Applegate et al. 2013). LLW Repository Ltd reported the mean value of the peak conditional doses⁶ as 120 $\mu\text{Sv y}^{-1}$. LLW Repository Ltd also undertook an analysis of the effects of varying the distribution of activity in the vaults and concluded that the resulting variation in conditional dose was more limited than for parameter uncertainty.

LLW Repository Ltd explored the effect of different specific locations for a well by undertaking a number of GoldSim calculations in which the well was assumed to be sited within each of the pipes used to represent the expected plume area. The mean value of the peak conditional dose was reported as 35 $\mu\text{Sv y}^{-1}$ and 95% of values were estimated to lie within a factor of 16 of the mean, which we consider reasonable.

⁶ The mean of individual realisation peak conditional doses presented cannot be meaningfully compared to the peak of the mean conditional dose, 5 $\mu\text{Sv y}^{-1}$ (derived as the expectation value in a probabilistic assessment). The two values are derived differently. These doses are also conditional on the exposure occurring, that is the likelihood of the exposure occurring has not been considered.

LLW Repository Ltd investigated the effect of spatial variability in the hydrogeological properties of the geological units on the migration of contaminated groundwater, using the ConnectFlow models described in the 2011 ESC. The company presented results from particle tracking simulations for cases in which the units were assumed to be homogeneous or subject to heterogeneity. These showed that significant variation in the distribution of dose within the expected plume area is possible. For the case in which LLW Repository Ltd assumed the units to be homogeneous, a peak risk of $8.8 \times 10^{-7} \text{ y}^{-1}$ was derived, although the company considers this estimate to be cautious⁷.

LLW Repository Ltd selected 3 of the spatial variability realisations of hydrogeological modelling presented in the 2011 ESC to assess the effects on potential exposures associated with the use of a well. The results display the greatest variability of any results presented, with 95% of the values lying within a factor of 40 of the central value. The groundwater flow in these realisations shows a tendency to channel through areas of the expected plume as a result of the heterogeneity. This leads to a corresponding variation in conditional doses. The analysis is useful in illustrating the effects of spatial variability on radiological impacts, however, a small number of spatial variability realisations were assessed by LLW Repository Ltd. Future assessments would benefit from a more detailed consideration of spatial heterogeneity (**Recommendation ASS15**). We also recommend that LLW Repository Ltd investigates the potential to develop this work further so that these estimates are more readily able to be compared directly with the assessment calculations. This might for example be achieved by better restricting the ConnectFlow calculations to the plume area between the site and the coastline (**Recommendation ASS16**).

In summary, LLW Repository Ltd's assessment of the well pathway has entailed expert judgement to characterise potential future human behaviour and has used both deterministic and probabilistic approaches to assess potential impacts. We welcome the further information that LLW Repository Ltd has provided in response to our review of the well pathway and its assessment. The further information clarified and supplemented the initial presentation in the 2011 ESC.

Given the magnitude and variation of potential exposures estimated to arise from use of a well it is important for the ESC to document a clear, comprehensive and robust assessment of this pathway. We recognise that the 2011 ESC includes uncertainties, such as those associated with the potential for future groundwater use. We recommend that LLW Repository Ltd undertakes further investigations into the nature and significance of uncertainties associated with the potential for future groundwater use in future assessments (**Recommendation ASS17**). We also recommend that LLW Repository Ltd improves the clarity of its presentation of complex assessment areas such as the effect of spatial heterogeneity in the hydrogeological properties of the geological units on the migration of contaminated groundwater and future groundwater use in future assessments (**Recommendation ASS18**).

Presentation and interpretation of the results for probabilistic assessments can be challenging and the use of visual approaches, such as those developed to illustrate the distribution of conditional dose in the expected plume area, can usefully support this. As noted above, we consider that the use of probabilistic assessments (where viable) throughout an ESC for a facility such as the LLWR represents best practice, rather than its presentation as a way of exploring a particular exposure pathway.

The risks to the smallholder PEG arising from the well pathway assessment for the RDA remain below the risk guidance level; however, the central values lie within an order of magnitude of this level and are subject to uncertainty. LLW Repository Ltd considers that the smallholder PEG is not the most exposed group and has provided additional arguments in support of this position in its

⁷ LLW Repository Ltd's assessments contained some simplifying assumptions (for example a constant source term and tracking particles rather than contaminants). It also considered a wider domain than the expected plume area (that is part of the disposal facility and area below mean high water were included within the ConnectFlow domain, where the location of a groundwater well is not considered credible). LLW Repository Ltd considers the results to be an overestimate of the potential exposures and thus regards them as illustrative only.

response to our technical queries. We consider that in future iterations of the ESC, LLW Repository Ltd should fully underpin its choice of PEGs, particularly where these are used in stylised assessment calculations. Present-day and historical patterns of human behaviour should be considered when developing analogues for potential future human behaviour (**Recommendation ASS19**).

2.3.3. Gas pathway

The release of radionuclides in the gaseous phase is another potential pathway to public exposure. The radionuclides of possible concern are those capable of chemically combining to form gases in the repository and those that are gaseous in elemental form. C-14 is of possible concern because it can combine to form methane and carbon dioxide. Radon-222 (Rn-222) is of possible concern because it is gaseous itself. Tritium-3 (H-3) is of interest only during the operational phase of the repository because of its short half life (12.3 years).

Rn-222 has a half-life of only 3.8 days but is generated from the decay of the long-lived radium-226 (Ra-226). The rate of production of Rn-222 in the waste is directly proportional to the inventory of its parent, Ra-226 (half-life 1,600 years).

LLW Repository Ltd presents results for the gas pathway primarily as conditional annual doses, the probabilities of which are not readily quantifiable. LLW Repository Ltd has carried out deterministic assessments because it considers that a meaningful probabilistic assessment cannot be supported with the present state of knowledge regarding the forward inventory waste characteristics, and the gas generation and gas transport processes. We agree with this.

In Environment Agency (2015e) and ESC-FI-024, we identified the need for a gas management strategy which outlines how gases will be managed throughout the period of authorisation. The gas management strategy should describe the nature and extent of gas collection and management requirements. We note that LLW Repository Ltd has not made a final decision on whether the gas vent in the final cap will be left open or closed at the end of the period of authorisation. We recommend that, once a final decision has been made, LLW Repository Ltd ensures that the assumptions and conclusions within the 2011 ESC are still applicable. If not, this issue should be addressed in future updates of the ESC (**Recommendation ASS20**).

Radon-222

LLW Repository Ltd considers that doses from Rn-222 are negligible, provided that the low permeability elements of the engineered cap remain intact. Doses from Rn-222 are only important if the gas can reach the surface in a relatively short time: for example, house foundations penetrating the cap and Rn-222 accumulating in a basement; or a house constructed over a substantially degraded cap. LLW Repository Ltd has analysed the performance of the gas collection layer cap vent and has shown that even by this route releases of Rn-222 are negligible.

The case giving the highest Rn-222 dose is where a dwelling is constructed either directly above the radium-bearing waste or on spoil created by excavation of repository cover materials and waste, including radium-bearing waste. LLW Repository Ltd considers that these pathways to Rn-222 exposure should be regarded as 'human intrusion', because human action has disturbed the engineered cap. We agree with this approach.

The GRA defines a dose guidance level of 3 to 20 mSv y⁻¹ for human intrusion scenarios (Requirement R7). LLW Repository Ltd presents assessments exploring the consequences of a degraded 'cap infiltration barrier' (as a result either of progressive natural degradation processes or of intrusive human actions) with a building constructed on the degraded area, assuming a specified inventory of Ra-226 (that may be a gross overestimate). Under these circumstances, annual effective doses greater than 3 mSv might be incurred by house occupants; this is for cases where only a single course of inert material is assumed to lie over the vaults (LLW Repository Ltd 2011c; Limer and Thorne 2011).

Assuming 1 m of inert material between the waste and the building foundations, LLW Repository Ltd assesses doses in the range 1.7 - 36 mSv y⁻¹. The estimated indoor air concentration of Rn-222 would exceed the Health Protection Agency (HPA) (now Public Health England (PHE)) Action Level for domestic housing of 200 Bq m⁻³ (HPA 2008). These results assume a forward inventory

of Ra-226 of approximately 2 TBq. However, there is uncertainty over the magnitude of existing and future Ra-226 disposals to the LLWR (principally those waste streams arising from clean-up of land owned by MoD either currently or historically), and it may be that future Ra-226 disposals to the LLWR will fall significantly below 2 TBq. However, LLW Repository Ltd proposes an emplacement strategy for some radium-bearing waste within the vaults. The company will place this waste lower in the waste stacks. The additional travel time for the Rn-222 through the higher stacks of waste will be sufficient for the potential exposure to reduce by 3 orders of magnitude. Doses will then be well within the dose guidance level. As part of optimising waste disposals, the company will be required to implement this strategy.

We also queried what the doses from Rn-222 would be if cap performance degraded more significantly than assumed in the ESC (ESC-TQ-INF-035). Because of the importance of the cap in limiting the release of Rn-222, we considered possible cap failure mechanisms. As a result of desiccation, degradation or settlement, the clay or Bentonite enhanced soil (BES) gas barrier could crack. Localised cracking of the clay or BES layer might lead to higher fluxes of Rn-222 through the cap, which in turn might lead to higher doses. This issue is discussed in our inventory report (Environment Agency 2015c). LLW Repository Ltd concludes that the effects of cap degradation and settlement will have no significant effect on Rn-222 release because of the chemical and physical properties of Rn-222 (inert and denser than air). We agree with this appraisal.

Carbon-14

LLW Repository Ltd's assessment for C-14 consists of a biogeochemical model to assess the evolution of C-14 labelled gases in the trenches and vaults and a biosphere model to assess how C-14 could then be taken up in vegetation and human foodstuffs (LLW Repository Ltd 2011c; Limer et al. 2011). C-14 is expected to be present in methane and carbon dioxide (CH₄ and CO₂) gases produced by degradation of organic waste and by other microbially-mediated reactions. Trench monitoring has confirmed that C-14 is evolved from the trenches both in the form of methane and of carbon dioxide. The highest release rates of C-14 labelled gas are assessed to arise from (a future) Vault 14, which is expected to contain the largest inventory of C-14 bearing decommissioning waste.

In the 2011 ESC, LLW Repository Ltd presents results for reference case assumptions, showing annual doses from the RDA vaults of 680 µSv at 100 years after vault closure (2180 AD) and 30 µSv at 300 years after vault closure (2380 AD). The company notes that the annual risk would only become consistent with regulatory criteria at around 300 years after repository closure. However, LLW Repository Ltd has stated that the C-14 modelling work described in the 2011 ESC is overly cautious, regarding both the assumptions for the near field release rates and the biosphere transfer factors (the assessment was revised in September 2013 - see below).

We agree with LLW Repository Ltd that the 2011 ESC C-14 assessment appears excessively cautious in relation to similar assessments carried out for near-surface repositories overseas. The company calculated that 45% of the total C-14 inventory disposed of is released as C-14 labelled methane and assumed that all this methane is then converted to C-14 labelled carbon dioxide for plant uptake into crops consumed by a smallholder residing on the cap. In practice, however, there is considerable uncertainty over the interaction of C-14 with soil microorganisms and organic matter, and the degree of uptake by plants. We requested an updated assessment of C-14, noting the shortcomings of the 2011 ESC assessment that LLW Repository Ltd had itself recognised (ESC-RI-ASO-005).

LLW Repository Ltd reported a revised scoping assessment to us in February 2012 (LLW Repository Ltd 2012b). This revised assessment, which incorporated more realistic modelling assumptions, showed that annual risks would fall below the risk guidance level at about 2180 AD. LLW Repository Ltd stated that an institutional control period of around 100 years after vault closure is sufficient to reduce assessed doses and risks from C-14 exposure to a level consistent with the risk guidance level. LLW Repository Ltd notes in its submission that, to manage this risk during the 100 year institutional control period, the only requirement is to prevent the cap area from being used for agriculture.

Unlike Rn-222, a fast-track pathway for C-14 to the surface through weaknesses in the cap (for example, from poor quality sealing on the gas vent port or poor quality seams in the strip-capping), would not lead to higher doses since exposure is primarily via plant uptake and ingestion, which dominates over exposure by inhalation. The international consensus view is that the principal exposure pathway for C-14 is uptake by plants with subsequent ingestion by humans (for a given surface area of C-14 emission, the dose from this route is 5 times that of direct inhalation of C-14 labelled carbon dioxide).

In September 2013, LLW Repository Ltd presented a revised and better underpinned assessment of radiological impacts from C-14 bearing gases (LLW Repository Ltd 2013a). The assessment provides: a more realistic appraisal of the physical and chemical form of C-14 bearing waste likely to be consigned to the LLWR in future; revised package and vault scale representation of C-14 release processes; and updated partitioning factors and biosphere factors. These changes result in a reduction in dose of nearly 2 orders of magnitude compared with the 2011 ESC dose assessment. Annual doses averaged over the whole vault area are now assessed to be about 3 μSv to a person representative of the group at greatest risk (a smallholder), with a corresponding annual risk of 1.8×10^{-7} . A range of alternative credible exposure cases are also presented, which indicate marginally lower doses and risks. All results are assessed for a smallholding established over the area of the vaults at 100 years after closure of the last vault. All dose and risk figures are now consistent with the GRA requirements. We agree with this appraisal. On the basis of these revised assessments, LLW Repository Ltd now proposes a radiological capacity limit for C-14 of 130 TBq (representing a reduction on the 2011 ESC figure of 320 TBq) (see Section 2.4).

We support LLW Repository Ltd's programme of longer-term work, which includes: maintaining an up-to-date scientific understanding of relevant processes and the characteristics of future C-14 bearing waste; further modelling work; maintaining an awareness of national and international initiatives to improve understanding of the partitioning of C-14 into plants; and, potentially, experimental work.

2.3.4. Natural disruption and dispersion pathway - coastal erosion

LLW Repository Ltd expects the erosion of the repository to commence in a timescale of a few hundreds to a few thousands of years. This is termed the Expected Natural Evolution Scenario and is underpinned by climate change and sea level rise assessments (LLW Repository Ltd 2011g). We consider that the company has appropriately characterised and understood the nature and timing of the disruption of the LLWR by coastal erosion (Environment Agency 2015d).

In line with the requirements of the GRA, the 2011 ESC assessment presented assumes that no remedial action is taken before or during the onset of repository erosion. This will result in the exposure of waste in the cliff and on the beach, and dispersal of the waste in the marine environment. Erosion is expected ultimately to result in the complete dispersion of the repository waste into the coastal and marine environment.

Radiological exposures may occur by a variety of pathways: external irradiation from waste in the cliff and on the beach and foreshore; and internal irradiation via inadvertent ingestion of contaminated particulate waste or via the consumption of marine foodstuffs. The concentrations of radionuclides in different parts of the shore environment will change over time as different parts of the LLWR are eroded. The radiological assessment in the 2011 ESC considered the most likely shore environments during the erosion process.

LLW Repository Ltd provided the results of 'stylised deterministic cases' (illustrative, 'what if' assessments) since a probabilistic approach cannot be substantiated because of uncertainties about future global CO₂ emissions, sea-level rise, local erosion under these conditions and peoples' likely habits and behaviour relating to an eroding landfill (LLW Repository Ltd 2011c; Towler et al. 2011). We agree that this approach is appropriate given the uncertainties. However, we queried why the coastal and marine biosphere considered in the coastal erosion assessment differed from that in the groundwater pathway assessment in ESC-TQ-ASO-003. LLW Repository Ltd justified the reasons for significant differences in Sumerling (2012a) to our satisfaction. We recommend that future ESCs should have a greater consistency between the models for different pathways, including both physical representations of the biosphere and PEG habits, and that

significant differences should be justified and implications on impacts identified (**Recommendation ASS21**).

In the 2011 ESC, LLW Repository Ltd provided a representative estimate of dose and compared it to an annual dose of 20 μSv (that is a dose equivalent to the risk guidance level, assuming exposure is certain to occur). LLW Repository Ltd presented results for 3 potentially exposed groups:

- a recreational user of the local beach
- an occupational user of the coast
- a high-rate consumer of local marine foodstuffs

All results were below the 20 $\mu\text{Sv y}^{-1}$ dose level. The dominant pathway was found to be exposure to external radiation from waste present on the beach and foreshore. LLW Repository Ltd's 'reference case' considered erosion of the vaults by the process of 'undercutting' by the sea, beginning at 1,000 years after the present and progressively eroding the facility along a front parallel to the coastline. The choice of 1,000 years as the reference case for the onset of coastal erosion is arbitrary given that the assessed range lies between a few hundred and a few thousand years. Our review of the site evolution work confirms that the choice of 1,000 years is reasonable bearing in mind the uncertainties (Environment Agency 2015d). The reference case yields a peak annual dose to the local recreational beach user of 19 μSv (principally attributable to past disposals of thorium-232 (Th-232) in Trenches 4 and 5). The peak annual dose to the inshore fisherman is 11 μSv (from Ra-226 and its progeny), and the peak annual dose due to ingestion of marine foods is 12 μSv (dominated by Pb-210 and polonium-210 (Po-210) from assumed future Ra-226 disposals to the vaults).

In addition to the reference case (giving a peak annual dose of 19 μSv), LLW Repository Ltd assessed variant cases exploring the effect of uncertainties in: the onset of erosion, between 300 and 3,000 years (early and late erosion with respect to the 1,000 years reference case); the angle of erosion; and the resistance of wasteform to erosion. These variant doses are estimated at between 3 and 57 $\mu\text{Sv y}^{-1}$. The highest peak annual dose assessed for the variant cases is to the local recreational PEG for a 'direct erosion' case. That is, the vaults and trenches are assumed to be eroding at sea level with no dilution due to the co-erosion of the underlying drift geology. LLW Repository Ltd states that the relationship between sea level rise and the rate of erosion indicates that this is possible, but less likely than the reference case, so that the 57 $\mu\text{Sv y}^{-1}$ 'variant case' dose, whilst exceeding 20 $\mu\text{Sv y}^{-1}$, should not be given dominant consideration for regulatory purposes. We accept this argument.

In ESC-TQ-ASO-006 we queried whether the assessment was sufficiently conservative regarding the exposure to undiluted waste in the eroding cliff or on the shore following erosion. In response, Sumerling (2012b) provided further evidence that addressed our concerns and substantiated the magnitude of doses calculated in the 2011 ESC. However, we recommend that the next assessment includes a thorough review of the implications of dilution of waste material in the cliff, beach and foreshore, covering both loose trench waste and vault waste with higher integrity (**Recommendation ASS22**).

Waste heterogeneity and particles

Since the 2002 PCSC, there have been several investigations into the effects on human exposure to ionising radiation of high activity particulate materials released into the environment. The most relevant case is Dalgety Bay in Fife, where Ra-226 particles have entered the environment as a result of the coastal erosion of a historical landfill.

We queried how representative LLW Repository Ltd's assumptions were about the nature and form of the waste as it may enter the accessible environment as a result of coastal erosion. Such a scenario is not typically assessed for near-surface repositories. However, near-surface repositories are typically subject to assessment of the consequences of human intrusion and of disruption resulting from the long-term degradation and erosion of capping materials. These disruption mechanisms may happen on a shorter timescale than coastal erosion and may also be of a lower probability. We expect generalised, representative assessments as part of any ESC submission. We thus consider it an omission that the 2011 ESC submissions did not specifically consider the

potential for people to incur doses directly from inhalation or ingestion of discrete particles of raw, undiluted waste ('hot spots') that may become accessible on the beach.

The current LLWR WAC state that all waste should consist only of 'waste deemed to be contaminated and not the primary contaminant itself'. However, in the past this WAC was used to control disposal of bulk product rather than contaminated materials and was not interpreted to exclude waste containing active particles. Additionally, past disposal practices dating back to 1959 have not been as rigorous as now, nor is it practical to assume that, even now, 100% of any discrete particles are identified and removed effectively from all waste streams. It is therefore reasonable to assume that some particles may be present in waste previously disposed of and that they may continue to enter the LLWR in the future, even if in small numbers.

The models used by LLW Repository Ltd for assessing doses from coastal erosion (and human intrusion) made use of a grid to map the known heterogeneity into a set of discrete modelling cells. These cells were developed as a compromise between representing waste heterogeneity and practical issues of modelling. The modelling grid (with 40-50 cells) reflected the presence of known, localised concentrations of radionuclides in the trenches and Vault 8. The grid approach was a significant advance on BNFL's 2002 assessments but the methodology and grid size still did not capture, in sufficient detail for the purpose of assessing human health effects, the potential for exposure to any 'hot spots' that may be present in the waste.

We requested that assessments be carried out using a more realistic representation of waste heterogeneity, using methodologies developed for assessing radiological consequences from radioactively contaminated land and beaches contaminated by radioactive objects (ESC-RI-ASO-010). These methodologies have been applied by PHE for assessing doses and risks from particles recovered from beaches at Sellafield, Dounreay and Dalgety Bay (Brown and Etherington 2011, Wilkins et al. 2006 and Brown and Oatway 2012 respectively).

In response, LLW Repository Ltd commissioned further assessments that broadly followed our suggestions to adopt PHE guidance, although with modifications to account for coastal erosion at the LLWR as a longer-term situation compared to present day particle finds elsewhere (Mobbs and Sumerling 2012). LLW Repository Ltd presented results for a range of potential wastefoms in a series of 'what if' assessments for different types of waste that may be present in the LLWR.

These illustrative assessments suggested that it is possible for someone to incur higher doses than assessed in the 2011 ESC, if waste heterogeneity is considered at the particulate scale. The likelihood of encountering a 'hot spot' (as opposed to encountering average level contamination as assumed in the 2011 ESC) is, however, much lower. Consequently, the risks are low and consistent with the risk guidance level. The illustrative assessments showed that significant doses could arise from ingestion of Ra-226 sources and alpha-rich particles, but that the probability of encountering these items is extremely low given the very low numbers of these deposits at the LLWR and the low likelihood of these radionuclides being present in particulate form.

As an illustration of the kind of assessment performed, the highest activity alpha-rich object recovered from the Sellafield beach to date is a particle containing 84 kBq plutonium-238 (Pu-238), 309 kBq Pu-239/240 and 634 kBq Am-241. There is no reason to suppose that these particles may be present in the LLWR. However, even assuming that the total inventory of relevant radionuclides in the LLWR is entirely in the form of particles, the probability of a random encounter with a high-activity particle on the beach following coastal erosion is very low. If such a particle were to be ingested, it could give rise to a committed effective dose of around 20 mSv to an adult (or 20 times the annual dose limit for a member of the public) and 55 mSv to a 1 year old child (Mobbs and Sumerling 2012, citing Brown and Etherington 2011). If the same particle were to be ingested by a 3 month old infant, the dose could be in the region of 300 mSv. However, caution is required when interpreting assessed doses to a 3 month old infant. Beach occupancy by children of this age is normally very low; direct contact with the beach is probably restricted (for example, if the child is in a pram or chair) and the child would not be independently mobile. Consequently, there is a much lower likelihood (assessed at less than 1 chance in a million) of such an infant encountering a particle than for the other age groups considered.

We commissioned PHE to carry out an independent review of LLW Repository Ltd's supplementary assessments. The main conclusion of the PHE review is that the LLW Repository

Ltd assessments generally follow the approach used by PHE in its recent work on assessing radiological consequences from the use of beaches contaminated by radioactive material (Oatway and Higgins 2013). The reviewers found that the methodologies used in the assessment generally employ a suitable level of caution and include the most significant exposure scenarios and pathways, together with the groups of people likely to be the most exposed. The reviewers suggested that more detailed information on some aspects of the methodology should be provided, including a discussion of the likely consequences of exposure scenarios not considered in detail.

After considering PHE's review, we produced supplementary guidance on the disposal of discrete items and particles to the LLWR (Smith 2014). A discrete item is a distinct item of waste that has become exposed and that, by its characteristics, is recognisable as unusual or not of natural origin and could thus be a focus of interest, out of curiosity or because of its potential for recovery and recycling/re-use. We stated that, in view of coastal erosion, an optimised approach to waste acceptance for future disposals is likely to entail imposing restrictions on disposal of items that individually carry a significant burden of radioactivity. Equally, we said this approach is likely to entail avoiding or preventing any processes within the LLWR, or as a result of coastal erosion, that might lead to the production of high-dose particles. We suggested that, as part of this optimised approach, these considerations may require improvements to waste characterisation and segregation for future disposals. We also stated that it is acceptable to use the risk guidance level as a criterion for random encounters with particles, but that a 'test of significance' should apply to casual curiosity and deliberate searches. Deliberate searches include intentional collection of a particle or multiple particles. We proposed that this new 'test of significance' should be the effective dose to any person during and after coastal erosion of the LLWR and should not exceed a dose guidance level in the range of around 3 mSv y⁻¹ to around 20 mSv y⁻¹ (consistent with the existing guidance for human intrusion under Requirement R7 of the GRA).

