LLW Repository Ltd

LLWR Environmental Safety Case

Consideration of Potential Emplacement Strategies for the LLWR

A report prepared by the National Nuclear Laboratory Ltd. for and on behalf of the Low Level Waste Repository Site Licence Company.

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National Nuclear Laboratory

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EXECUTIVE SUMMARY

The Low Level Waste Repository (LLWR) near the village of Drigg is the UK's principal facility for the disposal of solid low level radioactive waste (LLW). The LLWR Site License Company (SLC), LLW Repository Ltd., is currently undertaking a programme of work leading to the production of an Environmental Safety Case by May 2011 (2011 ESC). The 2011 ESC will be submitted to the Environment Agency in order to satisfy Requirement 6 of Schedule 9 of the LLWR's current Authorisation.

In support of the 2011 ESC, there is a need to demonstrate that all potential waste emplacement strategies for significant waste streams and types had been identified and assessed in terms of impacts on site operations, operational safety, environmental impacts (pre- and post-closure) and costs.

In developing potential emplacement strategies, we have considered a number of waste types, including those that are most likely to give rise to the most significant pre- and post-closure impacts:

- Wastes containing high concentrations of the radionuclides that are most likely to be the key contributors to post-closure radiological impact (e.g. C-14, Cl-36, Tc-99, I-129, Ra-226, Th-232, uranium isotopes, plutonium isotopes and Am-241).
- High activity packages that could give rise to operational constraints (e.g. containing Co-60).
- Waste containing materials or chemicals that may have a direct impact on safety (e.g. toxic metals, organics and asbestos).
- Waste containing materials that may influence the future evolution of the disposed waste matrix. These include:
    - metals, which contribute to reducing conditions;
    - concrete, which contributes to high pH conditions; and
    - soil, which may act as a substrate for sorption of radionuclides.
- Large volume (probably low activity LLW) waste, e.g. soil and rubble.
- Materials that, due to their physical size and shape (e.g. very large items such as hexafluoride (hex) cylinders and redundant flasks), require packaging and disposal methods different to the majority of routine waste streams.
- Wastes that could be subject to new treatment options (e.g. incineration, metal melting and chemical or physical decontamination).
- Wastes that could be packaged and conditioned in novel ways.

Taking into consideration these key waste types, a total of 11 potential strategies for the emplacement of waste in the future vaults at the LLWR (Vault 9 onwards) were elicited. These were:

A Place packages containing wastes likely to generate significant amounts of radon gas (i.e. those containing a significant radium inventory) lower in the waste stacks to reduce the probability that they are disturbed by human intrusion and to provide a longer decay path.

B Emplace packages or uncontainerised waste in an engineered sub-cell to improve containment. Sub-cell options could include a resistant/impermeable cap to discourage human intrusion and reduce releases in groundwater.

C Disperse packages containing high inventories in order to avoid small volumes of waste containing relatively high concentrations of key radionuclides and other potential effects associated with the co-location of similar waste types.

D Separate C-14 containing wastes from other gas producing waste to reduce enhanced release rates through entrainment with landfill gas.

E Consideration of the effects of micro and macro grouting specific wastes, including C-14 bearing waste, Tc-99 in hex cylinders, uranium wastes and secondary wastes.

F Reduce release of uranium and Tc-99 in the groundwater pathway by providing a local reducing environment, perhaps by co-disposal with directly-consigned metal waste.

G Place leachable wastes in locations where dilution would be relatively high.

H Place waste containing the highest activities (relating to operational as well as post-closure doses) deeper in the facility and avoiding areas where higher stacking is used and areas closest to the edge of the cap where the cap is thinner.

I Ensure separation of acidic ashes from wastes where acidity is likely to increase the mobility of contaminants.

J Use of alternative waste emplacement strategies to improve stack stability, e.g. emplacement of packages in a 'brick wall' configuration and placement of less robust packages higher in the stack.

K Place selected waste packages in the upper part of the vault where they are less likely to become saturated and less exposed to degradation processes prior to erosion of the site.

These strategies were then assessed in terms of impacts on site operations, operational safety, environmental impacts (pre- and post-closure) and costs, with the aim of determining whether each strategy would work, what are the main benefits and disadvantages/costs and whether the strategy is worth considering further.

For many of the strategies considered, it was difficult to identify or be confident of clear improvements in performance. For the majority of strategies, it was also concluded that the disadvantages outweigh any potential advantages. This was generally because no significant benefits were ascertained.

However, Strategy A (emplacement of packages containing wastes likely to generate significant amounts of radon gas lower in the waste stacks), offers a real potential for reducing post-closure impacts with minimal effects on site operations. This is because the majority of future Ra-226 arisings (the main source of radon over the likely lifetime of the facility) are contained in a relatively small volume of waste. Operationally, emplacement of this waste at the bottom of the stacks (i.e. in the bottom two ISOs) should be readily achieved and there would be no requirement for new buffer storage in addition to what will be already available on site. However, systems would need to be put in place to identify relevant waste streams prior to consignment in order to track waste held in temporary storage. The net effect of this strategy would be to directly reduce the probability of intrusion to the depth of the radium wastes. It will also increase the potential migration path for radon in the case of a building piercing the cap to such an extent that any radon gas entry to the building from this source would be negligible. No significant disadvantages were associated with this strategy.