For past disposals at the LLWR, it may not be regarded as an optimised approach to attempt to retrieve discrete items carrying a significant burden of radioactivity. This is because any or all of the following may not be adequately known: (a) the nature of the items; (b) the burden of radioactivity the items carry; and (c) the location of the items within the LLWR. We stated that, if LLW Repository Ltd considers that this general statement is true, it should submit an ESC to us that makes this argument. This ESC should identify all items that it covers to the extent that the available records make this possible.

If there are any items in past disposals at the LLWR for which LLW Repository Ltd considers that the above general statement is not true, it should submit proposals to us for the retrieval of these items. Any such proposals should include the appropriate operational and environmental safety cases for retrieval of the items. In addition, we may require LLW Repository Ltd to submit proposals for retrieval of items the Environment Agency may specify.

LLW Repository Ltd has re-evaluated its earlier supplementary assessment of potential doses from particle ingestion using more realistic assumptions (Sumerling 2013b). This report shows that, based on results from the previous assessment, inadvertent ingestion of particles is the limiting pathway (compared with external exposure, inhalation and skin contact routes). LLW Repository Ltd considers (and PHE agrees) that only particles of size 1 mm or less are capable of being inadvertently ingested and that deliberate ingestion of stone-sized objects (by children or pica sufferers) should not be considered when deriving WAC for future discrete items or particulates. We accept this position, which results in differing control and assessment mechanisms for particulate material likely to be ingested and for discrete items that would only be subject to encounter and contact.

Using more realistic parameters, LLW Repository Ltd tested a number of higher activity radioactive particles that might reasonably be presumed to be present and found that, of these, the only particles having the capacity to lead to a committed effective dose in the range 3 to 20 mSv are Ra-226 paint (manufactured to Admiralty specification), the highest alpha-rich Sellafield particle found to date and Pressurised Water Reactor (PWR) spent fuel particles (Sumerling 2013b). In no case is 20 mSv exceeded, although doses approach 20 mSv. These assessments are, as before, illustrative of the kinds of particle that cannot be confidently ruled out as absent from the LLWR, although they are not expected.

LLW Repository Ltd has not carried out quantitative assessments of higher activity particles from other waste materials such as Mixed Oxide (MOX) fuels, irradiated highly-enriched uranium (from materials test reactors and naval reactors), plus weapons-grade enriched uranium and plutonium. Whilst particles of these waste types are not expected to be disposed of at the LLWR in large quantities, we recommend that LLW Repository Ltd includes these waste types in future ESC assessments for completeness (**Recommendation ASS23**).

Through revised WAC, LLW Repository Ltd will seek to limit, as far as practicable, disposal of particles from any source that could carry an activity sufficient to give rise to a significant assessed effective dose in the event of particle ingestion. The focus will be on placing conditions on waste (consignments and waste streams) that have the potential to include particulate material having high-specific activity in significant amounts. Consignors of waste to the LLWR will be required to consider the possibility that a consignment may contain these particles through the following criterion: 'Waste containing or that may contain Active Particles, or that may breakdown to form Active Particles, may be accepted for disposal but only on approval of a Waste Consignment Variation Form by LLW Repository Ltd.'

'Active Particle' is defined in the glossary of the revised LLWR WAC as follows: 'Active Particle means a particle in the size range of 0.6 to 2.0 millimetres of high-specific activity material such that a single particle could bear of the order of a megabecquerel (1 MBq) or more of alpha-emitting radionuclides or 0.01 megabecquerel (0.01 MBq) or more of radium-226. This implies a fragment of a high-activity material, typically more than about 100 megabecquerel per gram (100 MBq/g) of most alpha-emitting radionuclides or 10 megabecquerel per gram (10 MBq/g) of radium-226. Examples of Active Particles include fragments of Admiralty specification radium-sulphide paint, fragments of irradiated nuclear fuel (especially PWR, MOX or highly enriched uranium fuels) or plutonium.'

LLW Repository Ltd may accept waste containing (or that may contain) these 'active particles' for disposal but only on approval of a Waste Consignment Variation Form. Taken together, these new requirements in the LLWR WAC represent a significant step towards minimising future disposal of active particles. We recognise that a positive declaration of whether or not a consignment or waste stream contains active particles may represent a challenge for some waste consignors. We will work with LLW Repository Ltd and consignors to understand better the practicalities and implications of these further measures. We will monitor the use of Waste Consignment Variation Forms for any trends in this type of waste.

Future disposal of larger, 'discrete items'

Other than for sealed, low activity sources, the 2011 ESC did not include an assessment of the potential consequences of people encountering, as a result of coastal erosion or human intrusion, discrete items (identifiable objects, larger than particle size) legally disposed of within the constraints of the existing or past WAC. We requested further information on the nature and distribution within the facility of discrete items that may have been disposed of at the LLWR, seeking an assessment of the exposures that people might receive as a result of contact with them. We also asked LLW Repository Ltd to derive a set of conditions that could be translated into a revised WAC (ESC-RO-ASO-006). In partial response, LLW Repository Ltd has responded with a relevant assessment of potential doses and basis for derivation of WAC (Sumerling 2013a).

'Discrete Items' are defined as distinct items of waste that, by their characteristics, are recognisable as unusual or not of natural origin and could be a focus of interest, out of curiosity or potential for recovery and recycling/re-use of materials should the waste items be exposed after repository closure. LLW Repository Ltd's revised approach to this potential future scenario involves assessing waste items according to a range of different discrete item sizes, assumed to be surface-contaminated or volume-contaminated spheres (a 'worst-case' geometry).

For future disposals, LLW Repository Ltd has developed an assessment framework for the identification and control of discrete items (Sumerling 2013a), including the adoption of a dose-rate guide value of $20 \mu\text{Sv h}^{-1}$ as a standard for future limits on the disposal of these items. This framework has led to additional WAC and procedures (LLW Repository Ltd 2013d), which have been consulted on across industry. The new WAC include a requirement to make sure that the

total activity and specific activity of individual discrete items are limited. LLW Repository Ltd uses a 'sum of fractions' approach to apply the activity limits to discrete items as shown in the Developments Report (Tables 3.8 and 3.9 of LLW Repository Ltd 2013c) and as implemented in the March 2014 WAC (LLW Repository Ltd 2014). We reviewed these measures and consider that they will provide an effective control for future disposals.

The LLWR WAC require consignors to use Best Available Techniques (BAT) to characterise, sort and segregate the waste to facilitate its management by optimal routes.

This work represents a further control on waste acceptance at the LLWR and does not relax the existing WAC or LLWR disposal limits in any way. Instead, it aims to reduce the radiological consequences of any discrete items that may reappear on the eroding coastline or be encountered via human intrusion.

At the end of our review of the 2011 ESC, LLW Repository Ltd had not submitted an ESC addressing discrete items historically disposed of. As a result, we raised a FI requesting LLW Repository Ltd to submit an update to the ESC addressing the application of our supplementary guidance to past disposals at the LLWR (ESC-FI-013). We note that the 2011 ESC need not be fully revised and only relevant parts of the ESC need be presented. We require this update to be submitted well in advance of any capping of the waste to allow the retrieval of any discrete items if found necessary. We suggested to LLW Repository Ltd that this ESC should make best use of currently available information about past disposals, but may also be usefully informed by considering the BAT for managing stored waste currently in Vaults 8 and 9.

Severe deterministic injury (applicable to past and future disposals)

Paragraph 6.3.40 of the GRA requires an operator to demonstrate that dose thresholds for 'severe deterministic injury' to individual body tissues are unlikely to be exceeded as a result of human intrusion into a near-surface disposal facility. Severe deterministic injury means injury that is directly attributable to the radiation exposure, that is irreversible in nature and that severely impairs health and/or the quality of life of that individual, for example, lung morbidity and early death.

LLW Repository Ltd has assessed that dose thresholds for deterministic tissue effects, for example erythema, skin ulceration or gastro intestinal tract damage, will not be exceeded given a few hours' contact time with the skin (for discrete items) or typical residence times in the gastrointestinal tract for particles (Mobbs and Sumerling 2012). Deterministic effects (tissue reactions) are radiation effects that have a threshold dose below which they do not occur.

We have been advised by PHE that no severe deterministic injury is likely to emerge from the activities of waste disposed at the LLWR. Threshold doses for the onset of acute exposure are of the order of a few gray (Gy) and skin residence times for particles would have to exceed 2-3 weeks for severe irreversible effects to occur (Brown 2013). Reversible effects, such as skin reddening, may occur at earlier times. LLW Repository Ltd indicates that deterministic effects (not severe or irreversible) could occur on timescales of the order of hours, depending on assumed particle activity. Caesium-137 (Cs-137) fuel fragments (such as those found in the environment around Dounreay) could give rise to deterministic effects within minutes. However, these calculations did not take account of radioactive decay that would occur between present day and possible exposure. LLW Repository Ltd has listed indicative times for deterministic effects to appear in Table 18 of Mobbs and Sumerling (2012).

2.3.5. Delayed coastal erosion / no erosion scenario

We accept LLW Repository Ltd's anticipated uncertainty range for the onset of coastal erosion (Environment Agency 2015d). However, to make sure that the 2011 ESC assessments encompass all potential erosion scenarios, we queried what the radiological consequences would be if erosion is significantly delayed or, for whatever reason, does not happen (ESC-RI-ASO-006). Delayed erosion up to 10,000 years was considered in the 2011 ESC but no discussion was provided of the radiological effects in the very long-term (more than 10,000 years). The assessment was presented as a hypothetical 'what if' scenario.

LLW Repository Ltd has provided a further evaluation of how the site might not be eroded within a few thousand years, together with an assessment based on assuming that the site continues to

exist up to 250,000 years after the present (LLW Repository Ltd 2012c). This supposes that, due to a fall in sea level within about 10,000 years, the LLWR site is not subject to coastal erosion. The fall in sea level is hypothesised as due to rapid cessation and control of global CO₂ emissions and of CO₂ levels in the atmosphere, leading to reversion towards a climate evolution near to the natural scenario in the absence of greenhouse gas emissions.

This additional assessment gives rise to conditional risks from the groundwater pathway about an order of magnitude above the risk guidance level after some 250,000 years. The highest assessed risks are to the well PEG and to a new terrestrial PEG inhabiting land exposed following the fall in sea level. For the well PEG, risks due to Pb-210 and Po-210 from consumption of foodstuffs dominate. For the terrestrial PEG, risks due to Ra-226 are most important, with Pb-210 and Po-210 also contributing. These radionuclides are all progeny of uranium-234 (U-234) disposed of to the LLWR and, to a lesser extent, of uranium-238 (U-238). The highest assessed doses, relating to human intrusion, are associated with indoor exposure to Rn-222 formed as a daughter product of uranium that has been disposed of. Peak doses of about 50 mSv y⁻¹ are derived at the end of 100,000 year assessment period.

This scenario is judged to be of very low likelihood since LLW Repository Ltd considers that it is almost certain that the LLWR will be disrupted by coastal erosion, with disruption commencing within a few hundred to a few thousand years from now. We recognise that the assessment identifies impacts greater than the relevant GRA guidance levels, but we regard it as a 'what if' case having a very low probability of occurrence, for this scenario to happen, a complete reversal of current sea level and climate trends would need to occur within the next few hundred years. We consider that this assessment has been presented for information and we do not envisage taking any regulatory steps based on its results.

2.3.6. Human intrusion

Our regulatory guidance seeks the assessment of inadvertent human intrusion; that is, action taken without full knowledge of the facility or potential hazards that the waste therein may present. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv y⁻¹ to around 20 mSv y⁻¹ (GRA Requirement R7).

An action taken with full knowledge of the facility and associated hazard is taken to be a reasoned action that is the responsibility of those who undertake the action. It has thus been excluded from evaluation of human intrusion events for assessment. This is consistent with international practice.

LLW Repository Ltd has classified human intrusion events into 2 categories: those that could occur at any time after the end of the period of authorisation (such as investigation of the site or occupancy following such an event); and those that can only occur after waste have been exposed by coastal erosion (such as scavenging and recovery of materials). LLW Repository Ltd assesses doses received from short-term exposures, as would be received by persons directly engaged in the intrusion operation, and annual doses to persons exposed over longer times to environmental contamination arising from the intrusion (LLW Repository Ltd 2011c; Hicks and Baldwin 2011).

This approach to the assessment of human intrusion is consistent with GRA Requirement R7. This specifies that human intrusion into a near-surface disposal facility after the end of management control of the site is to be assessed on the basis that it will occur (because human behaviour is unpredictable), and against a dose guidance level in the range of around 3 mSv y⁻¹ (for exposures continuing over a period of years) to around 20 mSv y⁻¹ (for exposures that are of limited duration).

Human intrusion assessment requires consideration of specific intrusion scenarios based on possible human behaviour. LLW Repository Ltd has presented a range of these scenarios (LLW Repository Ltd 2011c). For realistic and foreseeable human intrusion events, the company assesses doses consistent with the dose guidance level range, both to the intruders themselves and to those exposed in the longer term after the intrusion has occurred.

For intruders directly involved in geotechnical investigations, assessed doses are typically less than 0.05 mSv and, even making pessimistic assumptions about the location of the intrusion, no higher than 0.5 mSv.

For people occupying a house, or a dwelling with an agricultural smallholding, positioned on land contaminated by spoil from an earlier excavation, LLW Repository Ltd assesses annual doses in the range 0.5 to 4.0 mSv, depending on where in the disposal facility the spoil has been taken from. The doses are dominated by exposure to radon that may accumulate in a building due to Ra-226 in the contaminated spoil on which it is sited. The potential for these doses depends on the accessibility of Ra-226 bearing waste in relation to an intrusion event. LLW Repository Ltd proposes a future emplacement strategy for waste containing relatively high concentrations of Ra-226 waste so that it will not be placed in upper stack positions in the vaults (see Section 2.3.3). Application of that strategy results in assessed doses consistent with the 3 mSv y⁻¹ dose guidance level (applicable to exposures continuing over a period of years).

The cases LLW Repository Ltd has assessed for the period during which the site is being eroded are that of an individual making frequent informal visits to inspect the eroding cliff and that of a local contractor involved in a campaign of material recovery. At most times during the erosion of the facility, assessed doses are less than 0.7 mSv y⁻¹, whether to the individual inspecting the cliff or to the contractor recovering materials. During the time when thorium-containing mineral sands present in the trenches are being eroded, doses of up to about 2 mSv y⁻¹ may occur to a contractor attempting to recover material from those parts of the disposal facility. All the assessed doses are less than the applicable dose guidance level.

We queried the scale at which waste heterogeneity is modelled for intrusion events during coastal erosion (a similar issue to the one we raised for heterogeneity and coastal erosion) (ESC-RI-ASO-011). This issue arises because there will be a distribution in the size of individual items exposed on the cliff face and beach, and that people could directly encounter. Some of the waste will be in the form of small particles that could be inadvertently inhaled or ingested. We also requested further human intrusion scenario assessments to be carried out, including those for a range of known deposits of radioactive sources at the LLWR (ESC-RI-ASO-013). LLW Repository Ltd provided supplementary assessments addressing these issues (Sumerling and Mobbs 2012; Sumerling and Jackson 2012).

The only possible particle at the time of the earliest intrusion event that could give rise to an absorbed dose above the threshold for deterministic effects in skin is a fuel fragment containing strontium-90 (Sr-90) or Cs-137, similar to particles found at Dounreay. This scenario relates to a particle excavated from the last vault to be closed (Vault 14), that is the vault with the minimum decay time before the intrusion event. This particle is assessed to give rise to ulceration of the skin if trapped under a fingernail for more than about 2 hours. This assessment is based on a cautious estimate of the absorbed dose to skin because it neglects self-absorption in the particle. Intrusion at a date later than 2210, or into the trenches or other vaults would not give rise to deterministic effects in skin. Fuel fragments containing Sr-90 or Cs-137 disposed of in the LLWR are expected to be very few in numbers.

Requirement R7 of the GRA seeks a demonstration from the operator that dose thresholds for severe deterministic injury to individual body tissues are unlikely to be exceeded as a result of human intrusion into the facility. LLW Repository Ltd concludes that this requirement has been met and we agree.

Assessed cautiously, a particle of high-specific activity material, if encountered, could give rise to a committed effective dose in the range 3 mSv to 20 mSv. However, no particle that could realistically be present could give rise to a committed effective dose above 20 mSv.

LLW Repository Ltd's assessment makes several cautious assumptions. The estimated number of particles per gram in the waste ignores radioactive decay during the operating lifetime of the LLWR and assumes that all the activity is present in the form of 1 mm particles. The assumed thickness of the cap at the intrusion location neglects the profiling, leading to a minimum quantity of non-waste material excavated with the waste and an overestimate of the number of particles per gram of excavated material. This leads to a cautious estimate of the probability of encounter with a particle during the intrusion event.

Overall, human intrusion into the LLWR is unlikely to give rise to annual doses above the lower dose guidance level even assuming some of the most significant radionuclides in the waste at the LLWR are composed entirely of 1 mm particles, which constitutes a highly pessimistic assumption.

LLW Repository Ltd plans an improved waste emplacement strategy so that higher activity containers are not placed in the uppermost stack positions or in close proximity (for example, in the same or adjacent stacks) in the vaults. As a result, the probability of human intrusion intercepting 1 or more higher activity containers will become lower and the potential for higher doses will be reduced.

Human intrusion into historical Sellafield source pots

In reviewing LLW Repository Ltd's response to ESC-RI-ASO-013, we raised a further IRF on the dose consequence of hypothetical intrusion by drilling into pots containing low activity sources that were consigned from Sellafield and disposed of to Vault 8 in 2001-2002 (ESC-TQ-ASO-010). LLW Repository Ltd's response was to argue that the lead source pots would be deflected following contact with an intruding drill and that a direct hit was sufficiently unlikely that it could be discounted (Sumerling 2013c). However, the 5 source pots taken together contain thousands of redundant sources, although we accept that direct drilling into any 1 container is unlikely. We requested an assessment of the dose consequences of this case on a 'what if' basis.

In response, LLW Repository Ltd assessed the highest doses to a geotechnical worker as being about 90 mSv and 60 mSv for exposure to Pu-239 and Ra-226 source fragments respectively (Sumerling 2013c). There are, respectively, 1 and 11 of these sources in the pots that could give rise to a 1 mm fragment with the assumed level of radioactivity. The assessment indicates doses of a few mSv for each of the other source fragments, except for cobalt-60 (Co-60), where the assessed dose is negligible because of radioactive decay by the time of the intrusion.

Assuming an intruding drill strikes a source pot, LLW Repository Ltd assesses the probability of the worker then inadvertently ingesting an active fragment as 1 in 2 million. Furthermore, the chance of striking any of the 5 pots from a single borehole is about 1 in 80,000 (or 1 in 8,000 for a site investigation in which 10 boreholes are drilled into Vault 8). The chance of ingesting a Pu-239 fragment from a source only present in 1 of the pots is about 1 in 80 billion for 10 boreholes drilled. We accept the company's assessment.

These assessed doses may be overestimated given that LLW Repository Ltd has more recently updated its internal dose assessment approach to particles (making use of dose coefficients from International Commission of Radiological Protection (ICRP) Publication 68 instead of Publication 72).

LLW Repository Ltd has also assessed inhalation doses resulting from direct drilling into the Sellafield source pots. The dose consequences of inhalation are assessed for 10 µm fragments of sources with the same specific activity as assumed for ingestion (that is individual activities 1 millionth of the activities of 1 mm particles). The highest assessed doses are about 19 µSv and 1 µSv (for the Pu-239 and Am-241 source fragments respectively), although there are only 1 and 8 of these sources respectively in all the pots that could give rise to a 10 µm fragment with the assumed activity. No other source fragment yields an assessed dose above 0.1 µSv. We regard these doses as acceptable given the nature of the future drilling scenario considered.

Aircraft impact

Aircraft impact was screened out from the 2011 ESC assessment of human intrusion on the basis of low probability and that other intrusion scenarios would bound the dose consequences.

We requested evidence to support the claim that a light aircraft crash would not impart sufficient energy to penetrate the cap to waste depth (that is more than 3 m at its lowest profile) (ESC-TQ-ASO-005). LLW Repository Ltd undertook further work making some very cautious assumptions and concluded that a military combat aircraft could penetrate deeper than 3 m into the cap, assuming no additional cap profiling material were present (Jackson 2012).

LLW Repository Ltd has pessimistically assessed the dose from a military aircraft crash at about 65 mSv to a site occupier or smallholder residing over Vault 8. The dose from a large transport aircraft crash may be around twice that figure. Doses are dominated by exposure to Rn-222 due to Ra-226 assumed disposal from contaminated soils from clean-up of Defence Estates land. The estimated frequency of such an aircraft impact is of the order of 1 in a million per year or less.

LLW Repository Ltd has considered mitigation of the hazard from Ra-226 bearing waste in the human intrusion assessment (Hicks and Baldwin 2011), and has suggested that waste packages containing higher levels of Ra-226 would not be placed in the upper 2 stack positions in the vaults. These measures will be implemented by a specific emplacement strategy, described in the Developments Report (LLW Repository Ltd 2013c). This strategy will reduce the likelihood of interception of radium-bearing waste by intrusion events (including aircraft crash). If all future Ra-226 waste are below the impact depth, previous assessments show that the dose to a site occupier / smallholder falls to less than 6 mSv y⁻¹. If LLW Repository Ltd deploys this emplacement strategy for future waste disposals, we regard these doses as acceptable, noting the very low probability of the initiating event. We will expect LLW Repository Ltd to demonstrate that the stacking of currently stored radium-bearing waste will be optimised when they are emplaced for disposal in the BAT assessment that the company intends to undertake on waste stored in Vault 8 (**Recommendation ASS24**).

2.3.7. Waste and borehole fire scenario

The 2011 ESC did not include an assessment of the radiological consequences of a fire occurring in disposed combustible waste after the period of authorisation. We asked LLW Repository Ltd to carry out such an assessment in ESC-TQ-SUE-030.

In response, LLW Repository Ltd identified 2 scenarios for potential fires in trench waste; the first associated with the exposure of waste during coastal erosion and the second associated with the introduction of oxygen into the anaerobic trench waste during construction of geotechnical boreholes into the waste after the period of authorisation (Taylor and Sumerling 2013).

With respect to the first scenario, LLW Repository Ltd concluded that the materials and conditions in the trenches at any time after the period of authorisation are very unlikely to support combustion, and that any fire events that might occur would be confined to very small volumes of waste with little or no potential for release of radionuclides. As a result LLW Repository Ltd did not undertake a radiological assessment of the consequences of ignition and subsequent fire during the erosion of the trench waste. We accept that the likelihood of a fire event at any scale would be low, but because of the long period of waste exposure during the erosion sequence (potentially hundreds of years), the uncertainty over deliberate human interventions and the uncertainties associated with the exposed waste during the erosion period we consider that this scenario should be considered as a 'what if' scenario. We raised an FI (ESC-FI-028) that identifies the need for a more comprehensive understanding and conceptualisation of the behaviour of the repository waste during the predicted repository erosion sequence. Within the resulting forward programme we recommend the potential nature, extent and consequence of waste fires resulting from human actions are further investigated, considering appropriate 'what if' scenarios for waste fires (**Recommendation ASS25**).

LLW Repository also identified a human intrusion scenario associated with the construction of a geotechnical borehole into the waste mass that could give rise to a deep seated waste fire. The company assumed that any fire in a borehole would be short lived and not requiring the involvement of the fire service, with dose only being received by the drillers. The dose to a drilling engineer was calculated at about 5 times that received by the driller in the absence of the fire event and 2 orders of magnitude below the dose guidance value that applies to exposures of short duration from human intrusion events.

However, we disagree with the assumption that a borehole fire will always be short lived with dose only being received by the drillers. Experience of deep seated waste fires in landfills indicates that they can be difficult to extinguish and can burn for extended periods and, assuming the fire is significant, there would be a need for fire service involvement to extinguish the fire. We therefore requested that LLW Repository Ltd undertakes a further assessment to take account of an extended duration fire and the involvement of fire personnel as a 'what if' scenario (ESC-FI-003).

2.3.8. Assessment of criticality

LLW Repository Ltd has carried out a criticality assessment for the LLWR. A summary is provided in Section 9.2 of LLW Repository Ltd 2011c and in Putley et al. (2011) and Hay (2011) for the RDA and EDA respectively.

The GRA states that 'the environmental safety case should consider the issue of a criticality event, although we recognise that a simple analysis should be sufficient to demonstrate that such an event will not occur' (GRA paragraph 7.3.31). The waste disposed of at the LLWR are permitted to contain small quantities of enriched uranium and plutonium, and much greater quantities of non-fissile uranium, as either natural or depleted uranium.

LLW Repository Ltd's assessment approach draws on experience and practice from elsewhere in the NDA estate, including the Radioactive Waste Management Directorate (RWMD) (Putley et al. 2011). The approach also takes into account the British Standard on criticality safety (British Standards Institute 1998) as well as relevant standards and guides published by the International Atomic Energy Agency (IAEA 1998; 2005).

The reasons why criticality at the LLWR can be discounted include the following:

- The waste sent to the LLWR is only permitted to contain limited quantities of enriched uranium and plutonium.
- As emplaced, the fissile material will be dispersed throughout large volumes of other waste materials. In some cases, large volumes of non-fissile natural or depleted uranium may also be present in the waste. All the other waste materials will dilute the fissile material so that criticality is physically impossible.
- The post-closure design features of the LLWR will passively control the emplaced fissile materials and reduce water infiltration rates into the repository. Before the disruption of the LLWR by coastal erosion, only very gradual changes will take place post-closure and groundwater flows will not lead to criticality. During disruption by coastal erosion at the LLWR, mechanisms capable of concentrating fissile materials are considered highly improbable.
- The fissile inventory of the trenches is very small. A very substantial natural uranium inventory is also present. It follows that any relocation of trench waste by groundwater flows would not be expected to produce critical accumulations of fissile material. Also, fissile material and non-fissile uranium would be likely to aggregate together. In these cases the non-fissile uranium would provide sufficient neutron absorption to prevent criticality.
- In the vaults, the general conditions in the near field will be alkaline. This will help to limit fissile material movements, thereby reducing the likelihood of large scale accumulations of fissile material. The alkaline conditions are the result of the cement materials used in the waste container grout and the concrete structures of the vaults.

Nevertheless, LLW Repository Ltd has also carried out quantitative criticality assessments for both operational and post-closure phases (including site disruption by coastal erosion). During the operational phase, LLW Repository Ltd has determined that the safety limits are very conservative and that the grouted waste containers do not present any significant probability of criticality. After closure, the vaults will contain fissile inventories insufficient for criticality given the low fissile limits on each container. In summary, LLW Repository Ltd considers that, because the fissile inventory of the LLWR is very small, the possibility of criticality is so remote that it can be discounted. We agree with this view.

2.3.9. Management of uncertainty

A more general review of LLW Repository Ltd's management of uncertainty in the 2011 ESC is presented in our Safety Case Management review (Environment Agency 2015b). The review below focuses on the assessment uncertainties. LLW Repository Ltd's approach to classifying uncertainties is described in the Level 3 report by Baker et al. (2008), as follows, 'We will adopt a classification of uncertainties that is conventional in radioactive waste disposal assessment... focusing on their mode of treatment in the safety assessment:

- Scenario uncertainty – definition of a scenario, or scenarios, sufficiently broad to represent the possible evolutions of the disposal facility and its environment.
- Model uncertainty – models, including alternative model assumptions, that adequately represent the Features, Events and Processes (FEPs) that are important to radionuclide release, transport and exposure to humans.

- Parameter uncertainty – variation of model parameter values within their realistic or possible ranges.'

This 3-tier classification is commonly seen in radioactive waste disposal assessment. However, other than in this Level 3 report, the approach has not been clearly adopted in the 2011 ESC. 'Uncertainties', where they are reported in the 2011 ESC, are not classified according to this approach. In particular, 5 'key uncertainties' listed in LLW Repository Ltd (2011c) are not classified against this system. This last report also states that 'the treatment of uncertainty may, however, be constrained by limited data and the models that are available.' Implicit in this statement are examples of unquantifiable uncertainties ('limited data' and 'model availability'). If either or both of these affect the reliability of the assessments to a significant degree, they could reasonably have been discussed as potential key uncertainties.

LLW Repository Ltd has produced a FEP and uncertainty tracking system in support of the 2011 ESC (LLW Repository Ltd 2013b). This tool arrived relatively late in our review of the 2011 ESC and was produced to enable transparent identification of the means by which a specific FEP has been considered within the 2011 ESC and to track the key FEPs associated with each assessment scenario, model and case.

The FEP and uncertainty tracking system lists uncertainties according to exposure pathway and gives: the topic lead (expert) view on the 'local' significance (high, medium, or low); the LLW Repository Ltd view on 'significance' (negligible impact, significant for safety assessment, or significant for ESC); and, additionally, a subjective view of how well it has been addressed in the ESC (content, minor concerns (some work needed), or serious concerns). Although this tool arrived relatively late in our 2011 ESC review, it reflects LLW Repository Ltd's position as of 1 May 2011. Therefore, it does not take into account output from more recent studies. For example, LLW Repository Ltd assigns a 'major' significance to uncertainty in the C-14 assessment (LLW Repository Ltd 2013b). It is not clear to us whether the significance of the reported C-14 uncertainties would now be reduced from 'major' to 'content' or 'minor', given the recent (September 2013) re-assessment of C-14 impacts.

We consider that the FEP and uncertainty tracking system is a useful tool for clarifying how uncertainty in significant FEPs has been treated in the 2011 ESC. LLW Repository Ltd used the FEP list to audit the gas pathway calculations to ensure that all relevant FEPs were considered (Limer et al. 2011; Limer and Thorne 2011). We welcome this audit as representing good practice, but would have liked to see a similar audit carried out for the groundwater, human intrusion and coastal erosion calculations (**Recommendation ASS26**).

An established way of treating quantifiable uncertainties is by using a probabilistic approach. LLW Repository Ltd (2013b) states that probabilistic assessments have only been undertaken for aspects of the groundwater pathway, where, '...pdfs were used to represent the uncertainty in past and future disposals.' We understand that the use of probabilistic methods extended beyond consideration of the past and future inventories, and included probabilistic treatment of 9 different parameters, relating to near field (one inventory), engineering system and geosphere. Probability distribution ranges were derived using expert elicitation (Jackson et al. 2011); derivation of the associated probability distribution functions is discussed in Kelly et al. (2011).

For coastal erosion, LLW Repository Ltd (2013b) states that 'It is not possible to capture all uncertainties in a probabilistic assessment, because of the complex correlations that exist between different parameters, especially in relation to the future evolution of the site.' We agree that there are many instances of complex interactions and correlations but it would still be useful to list these 'uncertainties' (that is, complexities) and explore them in the ESC to test whether the 'alternative cases' appropriately bound these (unstated) complexities. This is in addition to the uncertainties recorded in the FEP and uncertainty tracking system. Discussing uncertainties in the ESC associated with complex relationships between different parameters can help improve confidence by demonstrating that the authors understand the complexities involved, even if some of those complexities can be bounded by framing assumptions.

In ESC-RO-SUE-007, we noted that the forward monitoring programme presented appeared to be focused on providing assurance of the LLWR performance, rather than on the systematic reduction of environmental uncertainties. In particular, it did not specifically address how the key

uncertainties identified in the 2011 ESC can be reduced to produce a more realistic assessment. We asked LLW Repository Ltd to demonstrate how the forward monitoring programme will be developed throughout the period of authorisation and how it will be linked to the ESC to reduce key uncertainties in the ESC where possible (ESC-FI-005).

2.3.10. Model code quality assurance and documentation

The GRA notes the need for ensuring, '...rigorous quality assurance of all modelling activities and associated data handling, including controls over changes to models and data and a detailed audit trail' (GRA Paragraph 7.3.23). While the 2011 ESC reports as a whole are certified under a quality assurance scheme, the extent to which quality assurance procedures have been applied to the modelling work described therein is less apparent. The ESC should provide adequate evidence that any model used in the assessment is fit for purpose and that model results can be considered meaningful. The 2011 ESC omits a list of the software codes and models in use. We found it difficult to identify how the various models interact or how model output is transferred between different models. We queried the absence in the 2011 ESC of evidence demonstrating the extent of quality assurance on the coding of assessment models and the lack of associated documentation. We requested information on the measures taken for each code or model to establish its reliability (ESC-RO-ASO-007).

LLW Repository Ltd (2011c) makes various claims about model checking and reliability but contains little referencing to underpinning reports. Some references point to program user guides while others point to unspecified parts of Level 2 and Level 3 reports. For example, Baker et al. (2008) discusses the treatment of uncertainty in models (Section 5 Assessment Approach) but not the broader issue of managing model quality.

We noted that an assessment model flowchart had been provided in BNFL's 2002 PCSC (BNFL 2002b) and suggested that LLW Repository Ltd should revisit that approach and take note of more recent work by SKB in Sweden for that organisation's repository application (SKB 2010).

In response to ESC-RO-ASO-007, LLW Repository Ltd produced a supplementary memo outlining the key assessment models and codes used in the 2011 ESC and a summary of model assurance measures, collated from other parts of the 2011 ESC (Shevelan 2013). The diagram clarified the extent and relationship of models used for the ESC and should provide a starting point for an updated ESC to build on. We recommend that, in order to clarify the modelling approach, LLW Repository Ltd should pay greater attention to documenting linkages between assessment models (**Recommendation ASS27**).

Properly documenting model quality helps to build confidence in the robustness of the model outputs and model management. An updated ESC should provide more discussion of whether the model is of a suitable complexity with an appropriate level of process description, in the light of how the model is being applied and the quality of the available data. The analyses can be very formal (especially for total system models) or informal (for smaller process models). Given the dependence of the 2011 ESC assessments on models, we recommend that more discussion is provided about model design and model selection (**Recommendation ASS28**). This only needs to be done once for each model. This discussion should help to communicate why a particular model was chosen, why the model is fit for purpose and how LLW Repository Ltd ensures correct interpretation of the model. Documentation on model quality would also assist in the effective communication of the reliability of model output and in ongoing quality assurance of the models.

As discussed in Environment Agency (2015b), in June 2013 we audited LLW Repository Ltd's contractors who prepared the hydrogeological flow model and the groundwater pathway assessment model. The aim of the audit was to gain confidence that the assessments had been carried out under a suitable quality assurance regime and that relevant procedures had been adhered to. We concluded that these contractor organisations have well-established quality management systems, which staff were familiar with and made active use of during the production of 2011 ESC materials (Fairhurst 2013). We suggested a number of areas for improvement in future assessments; none of these related to issues affecting the quality of the 2011 ESC, which we consider adequate.

2.3.11. Environmental safety indicators

The GRA notes that: 'Examples of environmental safety indicators that might be used to strengthen the environmental safety case include radiation dose, radionuclide flux, radionuclide travel times, environmental concentration and radiotoxicity. Where the radiological hazard presented by the waste warrants it, the ESC could provide a wide range of information, for example:

- assessments of radionuclide release characteristics from the waste and from the various barriers that make up the disposal system;
- assessments of the concentrations in the accessible environment of radionuclides released from the disposal system and comparison of these with naturally occurring levels of radioactivity in the environment;
- where appropriate, assessment of collective radiological impact (as a measure of how widespread any significant increase in risk may be as a result of radioactivity released into the accessible environment); and
- unifying statements that aim to place in context the different items of information that contribute to assuring environmental safety.' (GRA paragraph 7.3.7)

LLW Repository Ltd used measured environmental discharges to demonstrate conformity with GRA paragraph 7.3.7 (LLW Repository Ltd 2011a). Radionuclide releases from the LLWR are assessed for the reference case and an alternative near field case (LLW Repository Ltd 2011c). However, apart from this, LLW Repository Ltd has not identified any complementary safety indicators that it thinks useful for the safety case, since the long-term assessments (of environmental concentrations and radionuclide fluxes, for example) depend on the validity of the same models used to assess dose and risk.

LLW Repository Ltd does not think that 'collective dose' (to the public) is a useful attribute or concept to help discriminate between the various options considered and we agree that any assessment of collective dose must be treated with caution. However, given that coastal erosion is expected to destroy the site within a few hundred to a few thousand years, we requested a collective dose assessment, covering the anticipated period of coastal erosion. The resultant collective dose assessment employs conservative assumptions and is truncated to a time 500 years after the assumed time at which erosion leads to the first releases of radionuclides from the site direct into the marine environment (Soetens and Jackson 2013).

The main dose contributors are Ra-226 and C-14. The main dose pathway is ingestion of fish. The relative contribution of Ra-226 is more than 85% to the populations of the UK and Europe, and 67% to the world population; the contribution of C-14 rises from less than 5% to the populations of the UK and Europe to 28% to the world population. The results show that the average individual dose rates leading to these collective doses are no more than a few tens of nSv per year. Doses of this order fall into the range that ICRP would describe as 'trivial'.

2.3.12. Non-human biota assessment

GRA Requirement R9 requires the assessment of 'the radiological effects of a disposal facility on the accessible environment both during the period of authorisation and afterwards with a view to showing that all aspects of the accessible environment are adequately protected' (GRA Paragraph 6.3.60).

In addition, '...there is a specific need to be able to demonstrate that non-human species are protected under legislation related to conservation, for example that derived from the EC Habitats Directive (EC 1992)' (GRA paragraph 6.3.72).

No internationally established criteria for the assessment of radiological impacts to non-human biota currently exist. However, there are a number of ongoing projects in this subject area. We expect LLW Repository Ltd to use the best available information and methods at the time of the assessment. The company used the ERICA assessment tool to assess impacts to biota inhabiting the terrestrial, freshwater and marine environments surrounding the site (Beresford et al. 2007). We consider that use of this model represents current good practice. One protected site, the Drigg Coast marine Special Area of Conservation (SAC), could be affected by discharges from the LLWR. We reviewed the way LLW Repository Ltd has used the ERICA software tool, the general

approach taken to the assessment and the assessed dose rates to different wildlife species and populations. We conclude that the releases from the LLWR are likely to be generally low and are not likely to affect the wildlife or the environment.

However, our review identified a number of issues that LLW Repository Ltd should have addressed to make sure that current good practice was met. These are discussed below.

The period of authorisation assessment presented in the 2011 ESC (Thorne and Schneider 2011) draws heavily on a previous assessment (Eden and Barber 2007). We queried why updates had not been presented, for example, the ERICA assessment was based on environmental concentrations for a limited number of radionuclides measured in 2003-2004 and used a prototype version of the ERICA tool (ESC-RO-ASO-001). In response, LLW Repository Ltd provided evidence that the data used in the period of authorisation assessment were conservative. An updated assessment was not provided and there was no discussion of whether additional radionuclide specific data are now available (Jackson 2013a). We accept that present day impacts on biota from the LLWR are at levels below concern and are unlikely to increase significantly during the period of authorisation. However, we recommend that at the next major ESC update the assessment uses the latest (radionuclide specific where possible) discharge and monitoring data (**Recommendation ASS29**).

We noted that there has been no specific assessment of impacts on the Drigg Coast SAC from the LLWR discharges during the period of authorisation. Thorne and Schneider (2011) refer to the ERICA Drigg Dunes case study, which compared measured and predicted radionuclide concentrations in species collected in the SAC (Wood et al. 2008) and concluded that overall impacts on the biota in the SAC are below dose rates of concern. However, this study was carried out for a very different purpose (that is testing and validation of the ERICA tool) and sample locations are not provided (other than for soil/sediment, which were collected from 3 transects, all to the south of the LLWR). It also does not provide coverage of all the species of potential interest (for example, biota in the beach/intertidal area are excluded). Although we consider that impacts are likely to be low, there may be some pathways that require further consideration, for example impacts to biota near the south-western site boundary via external dose. We queried this issue through a Further Information Notice in support of the permit variation application for disposal of further radioactive waste at the LLWR (Environment Agency 2014b). In response, LLW Repository Ltd provided further information about potential impacts (URS 2014). We conclude that the LLWR will present no adverse impacts to the integrity of the Drigg Dunes SAC throughout the period of authorisation (Environment Agency 2014a).

Predicted dose rates to some organisms inhabiting the cliff and storm beach post-closure may exceed the $10 \mu\text{Gy h}^{-1}$ screening level, and plants and invertebrates inhabiting the storm beach during the onset of coastal erosion could be exposed to dose rates in excess of $100 \mu\text{Gy h}^{-1}$ (Thorne and Schneider 2011). However, we accept the evidence submitted regarding the relative radio-insensitivity of these species, concluding that these doses will not cause harm (Jackson 2013b).

We queried why some radionuclides in the LLWR inventory have been omitted from the ERICA assessment. In response, Jackson (2013b) stated that the missing radionuclides are not included in the default database and that they are not significant in terms of overall risk. Although we accept that the omission is not significant in terms of overall risk, we consider that to omit these radionuclides is not good practice as there are sufficient data in the ERICA assessment tool to allow for the inclusion of most of the missing radionuclides. We recommend that future non-human biota assessments should include all relevant radionuclides, using surrogate data as required, or substantiate the reasons for, and significance of, their omission (**Recommendation ASS30**). We also recommend that, alongside the summary of modelled environmental concentrations that were input to the ERICA tool, times of each peak for each radionuclide for each compartment should be provided to enhance clarity in future assessments (**Recommendation ASS31**).

We queried the lack of explicit uncertainty and sensitivity analysis in the assessment of non-human biota (ESC-RO-ASO-002). We had raised a similar query in our review of Eden and Barber (2007). In response, a description of uncertainties in the ERICA dose rate modelling is provided in Jackson (2013b). However, this omits any discussion of the implications of uncertainties in estimates of

environmental concentrations for input to the ERICA model. Given the magnitude of the peak dose rates provided by the assessment, we recommend that these uncertainties are fully explored in assessments carried out at the next major ESC update (**Recommendation ASS32**).

We also queried whether some of the assumptions made in the assessments of impacts on biota during coastal erosion were not sufficiently conservative, for example regarding occupancy rates and exposure to undiluted waste (ESC-RO-ASO-003). According to an updated assessment presented by Jackson (2013c), the removal of potentially non-conservative aspects of the assumptions could lead to an increase in total dose rate to a rat burrowing into the waste materials from 5.9 to 12.8 $\mu\text{Gy h}^{-1}$. The upper part of this dose rate range exceeds the screening level.

ICRP has specified a Derived Consideration Reference Level for a rat of 4 - 40 $\mu\text{Gy h}^{-1}$, defined as 'a band of dose rate within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals of that type of RAP⁸ (derived from a knowledge of expected biological effects for that type of organism) that, when considered together with other relevant information, can be used as a point of reference to optimise the level of effort expended on environmental protection, dependent on the overall management objectives and the relevant exposure situation' (ICRP 2009). However, the likelihood of a number of individual mammals receiving these doses needs to be balanced against the requirement to protect the population as a whole. These arguments are not fully developed by LLW Repository Ltd, but we consider that, given that very few animals are likely to be exposed in this manner, the intrusion doses assessed for small mammals are not high enough to cause significant concern.

We have the general comment that LLW Repository Ltd has carried out insufficient mapping of default generic habitats/biota from the ERICA model to habitats and biota that are observed on and around the LLWR. We accept that there does not need to be a one-to-one mapping of reference biota to species identified locally, but there is a need to demonstrate that the reference species chosen are suitable, for example by referring to recent LLWR ecological surveys and the Drigg marine biotope map (Natural England 2013). We recognise that future environmental changes will affect the size and distribution of populations of many species. However, the extent of these changes is difficult to foresee. In the absence of specific evidence on the effect of future climate and topographical change on the habitats (for example, it is debatable as to whether the dunes will disappear or migrate inland as a result of coastal erosion), we expect the next review of the ESC to include an assessment that concentrates on those species that are observed today and which assumes that similar populations will exist in the future (**Recommendation ASS33**).

We have not asked LLW Repository Ltd to update the 2011 non-human biota assessment to include assessments of the exposure of non-human biota to high activity particles and discrete items. We consider that, because these events will have a low probability of occurrence, deleterious impacts on non-human biota would be limited to individual organisms with no effect on the viability of a species or ecosystem. However, for future assessments, we recommend that the potential for harm to non-human biota coming into contact with high activity particles is considered further (**Recommendation ASS34**).

2.4. Radiological limits in the waste acceptance criteria

LLW Repository Ltd's approach to setting waste acceptance criteria (WAC) is set out in LLW Repository Ltd (2013d), which updates the proposals set out in the 2011 ESC (LLW Repository Ltd 2011d).

Our review of the broad approach to waste acceptance is addressed in the Safety Case Management report (Environment Agency 2015b). The discussion below focuses on LLW Repository Ltd's proposed approach to setting the radiological limits in the WAC. We examine the link between the 2011 ESC assessment and the proposed WAC, whether the 2011 ESC assessment results have been appropriately used, and how controls are implemented in applying the WAC to ensure that the 2011 ESC assessment assumptions are met.

⁸ Reference Animal and Plant

Our review of the 2002 PCSC identified that WAC should be based on assumptions and outputs from the ESC (Galson Sciences Ltd and Environment Agency 2005). We also suggested the radiological capacity assessments should be based on performance measures such as dose and risk (Environment Agency 2005). LLW Repository Ltd has taken these comments into account as its approach to setting WAC. In addition, the company has ensured that its approach is consistent with established approaches as recommended by the IAEA and implemented internationally.

To assess and manage the LLWR radionuclide inventory in relation to the radiological capacity, LLW Repository Ltd is proposing to use the IAEA 'sum of fractions' approach for the control of future disposals (IAEA 2003). As discussed in Environment Agency (2015b), we accept the sum of fractions approach as a valid way of managing the radionuclide inventory during LLWR operation.

LLW Repository Ltd has selected the reference case assessments for deriving radiological capacities for each main pathways considered (groundwater, gas, human intrusion and coastal erosion) for the period of authorisation and post-closure period. The reference case assessments represent the most likely evolution for each pathway, although not necessarily the 'worst-case' assessment. We agree that worst-case assessments are not a reasonable basis for deriving capacity figures. Subject to the proviso that worst-case assessments are excluded as appropriate, we consider that the limiting (most restrictive) capacity for each radionuclide should relate to the most limiting dose or risk assessed, irrespective of PEG, scenario or timing.

For the period of authorisation, radiological capacity assessments are based on the following criteria:

- 0.3 mSv y⁻¹ dose constraint from any source
- the additional dose guidance level of 20 µSv y⁻¹ for groundwater pathways

After the period of authorisation, the principal criteria used are:

- the risk guidance level of 10⁻⁶ y⁻¹
- the dose guidance levels for human intrusion of 3 mSv y⁻¹ for exposures continuing over a period of years and 20 mSv y⁻¹ for short-term exposures

Radiological capacity assessments for the groundwater pathway, the gas pathway, human intrusion and coastal erosion are presented in various Level 3 documents and are summarised in LLW Repository Ltd (2011d). However, LLW Repository Ltd has carried out further modelling work after submission of the 2011 ESC, resulting in updated capacities being assessed for the groundwater and gas pathways. These changes are described in the Developments Report (LLW Repository Ltd 2013c). In the discussion below we refer to the controls on the radiological inventory identified in the Developments Report and not those identified in the 2011 ESC.

For the period of authorisation, radiological capacities are proposed only for the gaseous radionuclides. Releases from other pathways, together with direct radiation, are excluded as these will be subject to ongoing monitoring. We reviewed LLW Repository Ltd's proposals for monitoring and consider them appropriate to achieve this objective. If appropriate, we can set out further requirements for environmental monitoring in the environmental permit. We expect effective leachate collection to prevent radionuclide releases from future disposals via the groundwater pathway during the period of authorisation, so that these do not contribute to the capacity assessments.

2.4.1. Groundwater pathway assessment

For the groundwater pathway after the period of authorisation, LLW Repository Ltd based radiological capacities on the well pathway smallholder PEG. LLW Repository Ltd has presented separate assessments for the RDA and EDA. C-14, Cl-36 and I-129 are the key contributing radionuclides for the groundwater pathway. RDA and EDA capacities are similar for Cl-36 and I-129.