It was also concluded that continued micro grouting of key waste streams (i.e. grouting within waste containers, in line with Strategy E), in particular wastes with a significant C-14 inventory, is likely to bring a benefit in terms of reducing releases via the groundwater and gas pathways. No disadvantages are associated with continuing this practice. Macro grouting is currently undertaken for large items that are directly grouted into the vaults, however, based on the current package design, the introduction of grouting between containers would have operational and cost implications and it was concluded that the disadvantages of this strategy outweighed any potential advantages.

In addition to the requirement noted above to put systems in place to identify relevant Ra-226 bearing waste streams prior to consignment, there is also a need for further management procedures to monitor future waste streams in order to identify changes that might result in additional controls being required. In particular, there is a requirement to monitor the metal inventory and assess how changes could affect the near field (metallic waste contributes to the creation of anaerobic conditions which reduce the mobility of key radionuclides such as Tc-99 and uranium).

Subsequent to the elicitation and assessment of potential emplacement strategies, changes to the design of the future vaults and closure engineering were proposed. The key design changes affect the cap design (allowing for higher stacking of ISOs), the heights of the internal vault walls and replacement of vertical drains by a vault under-drainage blanket. Appended to this report is an assessment of the effect of these changes on the elicited performance of the emplacement strategies. Most significantly, the potential greater depth of waste could further increase the effectiveness of Strategy A.

It is likely that the design change would alter near-field flow regimes by reducing the potential for bathtubbing and by encouraging horizontal flows within the vaults over 1 m depth of leachate towards the eastern and western edges. In addition, the lower internal vault walls and the vault under-drainage blanket are designed to allow only the lowermost waste to saturate. However, although saturation conditions and the near-field flow regime influence the effectiveness of a number of the strategies including B, D, E, F, G, I and K, it is considered that these effects would not be significant within the bounds of the associated uncertainties.

VERIFICATION STATEMENT

This document has been verified and is fit for purpose. An auditable record has been made of the verification process. The scope of the verification was to confirm that : -

- The document meets the requirements as defined in the task specification/scope statement
- The constraints are valid
- The assumptions are reasonable
- The document demonstrates that the project is using the latest company approved data
- The document is internally self consistent

HISTORY SHEET

Issue Number	Date	Comments
Issue 0.1	15/02/2010	NNL approved
Issue 1.0	10/09/2010	Updates in line with feedback from the LLWR on the issue 0.1 report. New appendix inserted to assess the implications of vault design changes, which were proposed subsequent to completion of the issue 0.1 report.
Issue 2.0	07/03/2011	Minor updates in line with feedback from the LLWR on the issue 1.0 report.

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1. Introduction

The Low Level Waste Repository (LLWR) near the village of Drigg is the UK's principal facility for the disposal of solid low level radioactive waste (LLW). The LLWR Site License Company (SLC), LLW Repository Ltd., is currently undertaking a programme of work leading to the production of an Environmental Safety Case by May 2011 (2011 ESC). The 2011 ESC will be submitted to the Environment Agency in order to satisfy Requirement 6 of Schedule 9 of the LLWR's current Authorisation.

In support of the 2011 ESC, consideration needs to be made of potential emplacement strategies for certain types of waste. The LLWR therefore initiated a project to elicit and assess potential emplacement strategies. A key aim of this project was to demonstrate that all potential waste emplacement strategies for significant waste streams and types had been identified and assessed in terms of impacts on site operations, operational safety, environmental impacts (pre- and post-closure) and costs.

The objectives of this work were to:

- run a workshop to elicit potential strategies;
- consider and document the potential benefits and drawbacks related to identified strategies;
- present the outcomes at a further workshop that will be used to finalise and agree the conclusions of the work; and
- produce a report documenting the work programme.

NNL was commissioned to assist the LLWR with this project. This report describes the outcomes of the study. The report is divided as follows:

- Section 2 provides background information to the project and details the key assumptions made during the elicitation process;
- Section 3 describes the processes taken for the elicitation of potential emplacement strategies, which resulted in a total of 11 strategies being taken forward for further consideration, and the review of these strategies;
- Sections 4 to 14 contain details of the review of each potential emplacement strategy in terms of impacts on site operations, operational safety, environmental impacts (pre- and post-closure) and costs;
- Section 15 provides a summary and conclusions;
- Appendix 1 contains the full output from the first project workshop, which included the elicitation of a total of 54 potential emplacement options and the initial assessment of these options which resulted in a total of 11 strategies being taken forward for further consideration; and
- Appendix 2 assesses the implications of proposed changes to the design of the future vaults and closure engineering, which were proposed subsequent to the completion of the original work programme, on the assessment of potential emplacement strategies.

2. Background and assumptions

The overall aim of the project was to elicit and assess potential emplacement strategies for certain key types of waste at the LLWR (Vault 9 onwards). The objective was to provide information that the LLWR management team could use in decision making; i.e. in deciding what operational strategies could be implemented in order to reduce impacts (pre- and post-closure).