In ESC-RI-ASO-007, we challenged the treatment of radionuclide chains in the groundwater pathway radiological capacity assessment. In response, LLW Repository Ltd acknowledged an error in the assessment relating to the treatment of radionuclide decay and ingrowth. The radiological capacity for a radionuclide with radioactive daughters should be related to the sum of the risks associated with that radionuclide and all its radioactive daughters (capacity for each

daughter radionuclide itself should then only be based on the inventory of this daughter directly disposed of). However, the 2011 ESC did not take into account the effect of daughter risks. This error only affected radionuclides that are part of significant chains.

To address this issue, LLW Repository Ltd derived updated radiological capacities for the groundwater pathway for both the RDA and EDA (Kelly 2012a). These assessments used an updated EDA model (Section 2.6). The company updated the assessments again to take account of the presence of complexants (Kelly and Berry 2013).

The radiological capacity assessments assume a linear relationship between the inventory disposed of and the risk. This assumption has been previously studied in the context of the LLWR (for example, Lean et al. 2005). Lean et al. (2005) explored the relationship between inventory and risk associated with solubility limited radionuclides using the 2002 PCSC near field model and concluded that the only radioelement for which a non-linear relationship between initial inventory and remaining inventory could affect the radiological capacity assessment was uranium at times after 6,000 years post-closure. The 2011 ESC does not consider whether this assumption remains appropriate for the updated models. We asked LLW Repository Ltd to review the validity of this assumption (ESC-FI-017).

The UKRWI includes activated reactor decommissioning waste that would be available for disposal to Vaults 15 to 20. These waste streams exhibit release characteristics for C-14 different from those of the waste streams assumed to be disposed in Vaults 8 to 14. We consider that the 2011 ESC assessment and further assessments carried out subsequently may not adequately represent the different release characteristics and their effects on the groundwater pathway risk and the associated radiological capacity. Since the release mechanism of C-14 is highly dependent on waste form, a simple linear relationship between inventory and risk cannot be assumed. The 2011 ESC does not address this issue. Given that disposal of most C-14 arisings is not expected until after 2050, we do not consider that it needs immediate resolution. However, via ESC-FI-017 we asked LLW Repository Ltd to investigate this matter further before the next update of the ESC.

Radiological capacity assessments for the groundwater pathway are based on the well pathway smallholder PEG (see Section 2.3.2). We considered that LLW Repository Ltd had not made the case when assessing radiological capacities for choosing the smallholder PEG over the caravan site manager PEG as the reference case (see IRF ESC-TQ-ASO-009a).

To understand why LLW Repository Ltd chose the smallholder PEG and a deterministic 'well pathway' assessment to derive radiological capacity, we asked LLW Repository Ltd in a Further Information Notice (Environment Agency 2014b) for a comprehensive analysis of the conservatism and optimism associated with this overall approach. We wanted to know how much further work would be required for a probabilistic assessment approach for radiological capacity and hence asked LLW Repository Ltd for an initial scope of work. We asked for a scope of work that would also include consideration of the EDA and take into account the presence of complexants such as EDTA. LLW Repository Ltd provided a response in Baker (2014). We reviewed LLW Repository Ltd's response and conclude that suitable substantiation for the use of the smallholder PEG is now provided. However, we wish to see better substantiation and underpinning for the choice of PEG in future ESCs.

LLW Repository Ltd employs a deterministic style well pathway assessment, in preference to a probabilistic assessment, to derive the radiological capacity limits. However, we consider that probabilistic calculations for the determination of radiological capacity may be more appropriate. In its response, LLW Repository Ltd defends its deterministic approach by comparing results with a simple set of illustrative probabilistic results in an attempt to demonstrate the two approaches lead to similar outcomes. Although LLW Repository Ltd does not present a probabilistic assessment for the groundwater pathway updated to take account of the presence of complexants such as EDTA (Kelly and Berry 2013), the reference case assessment presented in the 2011 ESC illustrated that a probabilistic approach would result in higher risks than a deterministic approach (for the RDA vaults, $1 \times 10^{-7} \text{ y}^{-1}$ compared with $4 \times 10^{-8} \text{ y}^{-1}$).

We also consider that probabilistic calculations generally provide a more appropriate basis for radiological capacity determinations than deterministic calculations given that probabilistic calculations include consideration of the effects of parameter combinations, uncertainty and

variability on radiological impacts. In addition, the 'expectation value' of risk derived from a probabilistic assessment includes an allowance for low probability/high dose combinations something lacking in the deterministic results. In Section 2.3.2 we made a recommendation regarding the use of probabilistic models for radiological risk assessment purposes where viable. We set out our future expectations for using the probabilistic groundwater pathway assessment model in derivation of radiological capacity in ESC-FI-012.

2.4.2. Gas pathway assessments

LLW Repository Ltd (2013d) presents updated radiological capacities for C-14, based on the gas pathway. It reports work carried out after submission of the 2011 ESC to remove overly cautious assumptions in the 2011 C-14 assessment, as described in Section 2.3.3. It establishes a single radiological capacity of 130 TBq as the limiting capacity for this radionuclide and is based on a smallholder PEG placed randomly within the vault area. We agree with LLW Repository Ltd that this assessment of radiological capacity provides an appropriate cautiously realistic estimate.

2.4.3. Coastal erosion and human intrusion assessments

LLW Repository Ltd (2011d), which was submitted as part of the 2011 ESC, presents radiological capacities assessed for the coastal erosion scenario. These radiological capacities are based on the two most limiting scenarios, comprising a PEG that makes recreational use of the coastline adjacent to the LLWR and a PEG consuming local marine foodstuffs. The limiting PEG depends on the radionuclide considered. We consider this a valid approach.

Because a human intrusion event is expected to be localised, LLW Repository Ltd does not consider it suitable for setting radiological capacities for the site as a whole. Instead, LLW Repository Ltd uses human intrusion scenarios to determine radiological values to be applied using the sum-of-fractions approach for individual consignments that will require application of specific emplacement strategies (LLW Repository Ltd 2011d). This deals with exposure scenarios in which people may come into direct contact with waste via human intrusion or coastal erosion. The company does not propose to use this approach to prevent disposal to the LLWR, only to ensure appropriate emplacement. Two sets of radiological values are defined to identify consignments that require management under an emplacement strategy: one set to be used for controlling all consignments that should not be co-located (i.e. in the same or adjacent stacks); and a second, more restrictive, set to be used to identify consignments that should not be emplaced in upper stack positions, within 5 m of the cap surface. These radiological values are additional to the site capacity assessments and do not replace, but supplement, the existing controls on consignments (4 GBq t^{-1} for alpha emitting radionuclides and 12 GBq t^{-1} for all other radionuclides).

LLW Repository Ltd bases controls on consignments to be emplaced in upper stack position on the most limiting assessment results relating to the site occupier and smallholder PEGs at either 100 years or 1,000 years after 2080; LLW Repository Ltd considers that neither of these PEGs would receive exposure to deeper waste. For some longer-lived radionuclides in decay chains, LLW Repository Ltd assesses more limiting capacities at 10,000 years. However, we agree with LLW Repository Ltd that these assessments are outside the reference case, given the reference case assumption of erosion of the site within a few hundreds to thousands of years. We accept LLW Repository Ltd's approach to human intrusion scenarios in the determination of radiological capacity.

LLW Repository Ltd bases controls applicable to all consignments on assessment results relating to the informal beach scavenger PEG, which LLW Repository Ltd considers to be the most limiting case after screening (LLW Repository Ltd 2011d). LLW Repository Ltd appears to have assessed this capacity using results at 1,000 years after 2080. Although this aspect is not made clear in the LLWR reports, it would be consistent with the reference assumption for the timing of the onset of coastal erosion. Whilst the informal beach scavenger PEG provides the limiting capacity for most radionuclides, the borehole driller PEG is more limiting for actinium-227 (Ac-227), Ac-242m,

curium-234 (Cm-234), Pu-238 and Pu-244⁹ (Hicks and Baldwin 2011). These data are not quoted in the all consignment limits because they are all above the 4 GBq t⁻¹ and 12 GBq t⁻¹ overall activity limits for LLW. The LLW activity limits are also more limiting for several other radionuclides, so that few consignments would actually require control using the consignment capacity limits.

As discussed in Section 2.3.4, specific WAC have also been derived to control potential radiological impacts from high-specific activity particles and discrete items that might occur or form within the waste.

We are satisfied that these WAC derived for coastal erosion and human intrusion assessments are appropriate, as are the proposed emplacement strategies.

2.4.4. Use of risk guidance levels as a basis for WAC

While we recognise that LLW Repository Ltd's 'sum of fractions' approach to assessing radiological capacity is an example of good practice, we note that the approach has a dual role in quantitative assessments. On the one hand, the assessed doses and risks are intended to represent best estimate values arising from the various pathways for exposure, so that they can be compared with regulatory guidance levels. On the other hand, these best estimate values are also used to assess the radiological capacity for the LLWR. This second assessment, in effect, works backwards from the regulatory guidance levels (for dose or risk) to derive a set of radionuclide capacity values that, if fully utilised, would result in doses or risks equalling the guidance levels, according to the current assessments. We consider that this is appropriate given that the dose and risk guidance levels are themselves defined to be sufficiently conservative without additional safety margins. As stated in the GRA 'We have chosen a cautiously low value for our risk guidance level. It is not necessary when expressing the aggregate risk for comparison with the risk guidance level to include an additional conservative bias' (GRA Paragraph 6.3.19; Environment Agency et al. 2009).

We recognise that assessed capacities are liable to change in future when the assessments are updated. We will require LLW Repository Ltd to reassess radiological capacities when the company undertakes major updates of the ESC. This will help manage the forward inventory of the LLWR, should new information emerge indicating that current risks or doses may have been underestimated. The updated capacity assessments should take into account existing and future disposals in all parts of the facility in an integrated manner.

2.4.5. Development of WAC

As discussed in Section 2.3.2, we note that some radiological capacities have been based on deterministic groundwater pathway assessments, which have subsequently been used to set radiological limits and manage the future capacity of the site (LLW Repository Ltd 2013d). We consider these radiological limits to be appropriate, although we discussed our preference for the derivation of radiological capacities for the groundwater pathway to be based on probabilistic assessment where viable and asked LLW Repository Ltd to consider further development in this area (ESC-FI-012). However, we consider that the radiological capacities defined within the 2011 ESC are not significantly different from those that might be derived from probabilistic assessment and are satisfied that LLW Repository Ltd provided sufficient evidence for this. Should further consideration of probabilistic assessments lead to changes in radiological capacities we expect these to be relatively small. At present we do not consider this an issue as the radiological capacity defined as a result of the groundwater pathway risks are dominated by C-14 and Cl-36. The majority of these radionuclides are not expected to arise in disposals for several decades and at this point in time there remains a large available margin in the assessed radiological capacity that will in practice take many decades to fill.

LLW Repository Ltd has included further controls in the latest version of the LLWR WAC on discrete items and high-specific activity particles, in line with the assessment of exposures to these items and particles (Section 2.3.4 and LLW Repository Ltd 2014). The latest WAC also include additional controls on fissile materials and non-radioactive contaminants (Section 2.5.8).

⁹ We note that Pu-244 is not present in the LLWR forward inventory, although it will ingrow from disposed Cm-248.

LLW Repository Ltd will also implement controls on the emplacement of specific consignments. As described in Section 2.4.3 the company has proposed controls on consignments requiring placement at least 5 m below the top of the cap and those that should not be placed within the same or adjacent stacks. This emplacement strategy is defined by a sum-of-fractions approach based on capacity values for limiting radionuclides (for example, in particular those which are long-lived and present significant risks through human intrusion scenarios).

In summary, we reviewed the radiological capacity assessment and WAC presented in the 2011 ESC and the subsequent Developments Report (LLW Repository Ltd 2013c) and conclude they are acceptable. However, we will require LLW Repository Ltd to continue to update them in line with developing information and assessments. The radiological limits set out in the WAC are in line with current industry good practice and are based on the 'available headroom' with respect to dose limits (for the period of authorisation) and risk and dose guidance levels (post-closure) set out in the GRA. They are consistent with the 2011 ESC together with LLW Repository Ltd's subsequent assessments.

The radiological capacity assessments presented in the 2011 ESC (together with the subsequent assessments presented in LLW Repository Ltd (2013c)) will remain subject to review and potential revision up to the end of the period of authorisation. The assessed radiological capacities are directly linked to the limiting pathways considered in the 2011 ESC and will be subject to review whenever the ESC is updated.

2.5. Non-radiological assessment

Principle 3 of the GRA states that 'solid radioactive waste shall be disposed of in such a way that the level of protection provided to people and the environment against any non-radiological hazards of the waste both at the time of disposal and in the future is consistent with that provided by the national standard at the time of disposal for wastes that present a non-radiological but not a radiological hazard' (GRA Paragraph 4.5.1).

Requirement R10 states that 'the developer/operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radiological hazards' (GRA Paragraph 6.4.1).

LLW Repository Ltd focused the quantitative assessment of non-radiological impacts presented in the 2011 ESC on the groundwater and coastal erosion release pathways, and addressed the gas and human intrusion pathways using simpler scoping assessments (LLW Repository Ltd 2011e).

Comments on the non-radiological impact assessment are provided in the following sections. Radioactive asbestos has been accepted for disposal at the LLWR in the past and this is also discussed below.

2.5.1. Non-radioactive inventory

The non-radioactive component of the LLWR inventory is subject to considerable uncertainty as non-radioactive contaminants in waste streams have historically not required characterisation by consignors to the same extent as the radiological content (Environment Agency 2015c). LLW Repository Ltd has used 2 methods to estimate the non-radioactive inventory, depending on whether a specific substance is declared by the consignor in the LLWR materials inventory or whether it is not declared, but has been detected in leachate, as described in Kelly and Berry (2011) and Dickinson and Kelly (2011). It is not ideal that more and better quality information is not available but, because of the lack of information on the non-radiological characteristics of the inventory, we consider the methods being used to estimate non-radiological inventory acceptable.

However, LLW Repository Ltd recognises that the declared inventory does not account for a significant proportion of the non-radioactive contaminants disposed of in the LLWR, given that a wide range of hazardous substances and non-hazardous pollutants that are not in the declared inventory have been identified in leachate. These include mercury, cadmium, tributyl phosphate, cyanide, selenium, arsenic, antimony, titanium, barium, beryllium, vanadium, tellurium, phosphate, fluoride, ammonium and nitrite. The 2011 ESC took the approach of estimating leachate concentrations for unit disposals of these contaminants. In the absence of solubility limitation, the leachate concentrations are directly proportional to the inventory disposed of. LLW Repository Ltd

recognises that this method cannot be used to provide assessments of environmental impact, but the data could be used to derive WAC if required in future.

There are some inconsistencies between the reporting of the inventory assessments in the Level 2 and Level 3 documents, which has made our review more difficult. For example, Kelly and Berry (2011) wrongly state that trench leachate data are used as a surrogate for vault leachate.

We recognise the challenges that developing a suitable inventory for non-radioactive substances presents given the lack of good past data. However, we consider that more could be done to characterise the future inventory. We do not fully understand why LLW Repository Ltd has excluded assessments that use a leachate source term based on observed trench leachate quality data. We understand that the company initially considered such assessments during the development of the 2011 ESC but subsequently withdrew them on the advice of the Peer Review Group (PRG). The PRG considered that present day trench leachate could not provide a suitable analogue for future trench leachate, given the scale of expected future changes in the chemistry of the trenches that could significantly affect contaminant sorption, solubility and degradation. We recognise this concern but, given the significant uncertainties in the other methods used to estimate the non-radioactive inventory, we disagree with the decision to omit these assessments from the ESC. In future non-radiological assessments, we expect the company to further consider how it could make better use of trench and vault leachate monitoring data to support the development of the trench, and potentially the vault, source term. LLW Repository Ltd should make sure that trench leachate is appropriately characterised to support this need (**Recommendation ASS35**). We would expect the effective characterisation of leachate to be included within the forthcoming leachate management strategy (ESC-FI-023).

In addition, the assessment does not take into account the composition of the grout in the vaults and its potential effect on leachate composition. The two main components of the grout, Ordinary Portland Cement and, in particular, Pulverised Fuel Ash, may contain several hazardous substances and non-hazardous pollutants. We raised this issue in ESC-RI-INF-002, which sought information on the influence of the presence of large volumes of grout on the leachate composition. In response, LLW Repository Ltd provided further information on the composition of the grout and its leachability. The company then undertook further work to assess the potential effect of the grout on groundwater (Kelly 2012b). The results show that it is unlikely that leachate from the grout will affect groundwater significantly. However, we recommend that the company should carry out further work to substantiate the leachability data used in this assessment, paying particular attention to the presence of hazardous substances, and that it should include grout in the source term for future non-radiological assessments (**Recommendation ASS36**).

The non-radioactive inventory in both existing and potential future disposals is thus subject to considerable uncertainty, as are the source terms used in the non-radiological assessment models. LLW Repository Ltd recognises this. However, we consider that LLW Repository Ltd has potentially presented an over-simplified inventory, which is not as representative of past waste disposals as it could be. Before further assessment work is carried out we will expect LLW Repository Ltd to further develop its assessment framework, to ensure that the requirements of the GRA and the Groundwater Daughter Directive continue to be met and the assessment is improved upon. Our expectations are further detailed in ESC-FI-006.

The non-radiological assessment in the 2011 ESC did not investigate or assess the potential presence of discrete small volumes of hazardous substances that could exist. We accept that, because of the wide range of waste consignors and the lack of good quality past records, it is impractical to identify and characterise these disposals. The non-radiological monitoring programme thus needs to be comprehensive enough to enable a wide range of hazardous substances and non-hazardous pollutants that might appear in the trench leachate to be identified. Accordingly, at regular intervals LLW Repository Ltd should analyse the leachate for a range of non-radioactive hazardous substances and non-hazardous pollutants. In addition, LLW Repository Ltd should pursue any opportunity to improve its understanding of the non-radiological component of the inventory (**Recommendation ASS37**).

The new LLWR WAC and improved consignor awareness means that the understanding of the non-radiological properties of the waste will be improved on in the future. We will work with LLW

Repository Ltd, NDA and waste consignors to improve the characterisation of the non-radioactive inventory of LLW. LLW Repository Ltd should use any new information to improve the accuracy of the vault leachate source term and the wider non-radiological assessment.

Overall we are satisfied that LLW Repository Ltd has met the requirements of the GRA. However, we expect the next major update of the ESC to include an improved understanding and assessment of past and future non-radiological environmental impacts. We will also be seeking improvements to shorter timescales within ESC-FI-006.

2.5.2. Asbestos

For the non-radioactive components of radioactive waste, we require LLW Repository Ltd to achieve equivalent levels of protection to the environment and to meet standards that are 'no less stringent' than would need to be met for non-radioactive waste disposal at landfills. This also applies to asbestos. The current regulatory framework for the disposal of asbestos to landfills does not specifically require an assessment of the risk associated with the exposure of asbestos by any mechanism during the whole lifetime of the site. Instead, all asbestos disposals must meet the specific requirements of the Environmental Permitting Regulations 2010 and Landfill Directive, which detail a number of prescriptive requirements on the manner of disposals which aim to ensure isolation of the asbestos hazard (for example, minimum cover depths over the asbestos).

LLW Repository Ltd compares its approach to asbestos disposal at the LLWR with current landfill disposal practices in Baker (2013c). The company concludes that current disposal practices at the LLWR offer better protection than that which would be provided at a landfill. We agree with this conclusion and therefore consider that LLW Repository Ltd has demonstrated that it meets the requirements of the GRA. Nonetheless, the company has carried out further work to assess the hazards presented by asbestos from the LLWR in the future following coastal erosion or human intrusion. This work is being carried out in the absence of any clear national or international assessment framework. We commend this work and support LLW Repository Ltd should it wish to take it forward.

To ensure continued consistency with the 2011 ESC, the GRA and taking into account LLW Repository Ltd's assessment work on asbestos disposal, LLW Repository Ltd requires each potential consignment of asbestos to be assessed on a case by case basis. This assessment takes into account the amount, type and form of the asbestos. Based on this, the company will determine whether or not it can accept the consignment.

Despite there being no requirement to assess the risk associated with asbestos as a result of exposure by coastal erosion or future human intrusion, we consider it important for LLW Repository Ltd to improve the quality of the inventory records of past and future asbestos disposals to the LLWR, as a matter of good practice, should future assessment be required (**Recommendation ASS38**).

2.5.3. Non-radiological groundwater pathway assessment

Both the Level 2 and Level 3 reports on non-radiological impacts provide a discussion about the strategy for the non-radiological assessment of impacts to groundwater. This discussion in particular considers LLW Repository Ltd's decision to use a radioactive 'repository' approach rather than a conventional 'landfill' approach to assessment (LLW Repository Ltd 2011e; Kelly and Berry 2011). The GRA provides no guidance on this issue but states that, whilst nationally accepted standards for disposing of hazardous waste need not necessarily be applied, 'a level of protection should be provided against the non-radiological hazards that is no less stringent than would be provided if the standards were applied' (GRA paragraph 6.4.2).

In addition to addressing GRA Principle 3 and Requirement R10, the non-radiological assessment for the groundwater pathway needs to demonstrate compliance with the Groundwater Daughter Directive (2006/118/EEC), as specified under Schedule 22 of EPR10. Supplementary guidance to the GRA related to the implementation of the Groundwater Directive states that 'the means of complying with the groundwater activity provisions of EPR10 for non-radiological hazards may be proportionate to the non-radiological hazard presented by the waste' (Environment Agency 2013).

LLW Repository Ltd set up a GoldSim assessment model to assess the transport of non-radiological contaminants in groundwater (Kelly and Berry 2011). The model was set up to mirror

closely the radiological assessment groundwater pathway model. The following approach was adopted:

- assess the release of non-radioactive contaminants from the facility based on the inventory of materials disposed of
- assess average concentrations in groundwater under the site and at a point between the site and the coastline, and also at locations relevant to exposure of the PEGs considered for radioactive contaminants
- compare these concentrations with appropriate criteria, focusing on the concentrations of hazardous substances and non-hazardous pollutants at compliance points identified by LLW Repository Ltd

We consider this to be a valid assessment approach. However, the use of this approach as opposed to an approach based on our guidance on hydrogeological risk assessments (HRA) for landfills (Environment Agency 2011) has made it difficult for us to determine compliance with the requirements of EPR10. Nevertheless, we consider that the differences in approach are largely valid and reflect the differences between the LLWR disposal concept and a conventional landfill.

The conclusions we have drawn include the following:

- LLW Repository Ltd's use of a materials-based source term instead of a leachate source term is a valid approach for assessment of the vaults, reflecting the lack of a leachate source term or suitable analogue.
- The trenches, as a historical method of disposal, were not constructed to modern containment standards. In future assessments, they should be modelled and presented separately from the vaults. This may provide improvements to flexibility of the assessment approach.
- In future assessments, compliance points for the vaults should be in line with our expectations for assessment of hazardous substances and non-hazardous pollutants to meet the requirements of the Groundwater Daughter Directive. As discussed in our landfill guidance (Environment Agency 2011), these are currently located at the base of the unsaturated zone for hazardous substances and at the site boundary for non-hazardous pollutants. LLW Repository Ltd should give separate consideration to compliance points for the trenches, to demonstrate legacy impact and provide baseline groundwater quality information for the assessment of the vaults performance.
- In future assessments, LLW Repository Ltd should give careful consideration to the selection of assessment criteria. For example, concentrations of hazardous substances in groundwater should be assessed against Minimum Reporting Values (MRVs) or baseline groundwater quality, as opposed to the more restrictive use of drinking water standards (DWS) or Environmental Quality Standards (EQS), as used in the 2011 ESC assessment. The company explains its reasoning for this approach in LLW Repository Ltd (2011e).

To ensure continued demonstration of protection of groundwater we require LLW Repository Ltd to produce an updated non-radiological hydrogeological risk assessment before the end of 2017. This updated assessment should have full regard to requirements of the GRA and Environment Agency guidance on hydrogeological risk assessments for landfills (Environment Agency 2011) including use of compliance points and criteria similar to those used for landfill disposals¹⁰. We will work with LLW Repository Ltd to achieve better alignment of the LLWR non-radiological assessment with best practice for hydrogeological risk assessment for conventional landfills (ESC-FI-006).

As for the radiological assessment, LLW Repository Ltd provided separate assessments with different assumptions for the period of authorisation (up to 2180) and for the post-closure period

¹⁰ LLW Repository Ltd presented us with updated hydrogeological risk assessment calculations in September 2014, which take into account more appropriate compliance points, the effect of EDTA on contaminant transport and a trench leachate source term. Due to the timing of receipt of the report, we have not included it in the scope of our ESC review, however, it provides evidence that work is progressing to address our recommendations and FI.

(from 2080). We queried this in ESC-TQ-ASO-008. Baker (2013a) presents combined graphs for the period of authorisation and post-closure periods for groundwater concentrations of significant non-radiological contaminants. Two sets of graphs are provided: one assuming 50 mm y⁻¹ infiltration through the interim trench cap during the period of authorisation (as presented in the 2011 ESC); and one assuming 300 mm y⁻¹ infiltration during this period (a variant assessment based on the results of recent water balance calculations indicating that infiltration was significantly underestimated in the 2011 ESC; Baker 2012).

We observed that discrepancies between the non-radiological contaminant concentrations in groundwater assessed at the end of the period of authorisation (both infiltration variants) and at the start of the post-closure period are much greater than in the radiological assessment. Rising trends in contaminant concentrations in groundwater are seen throughout the period of authorisation, reflecting the past and continuing performance of the trenches. However, concentrations at the start of the post-closure assessment are set at zero and are again seen to increase throughout the assessment period. This is appropriate for the vault disposals, but does not take account of the discharges from the trench disposals that occurred during the period of authorisation. Taking the 300 mm y⁻¹ infiltration rate case as an example, assessed concentrations of several contaminants (including molybdenum and chromium) in groundwater at the end of the period of authorisation are greater than concentrations at the end of the post-closure assessment. We expect a better integration of the period of authorisation and post-closure assessments in a future ESC. This integration is especially important for reporting on compliance with non-radiological performance requirements (**Recommendation ASS39**).

LLW Repository Ltd's assessment indicates that, throughout the period of authorisation, concentrations of all inorganic substances are below the relevant assessment standards (selected as the most restrictive of the relevant DWS or EQS) in the regional aquifer underlying the LLWR. However, the assessment projects that there would have been measurable concentrations of the hazardous substances benzene and vinyl chloride in groundwater underlying some of the trenches in the past. Due to degradation, present day concentrations of both substances in groundwater underlying the trenches are assessed to be negligible or below MRVs. Projected discharges from the LLWR vaults are assumed to be zero throughout the period of authorisation, due to the absence of any leachate and the effectiveness of the leachate management system.

For most substances there is a poor correlation between measured and assessed concentrations during the operational period (in groundwater under the trenches and between the LLWR and the coast). Assessed concentrations are generally lower, in particular for groundwater between the site and the coast. This is probably a reflection of the level of uncertainty in the trench non-radioactive inventory.

LLW Repository Ltd projects that concentrations of organic hazardous substances in groundwater underlying the site will be zero or below MRVs throughout the post-closure period. Concentrations of chromium¹¹, plus a number of pollutants currently classified as non-hazardous including lead, nickel¹², molybdenum and zinc, are assessed to exceed the relevant standards in groundwater under the trenches after several hundred years post-closure. The same contaminants, except zinc, are assessed to exceed the relevant standards in groundwater under the vaults. Concentrations of most inorganic substances increase throughout the assessment period, up to the assumed start of site disruption by coastal erosion.

Through our assessment we concluded that the LLWR currently meets the requirements of the GRA and the supplementary guidance related to the implementation of the Groundwater Directive. This assessment has taken into account the extended timeframes over which non-radiological discharges happen and is based on a proportionate approach taking account of the requirement to optimise for radiological aspects, but not non-radiological aspects, of disposals. We will require

¹¹ Chromium VI (Cr(VI)) is classified by JAGDAG as an interim hazardous substance; no valency data are available to determine the proportion of chromium likely to be in this form.

¹² Following recent consultation by JAGDAG, it is possible that some nickel species may be classified as hazardous.

LLW Repository Ltd to produce a more comprehensive and stand-alone assessment of impacts associated with potential inputs of hazardous substances and non-hazardous pollutants to groundwater before the end of 2017 (ESC-FI-006).

An objective of future non-radiological assessment work should be to improve the clarity of the assessment and its outcomes. We recommend that LLW Repository Ltd improves future HRAs by **(Recommendation ASS40)**:

- ensuring that the environmental monitoring and sampling programme can achieve necessary baseline and operational non-radiological monitoring capability in line with landfill guidance (Environment Agency 2011)
- working to improve estimates of the hazardous and non-hazardous components of trench and vault leachate, taking into account future disposals and utilising any opportunity to gain better information
- fully integrating the period of authorisation and post-closure assessments
- presenting a more comprehensive assessment of uncertainties and their effects, including the use of probabilistic models as appropriate
- taking better account of the requirements for landfill risk assessment (Environment Agency 2011) wherever possible
- taking into account the latest Environment Agency guidance on setting compliance points and standards for assessing inputs of hazardous substances to groundwater
- documenting the assessment in a stand-alone report containing all relevant monitoring, conceptualisation and assessment information and avoiding the need to refer to numerous supporting documents
- taking into account changes in the designation of hazardous substances by the Joint Agencies Groundwater Directive Advisory Group (JAGDAG)

ESC-FI-006 identifies requirements for future updates of the non-radiological groundwater assessment and, in these updates, demonstration of continued conformity with the GRA and associated supplementary guidance, together with better alignment with landfill practices.

Overall, we consider that the requirements of the GRA for the non-radiological groundwater assessment pathway have been adequately met, although we see scope for future improvement as discussed above. Uncertainty in the past non-radiological inventory, particularly for the trenches, is an important factor. It is therefore important that non-radiological monitoring is effectively used to supplement the limited inventory data, by determining any new contaminants arising, along with changes in trends. Greatly improved non-radiological information is now being collected for waste disposed at the LLWR and this must continue. This data on vault disposals will need to be used effectively to inform future assessments.

2.5.4. Surface water discharges

Throughout the period of authorisation, the LLWR will discharge surface water collected from the trenches and vaults via a permitted discharge point located offshore. At the end of the period of authorisation, this discharge route will be removed, with future environmental discharges minimised by the presence of an engineered capping layer. LLW Repository Ltd has not presented a formal assessment of the impacts of future non-radiological discharges in surface water during the period of authorisation. Instead, the company has characterised the current discharges from the vaults and trenches and has assumed that similar non-radioactive discharges will happen throughout the period of authorisation. We accept this approach as the nature of permitted activities is unlikely to change and trench discharges are exhibiting a declining source term typical of past disposals. As a condition of LLW Repository Ltd's environmental permits, we will continue to require the company to carry out discharge and environmental monitoring and to review and assess this data to confirm that the non-radiological content of the discharges remains consistent with assumptions and is not causing an unacceptable environmental impact.

2.5.5. Coastal erosion

GRA Requirement R10 states that, 'whilst national standards for disposing of hazardous waste may not be suitable to apply to waste that presents both radiological and non-radiological hazards,

a level of protection against non-radiological hazards should be provided that is no less stringent than would be provided if the hazardous waste standards were applied' (GRA Paragraph 6.4.2). Although LLW Repository Ltd has included an assessment of impacts from the exposure of hazardous waste during coastal erosion in the 2011 ESC (LLW Repository Ltd 2011e), this is not something that we currently require for landfills. We therefore present the results of our review for information only. However, we consider this assessment a positive addition to the 2011 ESC. As discussed in Environment Agency (2015d), it is possible that in the future a methodology suitable for assessing non-radiological impacts will be developed for landfills subject to coastal erosion. We would expect future ESC updates to use any such methodology to the extent applicable.

LLW Repository Ltd's 2011 ESC presents a non-radiological impact assessment based on a modified contaminated land approach for the coastal erosion pathway. We have made a number of recommendations below that the company should consider if it chooses to update the assessment. LLW Repository Ltd has used the results from the coastal erosion assessment to inform its derivation of future capacities for significant non-radiological contaminants (see Section 2.5.8).

LLW Repository Ltd's assessment of impacts on human health from exposure to the non-radiological hazards in the waste during coastal erosion is based on the reference case erosion model used for the radiological assessment (Kelly and Berry 2011). The assessment considers inhalation of dust from eroded debris or contaminated sand/sediment and ingestion by contact with the same materials. Consideration of exposure through inhalation and ingestion is consistent with the radiological coastal erosion assessment. The approach compares beach and foreshore concentrations of the relevant contaminants to environmental concentration criteria that are based on DWSs. LLW Repository Ltd concludes that most of the contaminants considered, except for chromium and copper, would be present on the beach and foreshore at concentrations below the relevant standards.

Kelly and Berry (2011) recognise that DWSs are not appropriate to inhalation exposures, but claim that this is a valid approach given the low contribution from this pathway. To investigate this, we undertook a brief review of published toxicity data for cadmium, chromium and nickel (all present within the LLWR). This showed that tolerable daily intakes or index doses for inhalation for all 3 of these substances are substantially lower than those for ingestion, by 4 orders of magnitude in the case of nickel (Defra and Environment Agency 2002; Environment Agency 2009b; 2009c). Thus the approach of Kelly and Berry (2011) might not be conservative for all substances.

The Environment Agency has issued ingestion and inhalation toxicity data for a wide range of non-radiological contaminants. We have also issued guidance on the evaluation of assessment criteria using the Contaminated Land Exposure Assessment (CLEA) model (Environment Agency 2009d; 2009e). It is not clear why LLW Repository Ltd did not generate site-specific assessment criteria using this methodology (or similar), which the company did for its human intrusion assessment (albeit using an out-of-date model as discussed below). We recommend that this is done in future assessments (**Recommendation ASS41**).

LLW Repository Ltd also omitted ingestion of seafood from the coastal erosion assessment. Although this exposure pathway is not generally considered in standard non-radiological impact assessments, it is a significant contributor to radiological risks from coastal erosion. We recommend that this exposure pathway is taken into account in any future assessments (**Recommendation ASS42**).

Any future non-radiological assessment of coastal erosion carried out by LLW Repository Ltd should take account of the distribution of non-radiological contamination (**Recommendation ASS43**). The non-radiological properties of the eroding waste are unlikely to be homogenous and analogous to contaminated land. The non-radioactive inventory is likely to include discrete items of hazardous material. The 2011 ESC non-radiological coastal erosion assessment uses a single assessment scenario based on mean concentrations of materials in the declared inventory and unit masses of other contaminants; variability and uncertainty, including exposure to undiluted waste and discrete items, are not considered. We understand that the assessment assumes a factor of 45 dilution between the cliff and foreshore sediment compartments; the assessed exposure of humans is dependent on this dilution factor.

The assessment includes only inorganic substances, on the assumption that all organic substances such as benzene and vinyl chloride will have degraded by the time of erosion. We expect this assumption to be reviewed in the future taking into account the expected biogeochemical evolution of the vaults and trenches (**Recommendation ASS44**).

In summary, LLW Repository Ltd has completed an assessment of non-radiological impacts as a result of coastal erosion of the LLWR. This has shown that there are no issues of regulatory concern. We broadly agree with this. However, we note that this assessment is one that is not completed as standard for non-radioactive landfills and has been developed in the absence of a good assessment framework. We therefore noted a number of areas that should be considered for further development if this assessment is progressed further. We recommend that LLW Repository Ltd maintains ongoing links with wider investigations into the characterisation, assessment and remediation of eroding historical landfills, and incorporates relevant learning into the ESC (see Recommendation SUE44 of Environment Agency 2015d).

2.5.6. Human intrusion

The 2011 ESC includes an assessment of impacts from exposure to non-radiological hazards incurred as a result of future human intrusion into the repository. It employs scenarios identical to those used for assessing the radiological effects from human intrusion. As for coastal erosion, there is no current requirement for the operator of a conventional landfill to assess the consequences of exposure to hazardous substances as a result of human intrusion. We therefore present the results of our review for information only, although we recognise that LLW Repository Ltd has used the results from the human intrusion assessment to inform its derivation of future capacities for significant non-radiological contaminants (see Section 2.5.8).

The non-radiological human intrusion assessment uses data from the radiological assessment smallholder scenario to assess the degree of dilution between the waste and soil. The assessment compares mean contaminant concentrations in soil with derived site-specific criteria. These criteria differ from the criteria used in the coastal erosion assessment and were originally derived for a 2008 assessment (Barber and Henderson 2008). In contrast to the coastal erosion scenario concentration measures, Barber and Henderson (2008) calculated site-specific assessment criteria using the CLEA model based on the CLEA 'residential with plant uptake' and 'allotment' scenarios, which include consumption of home grown vegetables but not animal products. This approach would have been consistent with our expectations at that time. However, the CLEA model and some of the supporting toxicological data were updated in 2009 (see Environment Agency 2009e, 2009f). Given that the superseded version of the CLEA model was formally withdrawn in 2009, we would have expected to see updated assessment criteria.

Kelly and Berry (2011) appear to have selected the 'allotment' scenario assessment criteria derived by Barber and Henderson (2008). The reasons for this are not made clear. The 'residential with plant uptake' scenario would be more analogous to a smallholder, and is the more restrictive of the 2 scenarios.

The assessment indicates that chromium, iron, lead, molybdenum, nickel and uranium would be present in the soil at concentrations above the derived criteria.

As with the coastal erosion assessment, the human intrusion assessment does not consider the effects of heterogeneity or uncertainty. Alternative scenarios are not assessed. Furthermore, the assessment includes only inorganic substances since it is again considered that all organic substances such as benzene and vinyl chloride will have degraded by the time of intrusion.

In any future assessment, we would expect LLW Repository Ltd to use an approach more closely in line with current UK practice for the assessment of human intrusion impacts associated with exposure to non-radiological contaminants in soil. We would also expect any future non-radiological assessment of human intrusion to include consideration of heterogeneity and uncertainty, including the potential for exposure to organic contaminants (**Recommendation ASS45**).

Similar to our conclusions for the coastal erosion non-radiological assessment, we have not identified any issues of regulatory concern arising from LLW Repository Ltd's non-radiological human intrusion assessment. However, should the assessment be progressed further, we see

scope for improvement. It is possible that in future a methodology suitable for assessing non-radiological impacts associated with human intrusion into landfills will be developed. We expect future ESC updates to use any such methodology to the extent applicable.

2.5.7. Gas pathway

LLW Repository Ltd has identified the presence of hydrogen, methane, carbon dioxide and hydrogen sulphide through routine monitoring for landfill gases in the trenches (LLW Repository Ltd 2011e). Concentrations are similar to those seen in aged landfill waste and reflect the presence of ongoing and declining biodegradation processes in the trench waste. Biogeochemical modelling of the repository near field using the Generalised Repository Model (GRM) has indicated that methane and carbon dioxide will be produced in greatest volume. Methane, hydrogen and hydrogen sulphide are flammable. Hydrogen sulphide is highly toxic and carbon dioxide is also an asphyxiant.

LLW Repository Ltd assessed concentrations of hydrogen sulphide and methane for a simple enclosed structure overlying Trench 7 (where rates of methane and carbon dioxide generation as assessed by GRM are greatest) using a simple scoping method (Kelly and Berry 2011). Assessed concentrations were low enough not to present an explosive or, in the case of hydrogen sulphide, toxic hazard.

LLW Repository Ltd assessed the effects of hydrogen and carbon dioxide qualitatively. Hydrogen will rapidly diffuse through the cap and will not accumulate at ground level. The low levels of hydrogen generated by corrosion in the waste will tend to be consumed by microbial processes. For carbon dioxide also, only low concentrations will be produced post-closure. LLW Repository Ltd thus considers that neither gas presents a hazard (LLW Repository Ltd 2011e).

We agree with LLW Repository Ltd's assessment that the hazard from the generation of the main landfill gases in the trenches and vaults is low both during and after the period of authorisation. The main significance of landfill gas is its potential to act as a carrier for radioactive gas, which is considered in the radiological assessment. We asked LLW Repository Ltd to carry out further monitoring and characterisation to obtain quantitative flow and volume data on gases to determine whether any active management of landfill gas is required (Environment Agency 2015d).

2.5.8. WAC for non-radiological substances

LLW Repository Ltd has derived revised WAC from the 2011 ESC so as to characterise and limit non-radiological substances based on their potential environmental impact (LLW Repository Ltd 2011d; 2013d). The WAC focus on contaminants that are:

- classified as hazardous under the Hazardous Waste Regulations
- considered either a hazardous substance or a non-hazardous pollutant under EPR10

LLW Repository Ltd has derived a non-radiological capacity for the LLWR. As presented in the Developments Report (LLW Repository Ltd 2013c), the company proposes non-radiological capacities that would be managed using the waste acceptance process. These capacities are chosen as being the most limiting of the capacities assessed for the groundwater pathway, the human intrusion pathway, or the coastal erosion pathway.

We accept LLW Repository Ltd's conclusion that, in general, it is not appropriate to apply capacity controls to disposals of routine metallic waste. The company has, however, proposed to apply capacity control to a number of contaminants including lead, asbestos, arsenic, beryllium, boron, cadmium, cyanide, mercury (not in metallic form), selenium and tributyl phosphate. All oils must be fixed in a solid matrix. We accept these proposals as reasonable and consistent with the requirements of the GRA and the 2011 ESC. However, in developing the non-radiological WAC in the future, we expect LLW Repository Ltd to take account of updates and improvements to the non-radiological groundwater risk assessment and to use improving inventory and ongoing groundwater monitoring information to confirm or refine the assumptions made in the risk assessment.

We recognise that the assessment of non-radiological capacities is based on many assumptions and is subject to uncertainties. Although we have no objection to the use of the assessment for deriving WAC for current application, we expect future updates of the ESC and WAC to make full

use of improving non-radiological characterisation information to inform and improve the assessment. We recommend that the non-radiological capacity assessment is subject to a comprehensive review at the next major ESC update so as to take account of the most recent non-radiological HRA (**Recommendation ASS46**).

2.6. Extended Disposal Area assessment

LLW Repository Ltd provides an assessment of impacts from the EDA in LLW Repository Ltd (2011f). The additional vaults in the EDA (Vaults 15 to 20) would take most of the LLW arisings from 'final stage' nuclear site decommissioning. This waste contains a higher inventory of C-14 and Cl-36, mainly in metal, graphite and concrete, than waste in the RDA trenches and vaults.

LLW Repository Ltd's approach for the EDA assessment is similar to its approach for the RDA. We identified no issues that we consider unique to the EDA and we raised no IRFs specific to the EDA assessment. However, when responding to ESC-RI-ASO-007 on the treatment of radionuclide chains in the groundwater pathway radiological capacity assessments (Section 2.4), LLW Repository Ltd identified some minor anomalies between the groundwater pathway assessments for the EDA and the RDA. The company addressed these anomalies by modifying the EDA model (Kelly 2012c). The anomalies were:

- a difference in the minimum thickness of the saturated zone permitted in the vault compartments in the RDA and EDA near field model
- a difference in the assumed degree of saturation in the upper Quaternary drift compartments that underlie the trench and vault compartments
- a stochastic element in the EDA assessment model that returned the mean value, rather than the most likely value, in deterministic assessments

LLW Repository Ltd re-ran the deterministic assessment cases from the 2011 ESC using the modified EDA assessment model. The company found the results to be within 50% of those obtained using the unmodified model. For the well, estuary and marine pathways, the results are within 30% or less of those using the unmodified model.

We present below brief summaries and comparisons with the equivalent assessments for the RDA (taken from LLW Repository Ltd 2011f):

- **Groundwater pathway.** Risks for all pathways assessed for the EDA are below the risk guidance level of 10^{-6} y^{-1} . For the well pathway, results from the EDA and RDA assessments are broadly similar. Risks for the marine, estuary and stream pathways are about 1 to 2 orders of magnitude higher for the EDA than for the RDA. For both EDA and RDA, C-14 is generally the radionuclide presenting the highest risk. For the stream pathway modelled using the Expected Natural Evolution Scenario, the peak risk for both EDA and RDA is still rising at the end of the period simulated, when the coast has eroded to the boundary of the LLWR site.
- **Gas pathway.** In terms of doses from C-14 gases, Vaults 15 to 20 (in the EDA) perform better than Vaults 8 to 14 because of the predicted lower amount of organic waste and hence lower gas production. Using the reference inventory (lifetime disposal of C-14 equals 24 TBq) the annual effective dose for the reference case PEG (a smallholder) for the EDA is $2.4 \text{ } \mu\text{Sv}$ (which, using a dose-risk coefficient of 0.06 per Sv, corresponds to a conditional risk of $1.4 \times 10^{-7} \text{ y}^{-1}$). Variant cases yield an annual effective dose up to $2.8 \text{ } \mu\text{Sv}$ (this corresponds to a conditional risk of $1.7 \times 10^{-7} \text{ y}^{-1}$).
- **Coastal erosion.** The highest assessed peak annual dose is $18 \text{ } \mu\text{Sv}$ to the local recreational beach user. This arises mainly from disposals of Th-232 in Trenches 4 and 5. The key radionuclides for coastal erosion are thorium-228 (Th-228) and Ra-228. The inventory of these radionuclides is dominated by past disposals to the trenches; there is thus little difference between the EDA and RDA inventories. Consequently, peak doses are the same for both EDA and RDA.
- **Human intrusion.** For the additional vaults (Vaults 15 to 20) of the EDA, all assessed doses for short-term intrusion events are substantially below the dose guidance level of 20 mSv y^{-1} . For longer-term exposures, the highest assessed dose rate is 5.4 mSv y^{-1} to a smallholder growing crops on land contaminated by an intrusion into the part of Vaults 15 to 20 having the

highest C-14 activity. This assessment is cautious, however, as it neglects losses of C-14 and Cl-36 from the waste before and after excavation. LLW Repository Ltd has since reassessed all impacts from C-14 (LLW Repository Ltd 2013a) and human intrusion doses for C-14 for the EDA are now reduced.

- **Criticality.** The WAC limits on fissile materials assessed for the RDA are conservative. LLW Repository Ltd has considered the possibility of significant quantities of graphite waste in the EDA inventory and has shown that it would not significantly increase the probability of criticality. The WAC limits proposed in the 2011 ESC are also applicable to future disposals in Vaults 15 to 20.
- **Non-radiological assessment.** This assessment considered the groundwater, coastal erosion, gas and human intrusion pathways. In all cases, and for both the period of authorisation and the long-term, the environmental impact of the additional vaults is small compared with impacts from the RDA repository.
- **Non-human biota.** Throughout the post-closure period, total dose rates to non-human biota from the EDA repository from all assessed pathways are below the screening threshold of $10 \mu\text{Gy h}^{-1}$, except for invertebrates and insects in the coastal erosion scenario, which could receive dose rates up to about $20 \mu\text{Gy h}^{-1}$. Further assessment demonstrates that these organisms are relatively insensitive to radiation (Thorne and Schneider 2011).

During our review of the 2011 ESC, LLW Repository Ltd reassessed the 2011 ESC groundwater pathway to quantify the effect of complexants. Results for the well pathway for the deterministic reference case show a risk from the RDA via the groundwater pathway similar to the assessed risk neglecting complexants (that is a peak risk of $4 \times 10^{-8} \text{ y}^{-1}$ occurring at around 2252 AD, with C-14 being the dominant radionuclide).

LLW Repository Ltd submitted an environmental permit application (LLW Repository Ltd 2013d) seeking a radiological capacity based on the EDA. The assessed EDA capacity for C-14 is approximately half the assessed RDA capacity, reflecting the effect of wasteform on C-14 release to the groundwater and gas pathways (in particular, the organic material content in Vaults 15 to 20, which is expected to be significantly less than in Vaults 8 to 14). We will require LLW Repository Ltd to fully integrate the EDA assessment into the ESC at the next major review of the ESC (ESC-FI-011).

3. Meeting our requirements

LLW Repository Ltd submitted the 2011 ESC as required by Schedule 9 Requirement 6 of the current LLWR environmental permit. This required the operator to 'update the Environmental Safety Case(s) for the site covering the period up to withdrawal of control and thereafter'.

We define an ESC as 'the collection of arguments, provided by the developer or operator of a disposal facility, that seeks to demonstrate that the required standard of environmental safety is achieved' (Environment Agency et al. 2009). In this section we provide a summary of our review of the assessment sections of the 2011 ESC and assess whether the relevant parts of Schedule 9 Requirement 6 of the environmental permit and the GRA have been met.

3.1. Requirements R5, R6 and R7: protection of human health against radiological hazards

Overall, we judge that LLW Repository Ltd has met the 3 GRA requirements pertaining to quantitative assessment criteria (that is R5, R6 and R7). LLW Repository Ltd has demonstrated that assessed radiological doses and risks for the periods before and after closure of the LLWR all fall within relevant guidance levels for both the RDA and EDA vaults. For radium-bearing waste, 'discrete items' and 'particles', the company has proposed further controls for inclusion in the WAC. LLW Repository Ltd's proposed emplacement strategies will also help to reduce assessed doses and risks for certain scenarios.

We consider that LLW Repository Ltd has made a reasonable range of cautious assumptions about future scenarios and human habits and behaviour. We have no reason to believe that the company's assessments have significantly underestimated potential impacts (doses and risks). However, we consider that LLW Repository Ltd should make efforts to manage uncertainties better and to make sure that all important uncertainties, some of which may currently be implicit, are made explicit in the register of significant uncertainties.

LLW Repository Ltd has assessed doses during the operational and active institutional control phases as being below both the source related (0.3 mSv per annum) and the site-related (0.5 mSv per annum) dose constraints. A dose roughly equivalent to the dose constraint suggested by PHE (0.15 mSv annual dose) could be received from direct radiation by a person living adjacent to Vault 9 during its operation. However, this location is currently uninhabited. In future, direct radiation exposures will be managed by an appropriate waste emplacement strategy and will be monitored. LLW Repository Ltd supplies us with periodic monitoring reports and this will continue. In due course, before the end of waste placement operations, LLW Repository Ltd will finalise proposals for subsequent active institutional control in consultation with stakeholders.

Currently, there are no wells utilised for the abstraction of drinking water in the area between the LLWR and the coast. We consider it unlikely that such a well will be drilled before the end of the operational phase. In any event, LLW Repository Ltd has assessed the annual dose from drinking groundwater from a hypothetical well intercepting the plume from the site to peak at 3 μ Sv, which would be received at the present day.

For the groundwater well pathway in the post-closure period (RDA assessment), LLW Repository Ltd assesses a peak risk (using a probabilistic approach) for the well pathway of about $1 \times 10^{-7} \text{ y}^{-1}$ at about 2230 AD (around an order of magnitude below the risk guidance level), dominated by the contributions from C-14 and Cl-36. LLW Repository Ltd's latest revised 'reference case' peak risk (deterministic approach) from the well pathway is $4 \times 10^{-8} \text{ y}^{-1}$ occurring at about 2250 AD (that is, about 170 years after completion of the final cap); the dominant radionuclides are Cl-36, C-14 and I-129.

LLW Repository Ltd has assessed peak risks via other exposure pathways in the post-closure period to be typically an order of magnitude lower, with C-14 as the dominant radionuclide.

The company has provided a deterministic assessment including a qualitative evaluation of human intrusion events before and during the coastal erosion period. The company carried out a

quantitative assessment of a representative range of potential future human intrusion scenarios and compared the results against the dose guidance range of 3 to 20 mSv y⁻¹. All the intrusion events LLW Repository Ltd has assessed are consistent with this dose guidance range and, consequently, no event has been identified that could give rise to 'severe deterministic injury'.

Requirement R7 of the GRA requires the operator to show that dose thresholds for severe deterministic injury to individual body tissues are unlikely to be exceeded as a result of human intrusion into the facility. We conclude that this requirement has been met.

While we judge that LLW Repository Ltd has met the GRA requirements for radiological assessment, we emphasise that our considerations here do not address all potential environmental detriments, for example visual impacts, which might result from the long-term evolution of the site after the withdrawal of active institutional control and in particular following coastal erosion. Other impacts are addressed by the planning authority as part of the planning permission process.

3.2. Requirement R9: Environmental radioactivity

Requirement R9 of the GRA states that the operator should carry out an assessment to investigate the radiological effects of a disposal facility on the accessible environment both during the period of authorisation and afterwards to show that the environment is adequately protected. We accept that the present day effects on biota from the LLWR are at levels below concern, and that the effects are unlikely to increase significantly during the period of authorisation. However, we recommend that at the next major ESC update the assessment should be updated to make appropriate use of the latest discharge and monitoring data (on a radionuclide specific basis where possible). We note that there has been no specific assessment of effects on the Drigg Coast SAC from the LLWR discharges during the period of authorisation. After closure of the LLWR, dose rates to some organisms may exceed the 10 µGy h⁻¹ screening level. In particular, during the onset of early coastal erosion, dose rates slightly in excess of 100 µGy h⁻¹ could be received by plants and invertebrates inhabiting the storm beach. However, we accept the evidence submitted by LLW Repository Ltd regarding the relative radio-insensitivity of these species, concluding that these doses will cause no perceptible harm. Overall we judge that LLW Repository Ltd has met the requirements of the GRA.

3.3. Requirement R10: Protection against non-radiological hazards

The non-radiological component of the LLWR inventory is subject to considerable uncertainty, generally greater than the uncertainty regarding the radiological component of the inventory. This reflects the lack of relevant waste characterisation and the limitations of the past waste classification systems. Many components of the inventory are identified as 'unknown' in the sense that their physical and chemical composition is not known, but it is known that they include a wide range of hazardous and non-hazardous substances, consistent with what would be expected for a historical landfill taking a wide range of industrial and process waste during the latter part of the 20th century. We will work with LLW Repository Ltd, NDA and waste consignors to improve the characterisation of the non-radioactive inventory of LLW. We are confident that this, together with new WAC and improved consignor awareness, will provide improved inventory information in the future.

LLW Repository Ltd's non-radioactive hydrogeological risk assessment indicates that, throughout the period of authorisation, projected future concentrations of all hazardous substances and non-hazardous pollutants remain below the relevant assessment standards in the regional aquifer underlying the LLWR trenches. Assessed discharges from the LLWR vaults are zero due to the low volumes of leachate likely to be generated and the effectiveness of the leachate management system. During the post-closure period, LLW Repository Ltd assesses concentrations of organic hazardous substances in groundwater underlying the site to be zero or very low. However, it assesses that concentrations of chromium, lead, nickel, molybdenum and zinc will exceed the relevant assessment standards in groundwater under the trenches after several hundred years post-closure. Given that the trench disposals represent a historically permitted disposal, and that the site development plan provides a robust final capping system and a developing BAT strategy for the trench disposals before the installation of the final cap, we consider that LLW Repository

Ltd should be able to provide a BAT solution for the trench disposals during the period of authorisation.

Although we are satisfied that the LLWR currently meets the requirements of the GRA and supplementary guidance to the GRA related to the implementation of the Groundwater Directive, we will require LLW Repository Ltd to produce an updated non-radiological hydrogeological risk assessment before the end of 2017. This updated assessment should have full regard to requirements of the GRA and Environment Agency guidance on hydrogeological risk assessments for landfills. We will work with LLW Repository Ltd to make sure that the non-radiological assessment is presented in such a way as to demonstrate appropriate protection of groundwater (ESC-FI-006).

The 2011 ESC includes non-radiological assessments for the human intrusion and coastal erosion scenarios. Criteria against which these can be judged do not currently exist. We provided feedback on the approach used and the suitability of the assessment parameters. We consider that the assessments provide useful quantification of the nature and significance of the non-radiological hazards and their effects during the operation of the LLWR and subsequently. If our requirements for assessment of non-radiological impacts associated with human intrusion and coastal erosion do not change, then we would not require these assessments to be included in future versions of the ESC.

3.4. Requirement R13: Waste acceptance criteria

We consider that LLW Repository Ltd has met GRA Requirement R13 on waste acceptance criteria. LLW Repository Ltd's radiological capacity assessments are consistent with the dose and risk assessments in the 2011 ESC. However, LLW Repository Ltd needs to consider how the LLWR inventory will be managed in future in relation to the assessed capacity, when assessments may change as a result of new information.

3.5. Summary

In summary, we consider that, for the purpose of our permitting the LLWR, LLW Repository Ltd has adequately addressed those parts of the GRA relevant to the radiological and non-radiological assessments. However, there are a number of areas, as discussed in Section 2 and summarised in Appendix 2 (Recommendations) and Appendix 3 (Forward Issues), where LLW Repository Ltd should make improvements to ensure that the ESC continues to meet the requirements of the GRA.

4. Conclusions

LLW Repository Ltd submitted the 2011 environmental safety case (2011 ESC) against Schedule 9 Requirement 6 of the current Low Level Waste Repository (LLWR) environmental permit. We consider that, in the 2011 ESC and relevant additional information provided as part of the permit application, the company demonstrates an understanding of the effects on human health and the wider environment, during the period of authorisation and subsequently, from the radioactive and non-radioactive hazardous components of past and future disposals to the LLWR. LLW Repository Ltd uses the available information to demonstrate that an appropriate standard of environmental safety is achieved at the LLWR at the present day and at all times in the future.

The overall quality of the 2011 ESC technical assessment submissions is of a high standard. The structure of the 2011 ESC is coherent and the arguments it presents are generally clear, with good referencing of associated and underpinning reports. We conclude that LLW Repository Ltd has presented an ESC that meets Requirement 6 of Schedule 9 of the environmental permit.

We judge that the 2011 ESC has met the Guidance on Requirements for the authorisation of near-surface disposal facilities on land for solid radioactive waste (GRA) pertaining to quantitative assessment of radiological doses and risks. We have no reason to believe that LLW Repository Ltd's assessments have significantly underestimated potential impacts (doses or risks). The company has made a reasonable range of cautious assumptions about future scenarios and human habits and behaviour. However, we consider that LLW Repository Ltd should make efforts to manage uncertainties better and to ensure that all important uncertainties, some of which may currently be implicit, are made explicit in the register of significant uncertainties.

We also consider that LLW Repository Ltd appropriately met GRA Requirement R10 on protection against non-radiological hazards at this stage of the development of the LLWR. The non-radioactive inventory is subject to significant uncertainty, but the company will make efforts to improve this. We will encourage LLW Repository Ltd to ensure that future hydrogeological risk assessments are presented in such a way as to have full regard to requirements of the GRA and Environment Agency guidance on hydrogeological risk assessments for landfills, so as to ensure groundwater protection.

LLW Repository Ltd has included a number of further criteria in the waste acceptance criteria (for example for radium-bearing waste, 'discrete items', 'particles' and non-radioactive components of disposals) and introduced new waste emplacement strategies. These will help reduce potential impacts on people and the environment in the future.

In this document, we identified a number of areas for continued improvement. These are set out in the recommendations and Forward Issues (FIs) that we raised and we will expect LLW Repository Ltd to demonstrate progress against them. Tables of Issue Resolution Forms (IRFs), Recommendations and FIs are listed in Appendices 1, 2 and 3 respectively.

Overall, regarding the topic areas addressed in this report, we consider that LLW Repository Ltd has met the requirements of the GRA and Schedule 9 Requirement 6 of the current LLWR environmental permit through the 2011 ESC and supporting documents. This evidence is of a suitable standard and quality to support an environmental permit decision on future disposals at the site.

5. References

- Applegate, D., Jackson, C. P. and Kelly, M., 2013. Response to Technical Query ESC-ASO-009A Regarding Wells. Amec Report AMEC/200719/001 Issue 1.1. August 2013.
- Baker, A. J., Cummings, R., Shevelan, J. and Sumerling, T. J., 2008. Technical Approach to the 2011 Environmental Safety Case. LLW Repository Ltd Report LLWR/ESC/R(08)10010 Issue 1, November 2008.
- Baker, A., 2012. Response to Issue Resolution Form ESC-RO-SUE-001.A1 (Final Capping of the Trenches). LLWR Technical Memo LLWR/ESC/Mem(12)147.
- Baker, A., 2013a. Response to IRF ESC-TQ-ASO-008: Integration between the Period of Authorisation and Reference Case Assessments. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(13)198.
- Baker, A., 2013b. Approach to Well Calculations. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(13)211.
- Baker, A., 2013c. LLW Repository Ltd. ESC Technical Memo. Comparison of Asbestos Disposal in Landfills and at the LLWR. LLWR/ESC/Mem(13)221.
- Baker, A., 2014. Response to Environment Agency Further Information Notice: Well Pathway calculations and Other Issues. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(13)240.
- Barber, N. and Henderson, E., 2008. LLWR Lifetime Project. Assessment of Human health and Environmental impacts Associated with the Non-radioactive Component of Disposals to the LLWR at Drigg. Nexia Solutions Report (08)9442 Issue 2.
- Beresford, N., Brown, J., Copplestone, D., Garnier-Laplace J., Howard, B.J., Larsson, C.-M., Oughton, D., Pröhl, G. and Zinger, I. (eds.), 2007. D-ERICA: An Integrated Approach to the Assessment and Management of Environmental Risks from Ionising Radiation, EC Contract No.: FI6R-CT-2004-508847, European Commission.
- BNFL, 2002a. Drigg Post-Closure Safety Case: Overview Report, British Nuclear Fuels plc, September 2002.
- BNFL, 2002b. Drigg Operational Environmental Safety Case, British Nuclear Fuels plc, September 2002.
- British Standards Institute, 1998. BS 3598 'Fissile Materials – Criticality Safety in Handling and Processing – Recommendations', ISBN 0 580 27931 6. June 1998.
- Brown, J., 2013. Threshold Doses for Tissue Reactions in a Radiation Protection Context. PHE Memo to Environment Agency. November 2013.
- Brown, J. and Etherington, G., 2011. Health Risks from Radioactive Objects on Beaches in the Vicinity of the Sellafield Site. HPA Report HPA-CRCE-018. April 2011.
- Brown, J. and Oatway, W., 2012. Scoping Health Risk Assessment for Beach Users at Dalgety Bay to Support Advice to Scottish Government Given in February 2012. HPA Report HPA-CRCE-040. October 2012.
- Cummings, R., 2013. Letter: EA LLWR 13 0198 03 Permit Application Clarification Cases 12 11 13.
- Defra and Environment Agency, 2002. Contaminants in Soil: Collation of Toxicological Data and Intake Values for humans. Chromium. Environment Agency R&D Publication TOX4.
- Dickinson, M. and Kelly, M., 2011. Technical Note: Review of Non-radiological Inventory Data. Serco Report SERCO/TAS/003756/001, Issue 2, April 2010.
- EC, 1992. Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora. Official Journal L 206, 22.7.1992, p.7–50.

Eden, L. and Barber, N., 2007, Assessment of the Impact of Radioactive Disposals and Discharges at the LLWR on the Ecosystem. Nexia Solutions Report (07) 8310: Issue 3, April 2007.

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

Environment Agency, 2005b. The Environment Agency's Explanatory Document to Assist Public Consultation on Proposals for the Future Regulation of Disposals of Radioactive Waste on/from the Low-Level Waste Repository at Drigg, Cumbria Operated by British Nuclear Group Sellafield Ltd, June 2005.

Environment Agency, 2009a. 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.

Environment Agency, 2009b. Contaminants in Soil: Updated Collation of Toxicological Data and Intake Values for humans. Chromium. Environment Agency Science Report SC050021/TOX3.

Environment Agency, 2009c. Contaminants in Soil: Updated Collation of Toxicological Data and Intake Values for humans. Nickel. Environment Agency Science Report SC050021/TOX8.

Environment Agency, 2009d. Human Health Toxicological Assessment of Contaminants in Soil. Environment Agency Science Report SC050021/SR2.

Environment Agency, 2009e. Updated Technical Background to the CLEA Model. Environment Agency Science Report SC050021/SR3.

Environment Agency, 2009f. CLEA Software (Version 1.05) Handbook. Environment Agency Science Report SC050021/SR4.

Environment Agency, 2011. Horizontal guidance Note H1 - Annex J 3. Additional Guidance for Hydrogeological Risk Assessments for Landfills and the Derivation of Groundwater Control Levels and Compliance Limits. Environment Agency Report GEHO0212BULU-E-E, Version 2.

Environment Agency, 2013. Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation: Supplementary Guidance Related to the Implementation of the Groundwater Directive.

Environment Agency, 2014a. Form HR02: Proforma For Stage 3 Appropriate Assessment, Drigg Low Level Waste Repository, Environmental Permit Variation EPR/YP3293SA/V002, July updated October 2014.

Environment Agency, 2014b. Request for further information to support your application EPR/YP3293SA/V002. Reference LLWR consultation/14/001/O. 20 May 2014.

Environment Agency, 2015a. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Overview Report, Issue 1.

Environment Agency, 2015b. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Safety Case Management, Issue 1.

Environment Agency, 2015c. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Inventory and near Field, Issue 1.

Environment Agency, 2015d. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Site Understanding, Issue 1.

Environment Agency, 2015e. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Optimisation and Engineering, Issue 1.

Environment Agency, 2015f. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Issue Resolution Forms, Issue 1.

Environment Agency, 2015g. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Forward Issues, Issue 1.

Environment Agency, 2015h. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Issue Assessment Forms, Issue 1.

Environment Agency, 2015i. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Non-technical Summary, Issue 1.

Environment Agency, Scottish Environment Protection Agency and Department of the Environment for Northern Ireland, 1997. Radioactive Substances Act 1993 - Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation. Environment Agency, Bristol.

Environment Agency, Northern Ireland Environment Agency and Scottish Environment Protection Agency, 2009. Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation. Environment Agency, Bristol.

Fairhurst, A., 2013. Audit of 2011 ESC Groundwater Pathway Calculations. Letter from A. Fairhurst of the Environment Agency to R. Cummings of LLW Repository Ltd, Reference LLWR/13/015/O. 8 November 2013.

Galson Sciences Ltd and Environment Agency, 2005. Report of the Radiological Capacity Review Group, Galson Sciences Ltd Report 0454-2.

Hartley L., Applegate D., Couch M., Hoek J., Jackson C. P. and James M., 2011. Hydrogeological Modelling for LLWR 2011 ESC, Serco Report No. SERCO/TCS/E003632/007 Issue 3, April 2011.

Hay, S., 2011. Criticality Assessment for the LLWR 2011 ESC (Extended Disposal Area). Serco Report TCS/004817/002 Version 1. April 2011.

Hicks, T. W. and Baldwin, T.D., 2011. Assessment Calculations for Human Intrusion for the 2011 LLWR ESC. Galson Sciences Ltd Report 0977-3 Version 2.

HPA, 2008. HPA Advice on Radon Protective Measures in New Buildings, HPA Board Meeting 21 May 2008.

IAEA, 1998. Safe Handling and Storage of Plutonium. Safety Reports Series No. 9. IAEA, Vienna.

IAEA, 2003. Derivation of Activity Limits for the Disposal of Radioactive Waste in Near Surface Disposal Facilities, IAEA TECDOC 1380. IAEA, Vienna.

IAEA, 2005. Regulations for the Safe Transport of Radioactive Material, 2005 Edition. IAEA Document TS-R-1. IAEA, Vienna.

ICRP, 2009. Environmental Protection: Transfer Parameters for Reference Animals and Plants ICRP Publication 114, Ann. ICRP 39 (6), 2009.

Jackson, D., 2012. Response to Issue Resolution Form ESC-TQ-ASO-005: Human Intrusion – Aircraft Impact. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(12)175. September 2012.

Jackson, D., 2013a. Response to IRF ESC-RO-ASO-001 Impacts to Non-human Biota During the Period of Authorisation. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(13)202.

Jackson, D., 2013b. Response to IRF ESC-RO-ASO-002 Post-closure Impacts to Non-human Biota. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(13)203.

Jackson, D., 2013c. Response to IRF ESC-RO-ASO-003 Assessment of Impacts to Non-human Biota Associated With Intrusion into Waste Materials. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(13)204.

Jackson, C. P., Couch, M., Yates, H., Smith, V., Kelly, M. and James, M., 2011. Elicitation of Uncertainties for LLWR. Serco Report SERCO/E.003796/010 Issue 2, April 2011.

Jackson, C. P. and Kelly, M., 2013. Response to Technical Query Regarding Wells, Amec Report D.000215/001 Issue 2.

Kelly, M., 2012a. Radiological Capacities for the RDA and EDA LLWR Repository Designs for the Groundwater Pathway. Serco Report SERCO/E005758/001, January 2012.

Kelly, M., 2012b. Technical Note on the Non-radiological Impacts of Leaching of LLW Grout. Amec Technical Note D000058 / SF0005008 Issue 2.

Kelly, M., 2012c. Reconciliation of Differences Between the RDA and EDA Calculations in the 2011 ESC for the Groundwater Pathway. Serco Report SERCO/E005758/002, January 2012.

Kelly, M., Applegate, D., Berry, J.A., Thorne, M.C. and Jackson, C.P., 2011. Radiological Assessment Calculations for the Groundwater Pathway for the LLWR 2011 ESC, Serco Report SERCO/TCS/E003796/011 Issue 6, April 2011.

Kelly, M. and Berry, J. A., 2011. Non-Radiological Assessment Calculations for the LLWR 2011 ESC. Serco Report Serco/TAS/003796/012 Issue 5.

Kelly, M. and Berry, J. A., 2013. Radiological and Non-radiological Capacities for the LLWR in the Presence of EDTA. Amec Report AMEC SF6817/001, September 2013.

Lean, C.B., Lennon, C. L., Graham, J., Kwong, S. and Tahar, B., 2005. Future Radiological Capacity of the Drigg Low Level Radioactive Waste Disposal Site, BNFL Report NSTS (04)5096 Issue 2.

Limer, L. M. C. and Thorne, M. C., 2011. Assessment Calculations for Radon for the LLWR 2011 ESC. Quintessa Report QRS-1443ZG-1, Version 3, April 2011.

Limer, L. M. C. Thorne, M. C. and Towler, G.H., 2011. Assessment Calculations for C-14 Labelled Gas for the LLWR 2011 ESC. Quintessa Report QRS-1443Z-1 Version 4.0, April 2011.

LLW Repository Ltd, 2011a. The 2011 Environmental Safety Case. Environmental Safety During the Period of Authorisation. LLW Repository Ltd Report LLWR/ESC/R(11)10027, May 2011.

LLW Repository Ltd, 2011b. The 2011 Environmental Safety Case. Environmental Safety Case – Main Report. LLW Repository Ltd Report LLWR/ESC/R(11)10016, May 2011.

LLW Repository Ltd, 2011c. The 2011 Environmental Safety Case. Assessment of Long-term Radiological Impacts. LLW Repository Ltd Report LLWR/ESC/R(11)10028. May 2011.

LLW Repository Ltd, 2011d. The 2011 Environmental Safety Case. Waste Acceptance. LLW Repository Ltd Report LLWR/ESC/R(11)10026. May 2011.

LLW Repository Ltd, 2011e. The 2011 Environmental Safety Case. Assessment of Non-radiological Impacts. LLW Repository Ltd Report LLWR/ESC/R(11)10029, May 2011.

LLW Repository Ltd, 2011f. The 2011 Environmental Safety Case. Assessment of an Extended Disposal Area'. LLW Repository Ltd Report LLWR/ESC/R(11)10035, May 2011.

LLW Repository Ltd, 2011g. The 2011 Environmental Safety Case. Site Evolution. LLW Repository Ltd Report LLWR/ESC/R(11)10023.

LLW Repository Ltd, 2012a. Updated Assessment Calculations based on the 2010 UK Radioactive Waste Inventory. LLW Repository Ltd Report LLWR/ESC/R(12)10045, Issue 1. March 2012.

LLW Repository Ltd, 2012b. Scoping Assessment of Carbon-14 Bearing Gas. LLW Repository Ltd Report LLWR/ESC/R(12)10046. February 2012.

LLW Repository Ltd, 2012c. Assessment of Radiological Impacts in the Very Long Term if the LLWR is not Eroded. LLW Repository Ltd Report LLWR/ESC/R(12)10047 Issue 1. February 2012.

LLW Repository Ltd, 2013a. Assessment of Carbon-14 Bearing Gases. LLW Repository Ltd Report LLWR/ESC/R(13)10059. September 2013.

LLW Repository Ltd, 2013b. 2011 Low Level Waste Repository Environmental Safety Case: Features, Events and Processes and Uncertainty Tracking System. LLW Repository Ltd Excel Spreadsheet Reference MASTER 2011 FEP List_LLWR04127061103_0_2 - ajb7 macro Jan 2013.

LLW Repository Ltd, 2013c. Developments Since the 2011 ESC. LLW Repository Ltd Report LLWR/ESC/R(13)10058 Issue 1.

LLW Repository Ltd, 2013d. The LLWR Environmental Safety Case. Application to Vary LLWR's Permit. LLW Repository Ltd Report LLWR/ESC/R(13)10057, Issue 1.

LLW Repository Ltd., 2014. Waste Services Contract. Waste Acceptance Criteria - Low Level Waste Disposal. LLW Repository Ltd Report WSC-WAC-LOW - Version 4.0 - March 2014.

Mobbs, S. and Sumerling, T., 2012. Assessment of impact of heterogeneity at the particulate scale. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(12)146, May 2012.

Natural England, 2013. EUNIS Biotope Map Ravenglass – Seascale.

NDA, 2010. Nuclear Decommissioning Authority. UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry. August 2010.

NDA, 2011. Nuclear Decommissioning Authority. The 2010 UK Radioactive Waste Inventory.

NDA, 2014. Nuclear Decommissioning Authority. 2013 UK Radioactive Waste Inventory. Available at <https://www.nda.gov.uk/ukinventory/>

Oatway, W. B. and Higgins, N., 2013. Review of Assessments of Prospective Exposure to Low Activity Sources or Particulate Material following Coastal Erosion of, and Intrusion into, the LLWR. HPA report to Environment Agency. April 2013.

Penfold, J., 2013a. 2011 ESC: Revision of Calculated Dust and Direct Radiation Doses for the Period of Authorisation. Extended Disposal Area. Quintessa Report QRS-1433ZB-REDA.

Penfold, J., 2013b. 2011 ESC: Revision of Calculated Dust and Direct Radiation Doses for the Period of Authorisation. Reference Disposal Area. Quintessa Report QRS-1433ZB-RRDA.

Putley, D., Hay, S., Jackson, C.P. and Harper, A., 2011. Criticality Assessment for the LLWR 2011 ESC. Serco Report SERCO/TCS/004817/001 Version 2. April 2011.

Shevelan, J., 2012. ESC Technical Memo: Response to Environment Agency Query About Vault 8 Flow Paths. LLWR Technical Memo LLWR/ESC/Mem(12)183a, October 2012.

Shevelan, J., 2013. Assessment Code Documentation and Quality Assurance. LLW Repository Ltd Technical memo LLWR/ESC/MeM(13)206. March 2013.

SKB, 2010. Model Summary Report for the Safety Assessment SR-Site. SKB Technical Report TR-10-51. December 2010.

Small, J., Lennon, C. and Abrahamsen, L., 2011. GRM Near Field Modelling for the LLWR 2011 ESC. NNL Report (10)11233.

Smith, R. E., 2014. Advice to Environment Agency Assessors on the Disposal of Discrete Items, Specific to the Low Level Waste Repository, Near Drigg, Cumbria. Issue 1.0, January 2014.

Soetens, T. and Jackson, D., 2013. Collective Dose to populations of UK, Europe and the World for coastal erosion of the LLWR. LLW Repository Ltd Technical Memo LLWR/ESC/MeM(13)209. April 2013.

Speed, C. and Fretwell, B., 2010. A Report on Hydrogeochemistry of Non-radioactive Contaminants in LLWR Leachate and Groundwater, Entec Report 27634 Issue 1.

Sumerling, T. J., 2012a. Coastal and Marine Biosphere and PEG Definitions. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(12)159. July 2012.

Sumerling, T. J., 2012b. Radiological Impacts During Coastal Erosion and Potential for Exposure to Undiluted Wastes and Most Highly Contaminated Foodstuffs. LLW Repository Ltd Technical Memo LLWR/ESC/Mem (12)167. October 2012.

Sumerling, T. J., 2013a. Assessment of Discrete Items and Basis for WAC. LLW Repository Ltd Technical Memo LLWR/ESC/R(13)10055.

Sumerling, T. J., 2013b. Assessment of Individual Radioactive Particles and WAC for Active Particles. LLW Repository Ltd Report LLWR/ESC/R(13)10056. August 2013.

Sumerling, T. J., 2013c. Response to IRF ESC-TQ-ASO-010 Potential radiological impact from drilling into Sellafield source consignments. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(13)210. April 2013.

Sumerling, T. and Jackson, D., 2012. Response to IRF ESC-RI-ASO-013: Dose Calculations for Human Intrusion into Radioactive Sources. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(12)165. September 2012.

Sumerling, T. and Jackson, D., 2013. Response to IRF ESC-RI-ASO-014: Total Doses to Representative Persons During the Period of Authorisation. LLW Repository Ltd Technical memo LLWR/ESC/Mem(12)177. February 2013.

Sumerling, T. and Mobbs, S., 2012. Response to IRF ESC-RI-ASO-011: Inventory Heterogeneity and Events in Human Intrusion Dose Assessment. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(12)148. June 2012.

Taylor, F. and Sumerling, T., 2013. Assessment of the Potential for Waste Fires after the Period of Authorisation. LLW Repository Ltd Technical Memo LLWR/ESC/Mem(19)194. February 2013.

Thorne, M. C., 2009. Data for Exposure Groups and for Future Human Actions and Disruptive Events. MTA/P0022/2007-4: Issue 3, July 2009.

Thorne, M. C., Kelly, M. and Lambers, B., 2010. Consolidation and Documentation of Biosphere Models. Serco Report SERCO/TAS/E003796/005 Issue 1, March 2010.

Thorne, M.C. and Schneider, S., 2011. Assessment of the Impacts on Non-human Biota for the LLWR 2011 ESC, Serco Report SERCO/TCS/00435/01 Issue 2, April 2011.

Towler, G. H., Penfold, J. S. S., Limer, L. M. C. and Paulley, A., 2011. Assessment Calculations for Coastal Erosion for the LLWR 2011 ESC. Quintessa Report QRS-1443ZC-R1 Version 3.0.

URS, 2014. LLWR: Permit Variation. Habitats Regulations Assessment Signposting Document. Draft for EA Review 2014-03-04.

Wilkins, B. T., Harrison, J. D., Smith, K. R., Phipps, A. W., Bedwell, P., Etherington, G., Youngman, M., Fell, T. P., Charles, M. W., Darley, P. J. and Sh Aydarous, A., 2006. Health Implications of Fragments of Irradiated Fuel at the Beach at Sandside Bay Module 6: Overall Results. Scottish Environment Protection Agency Report RPD-EA-03-2006.

Wood, M. D., Marshall, W. A., Beresford, N. A., Jones, S. R., Howard, B. J., Copplestone, D. and Leah, R. T., 2008, Application of the ERICA Integrated Approach to the Drigg coastal sand dunes, J. Environ. Radioact., 99, 1484-1495.

6. Appendix 1 - Issue Resolution Forms

6.1. Introduction

As outlined in Section 1.3, Issue Resolution Forms (IRFs) are detailed records of concerns and queries raised as part of our review of the ESC. Each IRF includes one or more actions. LLW Repository Ltd was required to provide a substantive response to the action(s) specified on the IRF by the specified date(s). Issues were only closed out when we had determined that the LLW Repository Ltd response adequately addresses the issue.

6.2. Assessments Issue Resolution Forms

Summaries of Regulatory Issues (RIs), Regulatory Observations (ROs) and Technical Queries (TQs) raised during our review of the 2011 assessments review work are provided in Table 2, Table 3 and Table 4 respectively. These IRFs are reproduced in full in Environment Agency (2015f). The IRFs are not sequentially numbered. This is because some IRFs were identified as possible queries but not issued, for example, following further detailed review of information provided in support of the 2011 ESC, or following on from clarifications provided by LLW Repository Ltd. All IRFs have now been closed.

Table 2 Regulatory Issues

Regulatory Issue number	Title	Summary
ESC-RI-ASO-005	Assessment of impacts of C-14-bearing gases	We requested that LLW Repository Ltd should carry out an adequately underpinned cautiously realistic assessment of the conditional risks from C-14-bearing gases.
ESC-RI-ASO-006	Very long-term impacts if the LLWR does not erode	We requested that LLW Repository Ltd provide an explicit case for the acceptability of risks associated with potential very long-term impacts if the facility were not to be eroded.
ESC-RI-ASO-007	Treatment of decay chains in deriving WAC for groundwater pathway	We asked LLW Repository Ltd to provide either an explanation of how the groundwater pathway assessment results were correctly used in the derivation of activity limits for the WAC or corrected calculations of the relevant limits.
ESC-RI-ASO-010	Inventory heterogeneity and PEGs in coastal erosion dose assessment	We asked LLW Repository Ltd to carry out further assessments to explore the impact of waste heterogeneity at the particulate scale for an additional range of PEGs.
ESC-RI-ASO-011	Inventory heterogeneity and events in human intrusion dose assessment	We asked LLW Repository Ltd to carry out further assessments to explore the impact of waste heterogeneity on human intrusion events.
ESC-RI-ASO-012	Dose calculations	We asked LLW Repository Ltd to carry out

Regulatory Issue number	Title	Summary
	from marine foodstuff during coastal erosion	further dose assessments to explore the potential human impact of higher activity particulate material via the marine foodstuffs pathway.
ESC-RI-ASO-013	Dose calculations for human intrusion into radioactive sources	We asked LLW Repository Ltd to carry out further human intrusion assessments for a range of known deposits of radioactive sources at LLWR.
ESC-RI-ASO-014	Total doses to representative person from LLWR during the period of authorisation	We asked LLW Repository Ltd to identify whether there are candidate critical groups who may be exposed to more than one exposure pathway during the period of authorisation and, if so, to present combined doses covering the entire period of authorisation.
ESC-RI-INF-001	Impact of 2010 Inventory	We requested an assessment of the implications of the 2010 UKRWI for the 2011 ESC and a demonstration that the 2011 ESC (as amended if necessary) is consistent with the best available information on future waste arisings.
ESC-RI-INF-002	Impact of grout on vault leachate composition	We requested further information on the impact of the leaching of components from the grout on the composition of the leachate from the site. In particular we were concerned about the impact of hazardous components such as Cr(VI).

Table 3 Regulatory Observations

Regulatory Observation number	Title	Summary
ESC-RO-ASO-001	Impacts to non-human biota during the period of authorisation	We asked LLW Repository Ltd to provide further assessment of radiological impacts to non-human biota during the period of authorisation to provide adequate assurance that impacts to non-human biota in all relevant ecosystems during this period will be low.
ESC-RO-ASO-002	Post-closure impacts to non-human biota	We asked LLW Repository Ltd to make a number of improvements to the post-closure assessment of radiological impacts on non-human biota as presented in the 2011 ESC.
ESC-RO-ASO-003	Assessment of non-human biota impacts associated with intrusion into waste materials	We asked LLW Repository Ltd to re-assess dose rates to non-human biota following intrusion into the facility during coastal erosion, including consideration of exposures to undiluted waste materials to biota both making transitory use of the cliffs

Regulatory Observation number	Title	Summary
		and biota permanently residing in the cliff environment.
ESC-RO-ASO-004	Management of uncertainty	We requested that LLW Repository Ltd provided evidence to show how significant uncertainties had been identified and managed across the 2011 ESC in a systematic manner. We also asked the company to explain what arrangements are in place to address key or significant uncertainties and describe what measures will be carried out to evaluate and improve confidence in the modelling projections.
ESC-RO-ASO-005	Safety functions	We asked LLW Repository Ltd to clarify the safety concept for the LLWR and explain why a safety function approach had not been formally used in the 2011 ESC. We also requested a copy of the FEPs and uncertainty tracking system.
ESC-RO-ASO-006	Effective linkage between the Environmental Safety Case and single item limits within the Waste Acceptance Criteria	We asked LLW Repository Ltd to identify the nature and extent of discrete items, which have been, or could be, disposed legally within the constraints of the WAC, where those items could challenge assumptions made within the ESC due to high-specific activity or otherwise. We asked the company to complete an assessment of the environmental impacts associated with the disposal of single items and propose appropriate WAC to control any unacceptable impacts. We also asked the company to consider past disposals of this nature, assess the possible implications and identify any resulting action required.
ESC-RO-ASO-007	Environmental Safety Case assessment code documentation and quality assurance	We asked LLW Repository Ltd to provide a list of the key models and codes used in the 2011 ESC and summarise how the different models interact and how information is transferred between different models and codes. We also requested details of quality assurance measures for the use of each model and code.
ESC-RO-SUE-007	The use of future monitoring to reduce uncertainties in the ESC	We asked LLW Repository Ltd to provide evidence of how the forward monitoring programme will be developed throughout the period of authorisation and linked to the ESC to reduce key uncertainties in the ESC.

Table 4 Technical Queries

Technical Query number	Title	Summary
ESC-TQ-ASO-003	Coastal and marine biosphere and PEG definitions	We requested that LLW Repository Ltd justify the discrepancies observed between the groundwater pathway and the coastal erosion pathway biosphere models and PEG definitions for the coastal/marine environment.
ESC-TQ-ASO-004	Incorporation of sea level change in the ConnectFlow model	We asked LLW Repository Ltd to provide evidence that the reference case and delayed coastal erosion scenarios for the groundwater pathway assessment and underpinning models encompass a reasonable range of future environmental risks.
ESC-TQ-ASO-005	Human intrusion - aircraft impact	We asked LLW Repository Ltd to further justify the screening out of aircraft impact from the human intrusion calculations presented in the 2011 ESC.
ESC-TQ-ASO-006	Radiological impacts to humans from direct shine and foodstuff pathways in a coastal erosion scenario that involves close contact with exposed, undiluted wastes	We asked LLW Repository Ltd to consider further scenarios involving contact with undiluted waste during coastal erosion.
ESC-TQ-ASO-008	Integration between the period of authorisation and reference case assessments	We asked LLW Repository Ltd to justify the differences between the groundwater pathway assessment models for the period of authorisation and the post-closure period. We requested updated presentation of the non-radiological assessment model to cover the period of authorisation and post-closure period combined.
ESC-TQ-ASO-009	Well calculations	We asked LLW Repository Ltd to clarify a number of queries on the groundwater pathway well calculations, including clarification of the probability of a well existing, heterogeneity in groundwater flow, impact of landscape change and the use of probabilistic calculations.
ESC-TQ-ASO-009a	Reply to LLWR's response to ESC-TQ-ASO-009 well calculations	LLW Repository Ltd's response to ESC-TQ-ASO-009 did not fully address all our queries. Therefore, we asked the company to undertake additional calculations illustrating the effect of heterogeneity on well pathway impacts.
ESC-TQ-ASO-	Human intrusion into	We asked LLW Repository Ltd to calculate

Technical Query number	Title	Summary
010	sources	the consequences of drilling into the 'worst-case' source pot (of the five known source pots disposed of to Vault 8) containing sources from Sellafield.
ESC-TQ-INF-035	Impacts on the radon gas pathway	We asked LLW Repository Ltd to clarify a number of statements presented in the 2011 ESC concerning radon gas release through the engineered cap. We sought confidence that the radon assessment in the 2011 ESC presented a worst-case scenario.
ESC-TQ-SUE-030	Development and assessment of waste fire scenarios during the post operational period	We asked LLW Repository Ltd to identify waste streams which could exhibit pyrophoric or exothermic properties. We also asked for the identification and assessment of reasonable post-closure fire scenarios.

7. Appendix 2 - Recommendations

7.1. Introduction

Recommendations raised as a result of our review of the 2011 ESC represent areas where we see scope for possible improvement or development, but which are relatively minor in nature relative to FIs. As a matter of good practice we expect LLW Repository Ltd to address these recommendations and will expect a mechanism to be put in place to track them.

7.2. Assessments recommendations

Table 5 summarises the recommendations made in this report. Further details are provided in Section 2.

Table 5 Assessments recommendations

Recommendation number	Summary of recommendation
ASS1	A future period of authorisation assessment should include a more thorough assessment of scenario, conceptual and parameter uncertainties.
ASS2	We recommend that future versions of the ESC seek to fully integrate the assessments for the period of authorisation and the post-closure period.
ASS3	We recommend LLW Repository Ltd undertakes a reassessment of doses and risks against the most recent version of the UKRWI as part of the company's submission for the next major ESC update.
ASS4	We recommend that LLW Repository Ltd assesses the implications of changes to the non-radiological component of the 2013 UK national inventory on the 2011 ESC.
ASS5	We recommend that LLW Repository Ltd considers a sensitivity study of the effects of inventory heterogeneity and configuration of the groundwater model on the assessment results in future assessments.
ASS6	We recommend that LLW Repository Ltd further explores the effect of cliff recession on the geosphere-biosphere interface in future ESCs. This should take into account the uncertainty associated with projected groundwater flow pathways in terms of pathway length, spatial variability and location of discharge to the beach.
ASS7	We recommend that PEG habits for each pathway, and associated uncertainties, are more transparently documented in future ESCs.
ASS8	Future versions of the ESC should assess the sensitivity of assessment calculations to significant assumptions and parameters in the biosphere.
ASS9	LLW Repository Ltd should build confidence in its future ESCs by assessing the effects on calculated results of the choices made when developing and configuring models.
ASS10	LLW Repository Ltd should present risks together with a clearer indication of the likelihood associated with the potential exposure to enable its context to be more readily understood in future ESCs.
ASS11	LLW Repository Ltd should consider a consistent set of variant calculations to take account of conceptual model and parameter uncertainty in both detailed process-scale models and assessment models, or explains why this has not been done, in future assessments.

Recommendation number	Summary of recommendation
ASS12	LLW Repository Ltd should provide a better explanation of how uncertainties are identified and prioritised for consideration in the probabilistic assessment in future ESCs. The company should also clarify the relationships between parameter ranges in probabilistic calculations and data used in variant deterministic calculations to build confidence in the overall robustness of the ESC.
ASS13	LLW Repository Ltd should undertake a structured analysis of uncertainty as part of a future ESC. This should prioritise uncertainties for assessment and consider the use of probabilistic assessment as the main way of comparing against the risk guidance level, where viable.
ASS14	We recommend that LLW Repository Ltd assesses the sensitivity of estimated impacts arising from a well to the location of the coastline and the effects of saline intrusion.
ASS15	We recommend that future groundwater pathway assessments would benefit from a more detailed consideration of spatial heterogeneity.
ASS16	We recommend that LLW Repository Ltd develops the groundwater flow model so that projections of spatial variability of contaminant concentrations in the groundwater are more readily able to be compared directly with the assessment calculations.
ASS17	We recommend that LLW Repository Ltd undertakes further investigation into the nature and significance of uncertainties associated with the well pathway assessment, such as the potential for future groundwater use.
ASS18	LLW Repository Ltd should improve the clarity of its presentation of complex assessment areas such as the effect of spatial heterogeneity in the hydrogeological properties of the geological units on the migration of contaminated groundwater and future groundwater use in future assessments.
ASS19	We recommend that present-day and historical patterns of human behaviour should be considered when developing analogues for potential future human behaviour.
ASS20	We recommend that LLW Repository Ltd reviews the ESC to make sure that the assumptions and conclusions are still applicable when the final decision on whether the gas vent in the final cap will be left open or closed is made. If not, this issue should be addressed in future updates of the ESC.
ASS21	We recommend that future ESCs should have a greater consistency between the models for different pathways, including both physical representations of the biosphere and PEG habits, and that significant differences should be justified and implications on impacts identified.
ASS22	We recommend that a future coastal erosion assessment includes a thorough review of the implications of dilution of waste material in the cliff, beach and foreshore, covering both loose trench waste and vault wastes with higher integrity.
ASS23	LLW Repository Ltd has not carried out quantitative assessments of higher activity particles from other waste materials such as MOX fuels, irradiated highly-enriched uranium, weapons-grade enriched uranium and plutonium. Whilst particles of these waste types are not expected to be disposed of in large quantities at the LLWR, we recommend that LLW Repository Ltd includes these waste types in future ESC assessments for completeness.

Recommendation number	Summary of recommendation
ASS24	We recommend that LLW Repository Ltd demonstrates that the stacking of currently stored radium-bearing waste will be optimised when they are emplaced for disposal in the BAT assessment that the company intends to undertake on waste stored in Vault 8.
ASS25	We recommend that LLW Repository Ltd further assesses the likelihood and radiological consequences of a shallow waste fire occurring in the trench waste during the erosion sequence.
ASS26	We recommend that LLW Repository Ltd audits future assessment calculations for all pathways against the FEP list to make sure that all relevant FEPs are considered.
ASS27	We recommend that, in order to clarify the modelling approach, LLW Repository Ltd should pay greater attention to documenting linkages between assessment models in future ESCs.
ASS28	We recommend that more discussion is provided about model design and model selection in future ESC updates.
ASS29	We recommend that at the next major ESC update the non-human biota assessment uses the latest (radionuclide specific where possible) discharge and monitoring data.
ASS30	We recommend that future non-human biota assessments should include all relevant radionuclides, using surrogate data as required, or substantiate the reasons for, and significance of, their omission
ASS31	We recommend that LLW Repository Ltd fully documents all input data to the non-human biota assessment, including peak modelled environmental concentrations and times for each peak.
ASS32	We recommend that LLW Repository Ltd explores the effect of uncertainties in projections of future radionuclide environmental concentrations in future non-human biota assessments.
ASS33	We recommend that future non-human biota assessments concentrate on those species that are observed today and assume that similar populations will exist in the future.
ASS34	We recommend that the potential for harm to non-human biota coming into contact with high activity particles is considered further in future assessments.
ASS35	We recommend that LLW Repository Ltd further considers how it makes better use of trench and vault leachate monitoring data to support the development of the trench, and potentially the vault, source terms and ensure that leachate is appropriately characterised to support this need.
ASS36	We recommend that LLW Repository Ltd carries out further work to confirm the non-radioactive contaminant leachability data used in the assessment of leaching from grout and that it should include grout in the source term for future non-radiological assessments of the vaults.
ASS37	We recommend that LLW Repository Ltd should pursue any opportunity to improve its understanding of the non-radiological component of the inventory.
ASS38	We recommend that LLW Repository Ltd improves the quality of the inventory records of past and future asbestos disposals to the LLWR.

Recommendation number	Summary of recommendation
ASS39	We recommend that LLW Repository Ltd improves the integration of the period of authorisation and post-closure non-radioactive contaminant assessments. This integration is especially important for reporting on compliance with non-radiological performance requirements. (Also see Recommendation ASS2.)
ASS40	<p>We recommend that LLW Repository Ltd improves future hydrogeological risk assessments by:</p> <ul style="list-style-type: none"> • ensuring that the environmental monitoring and sampling programme can achieve necessary baseline and operational non-radiological monitoring capability in line with landfill guidance (Environment Agency 2011) • working to improve estimates of the hazardous and non-hazardous components of trench and vault leachate, taking into account future disposals and utilising any opportunity to gain better information • fully integrating the period of authorisation and post-closure assessments • presenting a more comprehensive assessment of uncertainties and their effects, including the use of probabilistic models as appropriate • taking better account of the requirements for landfill risk assessment (Environment Agency 2011) wherever possible • taking into account the latest Environment Agency guidance on setting compliance points and standards for assessing inputs of hazardous substances to groundwater • documenting the assessment in a stand-alone report containing all relevant monitoring, conceptualisation and assessment information and avoiding the need to refer to numerous supporting documents • taking into account changes in the designation of hazardous substances by JAGDAG.
ASS41	We recommend that LLW Repository Ltd assesses the impact of non-radioactive soil contamination using the latest models and data and derives site-specific screening criteria where appropriate.
ASS42	We recommend that ingestion of seafood is considered in any non-radioactive contaminant assessment for the coastal erosion pathway.
ASS43	We recommend that LLW Repository Ltd takes into account heterogeneity in the distribution of non-radiological contamination in any future assessments of coastal erosion.
ASS44	We recommend that LLW Repository Ltd carries out a more detailed review of the probable biodegradation of organic contaminants, taking into account the expected biogeochemical evolution of the vaults and trenches, within any coastal erosion assessment.
ASS45	LLW Repository Ltd should use an approach more closely in line with current UK practice for the assessment of human intrusion impacts associated with exposure to non-radiological contaminants in soil. We would also expect any future non-radiological assessment of human intrusion to include consideration of heterogeneity and uncertainty, including the potential for exposure to organic contaminants.
ASS46	We recommend that the non-radiological capacity assessment is subject to a comprehensive review at the next major ESC update so as to take account of the most recent non-radiological HRA.

8. Appendix 3 - Forward Issues

8.1. Introduction

Forward Issues (FIs) raised as a result of our review of the 2011 ESC represent areas that we believe require, or could benefit from, further work or clarification in the future.

FIs are categorised in terms of the importance of the issue (for example the scope for improvement of the ESC against the GRA) and likely effort required to address the issue (Table 6).

Table 6 FI categories

Category	Priority	Explanation
A1	More important, shorter term	<p>An issue that is expected to be important in supporting the delivery of an acceptable update of the ESC in the future and where we believe there is a need to address the issue well in advance of the next major ESC update.</p> <p>LLW Repository Ltd is likely to need to provide substantial additional information, or to significantly change approach. We expect plans to be put in place to address these issues and ongoing reports on progress. Such reporting might, for example, include detailed plans of action, descriptions of proposed approaches, models or data, or results from interim or provisional analyses.</p>
A2	More important, long-term	<p>An issue that is expected to be important in supporting the delivery of an acceptable update of the ESC in the future, but where this improvement can be delivered over relatively long timescales.</p> <p>LLW Repository Ltd is likely to need to provide substantial additional information, or to significantly change approach. We expect ongoing but infrequent reports on progress with these issues. Such reporting might, for example, include detailed plans of action, descriptions of proposed approaches, models or data, or results from interim or provisional analyses.</p>
B1	Important, shorter term	<p>Issues of less importance than category 'A'. LLW Repository Ltd will need to provide some additional information, evidence or analysis well in advance of the next major ESC update. Plans should be put in place to deliver this information. Generally we estimate the level of effort needed to address this category of issue will be substantially less than for category A. We expect reports on progress with these issues, but with less emphasis than for Category A.</p>
B2	Important, long-term	<p>Issues of less importance than category 'A'. LLW Repository Ltd will need to provide some additional information, evidence or analysis, but over relatively long timescales or as part of the next ESC update. Generally we estimate the level of effort needed to address this category of issue will be substantially less than for category A. We expect only infrequent reports on progress with these issues and with less emphasis than for Category A.</p>
C	Additional evidence /	<p>Of lesser importance but of value in improving the ESC. Issues where we require limited reporting or information in advance of</p>

Category	Priority	Explanation
	improvements in approach	any updated ESC.

We will agree with LLW Repository Ltd when and how it intends to address these issues, and will track progress made to resolve them.

8.2. Assessment Forward Issues

A summary of FIs raised during our review of the 2011 ESC assessment work is provided in Table 7. FIs are reproduced in full in Environment Agency (2015g).

Table 7 Assessment Forward Issues

Forward Issue number	Title	Categorisation	Summary of issue
ESC-FI-003	Revised borehole fire assessment	C	LLW Repository Ltd should present a 'what if' type assessment of a deep seated fire occurring during the construction or operation of a borehole drilled into trench waste.
ESC-FI-005	Use of monitoring to reduce uncertainties in the ESC	B1	LLW Repository Ltd to collate and integrate monitoring objectives, strategies and procedures in a single document, so as to provide evidence of how the forward monitoring programme will be implemented and developed throughout the period of authorisation and linked to the ESC to reduce uncertainties.
ESC-FI-006	Non radioactive groundwater assessment reporting	A1	LLW Repository Ltd should update the hydrogeological risk assessment for the LLWR for issue by December 2017.
ESC-FI-008	Management of uncertainty	A2	LLW Repository Ltd should further develop the FEPs and uncertainty tracking system (or alternate tools) as a tool to manage uncertainty in the ESC and feed into the forward programme.
ESC-FI-011	Forward review of the extended disposal area	A2	LLW Repository Ltd should fully integrate the EDA assessment into the ESC at the next periodic review of the ESC.
ESC-FI-012	Use of probabilistic calculations in derivation of radiological	A1	LLW Repository Ltd should consider update of the probabilistic groundwater pathway assessment model and as appropriate recalculate

Forward Issue number	Title	Categorisation	Summary of issue
	capacity		radiological capacity calculations based on the expectation value of the model output.
ESC-FI-013	Assessment of discrete items in stored and disposed waste	A1	LLW Repository Ltd should review the disposed records for stored waste located in Vault 8. LLW Repository should provide a BAT case for disposal of these items within Vault 8.
ESC-FI-017	Radiological capacity calculations	B1	LLW Repository Ltd should explore the relationship between disposed inventory and dose or risk to determine the suitability of the linear relationship assumption. Particular emphasis should be placed on C-14. If required, outputs should be fed into the WAC.
ESC-FI-028	Improved understanding of the repository erosion process	A2	LLW Repository Ltd should seek to improve its conceptualisation and understanding of the repository erosion sequence.

List of abbreviations

AD	Anno Domini
ALARA	As low as reasonably achievable
BAT	Best available techniques
BES	Bentonite enhanced soil
BNFL	British Nuclear Fuels Limited
BNGSL	British Nuclear Group Sellafield Limited
CLEA	Contaminated Land Exposure Assessment (model)
Defra	Department for Environment, Food and Rural Affairs
DWS	Drinking water standard
EC	European Commission
EDA	Extended disposal area
EDTA	Ethylene diamine tetra-acetic acid
EPR10	Environmental Permitting (England and Wales) Regulations 2010, as amended
EQS	Environmental quality standard
ERICA	Environmental Risks from Ionising Radiation in the Environment: Assessment and Management
ESC	Environmental safety case
FEP	Features, events and processes
FI	Forward issue
GBq	Gigabequerel
GRA	Guidance on Requirements for Authorisation (of near-surface disposal facilities on land for solid radioactive wastes)
GRM	Generalised Repository Model
HPA	Health Protection Agency (now Public Health England, PHE)
HRA	Hydrogeological risk assessment
IAEA	International Atomic Energy Agency
IAF	Issue assessment form
ICRP	International Commission on Radiological Protection
INF	Inventory and near field
IRF	Issue resolution form
ISO	International Standards Organization
JAGDAG	Joint Agencies Groundwater Directive Advisory Group
Kd	Partition coefficient or ratio

LLW	Low level waste
LLWR	Low Level Waste Repository near Drigg, Cumbria
LLWRAS	LLW Repository Assessment Standards
MBq	Megabequerel
MoD	Ministry of Defence
MOX	Mixed oxide
MRVs	Minimum Reporting Values
MSDS	Material Safety Data Sheet
mSv	Millisievert
NDA	Nuclear Decommissioning Authority
NDAWG	National Dose Assessment Working Group
NEA	Nuclear Energy Agency of the OECD
NNL	National Nuclear Laboratory
OESC	Operational environmental safety case
ONR	Office for Nuclear Regulation
PCSC	Post-closure safety case
PDF	Probability density function
PEG	Potentially exposed groups
PHE	Public Health England
PRG	Peer Review Group
PWR	Pressurised water reactor
R&D	Research and development
RDA	Reference Disposal Area
RI	Regulatory issue
RO	Regulatory observation
RSA 93	Radioactive Substances Act 1993 (as amended)
RWMD	Radioactive Waste Management Directorate (of the NDA), now Radioactive Waste Management Ltd
SAC	Special area of conservation
SI	International System of units
SLC	Site Licence Company
SSSI	Site of special scientific interest
SUE	Site understanding
Sv	Sievert
TBq	Terabequerel
TQ	Technical query
UKRWI	United Kingdom radioactive waste and materials inventory

WAC	Waste acceptance criteria
WHO	World Health Organisation
μSv	Microsievert
μGy	Microgray

Glossary

Term	Definition
Absorbed dose	The quantity of ionising radiation absorbed by a body, measured (usually in grays) as the energy absorbed per unit mass.
Active institutional control	Control of a disposal site for solid radioactive waste by an authority or institution authorised under EPR10, involving monitoring, surveillance and remedial work as necessary, as well as control of land use.
Activity	In radioactive-decay processes, the number of disintegrations per second, or the number of unstable atomic nuclei that decay per second in a given sample.
Adsorb	To gather (a gas, liquid, or dissolved substance) on a surface in a condensed layer.
Advective flux	The mass transport of a substance in response to a pressure gradient. The pressure gradient results in movement of groundwater.
Alkali	A substance with a relatively low concentration of hydrogen ions and a pH greater than 7.
Alpha particle	A positively charged particle consisting of two protons and two neutrons, emitted in radioactive decay or nuclear fission; the nucleus of a helium atom.
Anaerobic	An environment or condition where oxygen is absent.
Assessment code	A code used to assess the performance of some aspect of a system.
Becquerel (Bq)	Becquerel is the derived SI unit of radioactivity equal to one disintegration per second. Activities are commonly documented in terms of megabecquerels (MBq or 10^6 Bq), gigabecquerels (GBq or 10^9 Bq) and terabecquerels (TBq or 10^{12} Bq).
Best available techniques (BAT)	The latest stage of development (state of art) of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting discharges, emissions and waste.
Beta particle	An electron or positron emitted from an atomic nucleus in a certain type of radioactive decay.
Biosphere	The part of the earth's crust, waters, and atmosphere that supports life.
Calculation case	A calculation case is a specified combination of events, circumstances, conditions or their evolution, including specification of model boundary conditions and data, which represents a particular realisation of the disposal system, its evolutions and radionuclide or contaminant release, migration and exposures. A large number of cases may be required to adequately explore aspects of, or uncertainties

within, a scenario. Where the meaning is clear the abbreviated term, 'case', is used.

Cap	Engineered layer covering waste in the trenches and vaults to limit the amount of water entering the disposed waste and minimise the risk of intrusion from human and animal activities.
Collective dose	Collective dose is the sum of all the effective doses received by an exposed population.
Compartment flow model	A compartment-based numerical model of the LLWR near field used to calculate groundwater flows through the near field.
Complexant	'Complexing agents' are chemicals that can bind strongly to metal ions and significantly increase their solubility or decrease their ability to sorb onto solids. They may be an individual atom, molecule or functional group that binds to metal with one or more bonds. The bonding may be ionic or coordinate bonds.
Computer code (or code)	A software implementation of a numerical model that uses a computer processor to solve equations.
Conceptual model	A set of qualitative assumptions used to describe a system, or part of a system, in the real world.
Conservative (of assumptions and data)	Cautious in the sense that impacts would be overestimated.
Consignment	A consignment is a container or item of waste sent by a waste producer (consignor) to a disposal facility (such as LLWR).
Consignor (of waste)	An organisation or person that sends waste to the repository.
Critical group	A group of members of the public that is reasonably homogeneous with respect to its exposure for a given radiation source, such as a near-surface disposal facility, and is typical of individuals receiving the highest effective dose or equivalent dose (as applicable) from that source.
Criticality	A condition in which a sufficient quantity of fissile material is assembled in the right arrangement for a self-sustaining neutron chain reaction to take place.
Daughter isotope	An isotope that is the product of the radioactive decay of a parent.
Decay chain	A sequence of radioactive decay processes, in which the decay of one element creates a new element that may itself be radioactive. The chain ends when stable atoms are formed.
Deterministic	A deterministic analysis is one in which each input parameter is assigned a single numerical value, leading to a single value for the result.
Discrete items	Discrete items are distinct items of waste that may in future be recognisable as unusual or not of natural origin and so could be a focus of curiosity or interest and potentially recovered, recycled or re-used by persons.

Disposal	Disposal is the emplacement of waste in a specialised land disposal facility without intent to retrieve it at a later time; retrieval may be possible but, if intended, the appropriate term is storage.
Dose guidance level (for human intrusion)	In the context of near-surface disposal facilities, the dose standard against which the radiological consequences of human intrusion are assessed. It indicates the standard of environmental safety expected but does not suggest that there is an absolute requirement for this level to be met.
Dose constraint	A restriction on annual dose to an individual, which may either relate to a single source or to a complete site, in order to ensure that when aggregated with doses from all sources, excluding natural background and medical procedures, the dose limit is not exceeded. The dose constraint places an upper bound on the outcome of any optimisation study and, therefore, limits any inequity which might otherwise result from the economic and social judgements inherent in the optimisation process. The Government has set a maximum dose constraint value of 0.3 mSv y^{-1} when determining applications for discharge authorisations from a single new source, and a dose constraint value of 0.5 mSv y^{-1} for a complete site (which may include several sources with more than one operator).
Dose rates	The radiation dose (dosage) absorbed per unit of time.
Effective dose	The sum of the equivalent doses from internal and external radiation in all tissue and organs of the body, having been weighted by their tissue weighting factors. The unit of effective dose is the sievert (Sv).
Emplacement	The placement of a waste package in a designated location for disposal, with no intent to reposition or retrieve it subsequently.
Emplacement strategy	A strategy to control the locations in which certain waste streams and waste consignments are emplaced in the vaults. For example, not placing certain waste in the upper levels of stacks in the vaults in order to reduce the probability of inadvertent human intrusion into such waste. An emplacement strategy may be necessary to meet dose constraints and dose guidance levels, or it might be an optimisation measure to minimise the environmental impact of disposals to the LLWR.
Environmental permit	A permit issued under the Environmental Permitting (England and Wales) Regulations 2010.
Environmental safety	The safety of people and the environment both at the time of disposal and in the future.
Environmental safety case (ESC)	The collection of arguments, provided by the developer or operator of a disposal facility, that seeks to demonstrate that the required standard of safety for people and the environment, both at the time of disposal and in the future, will be achieved.
Environmental safety functions	The various ways in which the components of the disposal system may contribute towards environmental safety.

Ephemeral	Lasting a short time; transitory.
Exposed group	For a given source, any group of people within which the exposure to radiation is reasonably homogeneous; where the exposure is not certain to occur, the term 'potentially exposed group' is used.
Exposure pathway	An exposure pathway refers to the way a person can come into contact with a hazardous substance. There are three basic exposure pathways: inhalation, ingestion, or direct contact. A person can also receive dose from radioactive substances via external irradiation.
Extended disposal area (EDA)	An extended area of the repository, beyond but including the Reference Disposal Area, which is considered in the 2011 ESC to be sufficient to dispose of all waste requiring vault disposal in the United Kingdom Radioactive Waste Inventory.
External irradiation	External irradiation occurs when all or part of a body is exposed to penetrating radiation from an external source. During exposure, this radiation can be absorbed by the body or it can pass completely through.
Far field	The far field represents the geosphere beyond the near field.
Features, events and processes (FEPs)	Any factors that may influence the disposal system.
Fissile	Fissile material is material capable of sustaining a nuclear fission chain reaction. By definition, fissile material can sustain a chain reaction with neutrons of any energy (as opposed to 'fissionable' material requiring high-energy neutrons).
Forward issue (FI)	Areas of work that we believe it is important for LLW Repository Ltd to progress as part of its forward improvement plan. Areas where we see scope for continued improvement in the ESC and its implementation.
Geological strata	A geological stratum is a layer of sedimentary rock that has characteristics that distinguish it from other layers.
Geosphere	The geological formations and subsurface environment through which radionuclides may migrate.
Gray (Gy)	A measure of absorbed dose in the body, with one Gray equivalent to one joule of energy absorbed per kilogram of body weight. A microgray is equivalent to a millionth of a Gray.
Greenhouse gas	Gases whose absorption of solar radiation is responsible for the greenhouse effect, including carbon dioxide, methane, ozone and fluorocarbons.
Groundwater	Water which is below the surface of the ground in the saturated zone and in direct contact with the ground or subsoil.
Half life	For a radionuclide, the time taken for the activity to decrease, by a radioactive decay process, to half of its initial value.

Human intrusion	Any human action that accesses the waste or that damages a barrier providing an environmental safety function after the period of authorisation.
Hydraulic conductivity	A property of soil or rock, that describes the ease with which a fluid (usually water) can move through pore spaces or fractures. It depends on the intrinsic permeability of the material, the degree of saturation, and on the density and viscosity of the fluid.
Hydraulic gradient	A measure of the change in groundwater head over a given distance.
Infiltration	The process in which a fluid passes into the pores of a solid.
Ingrowth	Additional radioactivity produced as a result of radioactive decay of parent radionuclides.
Inorganic	Not having the structure or characteristics of living organisms; not organic.
Intermediate level waste (ILW)	Radioactive waste exceeding the upper activity boundaries for low level waste but which does not need its radiogenic heat to be taken into account in the design of disposal facilities.
Internal irradiation	Irradiation of a person from a source of radioactive material within the body following ingestion, inhalation or absorption through wounds.
ISO freight container	A steel container built to standard dimensions defined by the International Standards Organization (ISO), which can be loaded and unloaded, stacked and transported efficiently over long distances without being opened. Currently, most wastes intended for disposal in the vaults at LLWR are placed in half-height ISO containers licensed for LLW transport. The 2011 ESC assumes that this will continue to be the case.
Issue assessment form (IAF)	Issues raised during our review of the 2002 ESCs, which the operators of the LLWR were required to address as part of the development of the 2011 ESC.
Issue resolution form (IRF)	A template form used to record and track issues raised as part of the 2011 ESC review, along with their resolution. Each form provides a record of concerns or questions along with one or more actions for LLW Repository Ltd. LLW Repository Ltd recorded or summarised its response on the form, which was then reviewed by the Environment Agency and closed when a satisfactory response was received.
Leachate	Any liquid which has been in contact with wastes. Leachate is collected in the base of vaults and trenches and arises as a result of the infiltration of rainwater or groundwater.
Lithofacies unit	A subdivision of rock layers distinguished on the basis of similar physical characteristics and facies associations. Lithofacies units have been defined to create a regional three-dimensional model of the geology underlying the LLWR.

Low level waste (LLW)	In government policy, low level waste is defined as 'radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq te ⁻¹) of alpha or 12 GBq te ⁻¹ of beta/gamma activity'. It consists largely of paper, plastics and scrap metal items that have been used in the nuclear industry, hospitals and research establishments. In future, there will also be large volumes of LLW in the form of soil, concrete and steel, as existing nuclear facilities are decommissioned.
New build programme	The proposed development of a number of new nuclear power reactors within the UK.
Non-standard disposals	Disposals to the LLWR vaults not made within the commonly used ISO freight containers. Examples include the direct disposal of cylinders, flasks, ingots or alternative waste containers.
Operational environmental safety case	The 2002 ESC submitted by LLW Repository Ltd was split into two parts, the first being the operational environmental safety case, which addressed matters of environmental safety during the period of authorisation.
Optimisation	Optimisation is the principle of ensuring that radiation exposures are as low as reasonably achievable (ALARA) in the given circumstances. It is a key principle of radiation protection recommended by the International Commission on Radiological Protection (ICRP) and incorporated into UK legislation.
Organic	A class of chemical compounds that include carbon within their structure.
Pathway	A route or means by which a receptor could be, or is exposed to, or affected by a contaminant. Four pathways are considered in the 2011 LLWR ESC: groundwater, gas, natural disruption (coastal erosion) and human intrusion.
Peer review	A formally documented examination of a technical programme or specific aspect of work by a suitably qualified expert or group of experts who have not been directly involved in the programme or aspect of work.
Period of authorisation	The period of time during which disposals are taking place and any period afterwards while the site is under active institutional control.
Permeability	A measure of the capability of a porous rock or sediment to permit the flow of fluids through its pore spaces.
Post-closure safety case	The safety case presented as part of the ESC that covers the time after the end of the period of authorisation.
Potentially exposed groups (PEGs)	For a given source, such as a near-surface disposal facility, an exposed group is any group of people within which the exposure to radiation is reasonably homogeneous. Where the exposure is not certain to occur, the term 'potentially exposed group' is used.
Quaternary	The latest period of time in the stratigraphic column, 0 to 2 million years before present, typically represented by local accumulation of glacial (Pleistocene) and post-glacial (Holocene) deposits.

Radioactive decay	Spontaneous disintegration of a radionuclide accompanied by the emission of ionising radiation in the form of alpha or beta particles or gamma rays.
Radioactivity	The emission of alpha particles, beta particles, neutrons and gamma or x-radiation from the transformation of an atomic nucleus.
Radiological capacity	An inventory of radioactive material that the facility is capable of accepting based on the ESC.
Radionuclide	An unstable form of an element that undergoes radioactive decay.
Radiotoxic	A radioactive substance that is toxic to living cells or tissues.
Reducing conditions	Conditions that promote the gain of electrons or a decrease in the oxidation state of a molecule, atom or ion.
Reference case	The baseline set of assumptions about the disposal facility and its evolution with time that is used in the calculations of dose and risk.
Reference disposal area (RDA)	The disposal area including the trenches and Vaults 8 to 14.
Regulatory issue (RI)	An issue raised in an issue resolution form during our review of the 2011 ESC where deficiencies in the case were identified. An RI is a deficiency sufficiently serious that, unless or until it is resolved, we will either: (a) not grant a permit; or (b) grant a permit constrained by major limiting conditions (as distinct from information or improvement conditions) defined by us to mitigate the consequences of the RI.
Regulatory observation (RO)	An issue raised in an issue resolution form during our review of the 2011 ESC where deficiencies in the case were identified. An RO is a deficiency not sufficiently serious to prevent us issuing a permit but sufficiently serious that, unless or until it is resolved, we will include an improvement or information condition in the permit requiring defined actions on defined timescales to resolve it (or to demonstrate suitable and sufficient progress towards resolving it).
Retardation	A measure of the reduction in solute velocity relative to the velocity of the flowing groundwater caused by processes such as adsorption.
Retrievability	A characteristic of the design of the waste package and/or the disposal facility that facilitates recovery of waste after emplacement.
Risk guidance level	A level of radiological risk from a disposal facility that provides a numerical standard for assessing the environmental safety of the facility after the period of authorisation.
Scenario	One of several possible descriptions of the evolution of the disposal facility and its surroundings from the time of site

closure as a result of natural and human-induced, events and processes.

Sievert (Sv)	The International System of Units (SI) unit of effective dose, obtained by weighting the equivalent dose in each tissue in the body with ICRP-recommended tissue-weighting factors, and summing over all tissues. Because the Sievert is a large unit, effective dose is commonly expressed in milli-Sieverts (mSv) – that is, one thousandth of one Sievert, and micro-Sievert (µSv) – that is, one thousandth of one milli-Sievert.
Site Licence Company	The legal entity (LLW Repository Ltd) that operates the LLWR on behalf of the Nuclear Decommissioning Authority (NDA).
Soakaway test	Soakaway tests are normally carried out in trial pits. The pits are filled with gravel to ensure the sides of the trial pit remain stable during charging and draining. The time for 75% of the volume of water to drain away is used as a means of assessing the permeability of the soil
Source term	Description of the characteristics of the waste inventory (for example radioactivity, chemical hazard and volume) used as a basis in assessments of environmental impacts.
Specific activity	Radioactivity per unit mass of a waste.
Stochastic radiation effect	A radiation-induced health effect for which the probability but not the severity of the effect is related to the magnitude of the exposure.
Sum of fractions	An approach to setting limits on the total quantities and specific activity of radionuclides that may be disposed of at a radioactive waste repository. The approach is based on derivation of values of radiological capacity for each assessment case and for each radionuclide. A key characteristic of the approach is that it addresses the additive contributions of different radionuclides to overall impacts.
Technical query (TQ)	An issue raised in an issue resolution form during our review of the 2011 ESC where deficiencies in the case were identified. TQs are the least significant of the issues raised and represent a deficiency not sufficiently serious for us to require defined action by LLW Repository Ltd but sufficiently significant that we would request action.
Trench	A trench is an excavation in the ground into which loose waste was tumble tipped.
Uncertainty	Lack of certainty. A state of limited knowledge that precludes an exact or complete description of past, present or future.
Unsaturated	A volume of material is unsaturated when some or all of the pore space is filled with air.
Variant cases	Alternative calculation cases that are defined to investigate the effect of uncertainty in FEPs on the risk and dose calculations.

Vault	A space constructed of reinforced concrete base slabs and walls where wastes are emplaced.
Waste acceptance criteria (WAC)	Quantitative and qualitative criteria, specified by the operator of a disposal facility, for solid radioactive waste to be accepted for disposal. WAC form part of the set of waste acceptance arrangements that ensure the safety of waste disposal at the site.
Waste Consignment Variation Form	A form that customers complete when seeking agreement to vary a condition within LLW Repository Ltd's Waste Acceptance Criteria.
Waste form	The waste and its immediate packaging (for example grout and container) that is disposed of at the LLWR.
Waste stream	Waste streams are designated in the UKRWI to summarise waste or a collection of waste items at a particular site, usually in a particular facility or from particular processes or operations. A waste stream is often distinguishable by its radioactive content and, in many cases, also by its physical and chemical characteristics.
What-if scenario	A scenario put forward to explore the consequences of a defined set of assumptions that have a low likelihood of occurring.

**Would you like to find out more about us
or about your environment?**

Then call us on

03708 506 506 (Monday to Friday, 8am to 6pm)

email

enquiries@environment-agency.gov.uk

or visit our website

www.gov.uk/environment-agency

incident hotline 0800 807060 (24 hours)

floodline 0345 988 1188 (24 hours)

Find out about call charges (www.gov.uk/call-charges)



Environment first: Are you viewing this on screen? Please consider the environment and only print if absolutely necessary. If you are reading a paper copy, please don't forget to reuse and recycle if possible.