The LLWR is currently undertaking a number of other optimisation projects. These include:

- pre-closure and closure optimisation, including the design of the post-closure engineering and leachate management system (of particular relevance to the current project is the final cap design, which is not yet fixed);
- review of the overall arguments for the continued use of the LLWR, based on national policy and the NDA LLW strategy;
- considering potential trench remediation options;
- setting out institutional control requirements; and
- changes in packaging to improve disposal efficiency and performance.

Areas of potential overlap between these projects were taken into account in the definition of the scope of this study. In particular, consideration of vault design, for example different types of vaults for different waste types, was excluded from the scope. Instead, elicited strategies focused on the merits of emplacing specific wastes in particular locations. The requirement was to consider what emplacement strategies could be implemented for Vault 9 and the future vaults in order to reduce impacts (pre- and post-closure).

In line with the scope of the 2011 ESC, four pathways were considered:

- groundwater pathway;
- gas pathway (radon and C-14 are the key radionuclides);
- inadvertent human intrusion (which is assumed to only take place after the end of institutional control); and
- coastal erosion (it is envisaged that the vaults would be undercut by coastal erosion, resulting in the dispersal of waste on the beach).

With reference to Sumerling (2009a), the key radionuclides of relevance to post-closure performance are expected to be: C-14, Cl-36, Tc-99, I-129, Ra-226, Th-232, uranium isotopes, plutonium isotopes and Am-241. Key radionuclides in the operational period are expected to be: H-3, Co-60, Sr-90 and Cs-137. As a basis for this study, it was assumed that the period of institutional control would last for at least 100 years and possibly up to 300 years following completion of disposals.

Some key assumptions of the study were:

- Options involving un-containerised waste were not considered (with the exception of emplacement of material such as soil and rubble in the gaps between the International Standards Organisation containers or ISOs). [The current practice of grouting large items, which are too big to fit into ISOs directly into the vaults will continue.]

- A single vault design will be used, similar in the broadest sense to the design of Vault 9.

- Packaging will remain broadly similar to what is currently used, i.e. like the current ISO-freight containers.

- Higher stacking of ISO containers will take place to a maximum of six high.

3. *Elicitation of emplacement strategies*

The first project workshop was held on 17 November 2009. The aim of this workshop was to define the boundaries of the study (e.g. key waste types and waste streams and engineering considerations) and to elicit potential strategies for the future emplacement of waste at the LLWR.

The workshop was attended by technical specialists from NNL and the LLWR, as follows:

Richard Cummings	LLWR, ESC Project Manager
Amy Huntington	LLWR, Technical Lead for the Emplacement Strategies Project
Andy Baker	LLWR, ESC Technical Integrator
Scott Anderson	LLWR, Head of Programme Delivery, Operations
Paul Blenkinship	LLWR, Operations Team
Bill Robson	LLWR, Project Engineer, Consigner Support
Alan Wareing	NNL, inventory specialist
Candida Lean	NNL, ESC specialist
Andras Paksy	NNL, safety and risk assessment specialist
Neil Dickinson	NNL, workshop facilitator

The types of waste that were considered to be of significance to the elicitation of strategies (e.g. in terms of giving rise to potentially significant pre- or post-closure impacts) are listed below.

Significant waste types

- Waste containing high concentrations of radionuclides that are most likely to be the key contributors to post-closure radiological impacts (see Section 2).
- High activity packages that could give rise to operational constraints (e.g. wastes containing Co-60).
- Waste containing materials or chemicals that may have a direct impact on safety (e.g. toxic metals, organics and asbestos). It was noted that the LLWR conditions for acceptance (CFA) contains constraints on concentrations of non-radioactive hazardous substances and that issues associated with asbestos would be analogous to those faced by landfill sites accepting this waste type.
- Waste containing materials that may influence the future evolution of the disposed waste matrix. These include:
    - metals, which contribute to reducing conditions;
    - concrete, which contributes to high pH conditions; and
    - soil, which may act as a substrate for sorption of radionuclides.
- Large volume (probably low activity LLW) waste, e.g. soil and rubble.
- Materials that, due to their physical size and shape (e.g. very large items such as hexafluoride (hex) cylinders and redundant flasks), require packaging and disposal methods different to the majority of routine waste streams.
- Wastes that could be subject to new treatment options (e.g. incineration, metal melting and chemical or physical decontamination).
- Wastes that could be packaged and conditioned in novel ways.

The following design issues were considered during the elicitation of the potential emplacement strategies[1]:

Design issues
• The design of the final closure cap is not fixed or optimised, however, a gull wing design could be used. This cap, including profiling material, will be of a considerable thickness (generally of the order of 5-6 m or more). This will help prevent human intrusion over the anticipated lifetime of the facility, although reduced cap thickness at edges of facility due to doming of cap could be significant. • There is currently four high stacking of disposed International Standards Organisation containers (ISOs) in Vault 8. However, six high stacking is used in the centre of Vault 8 (currently licensed for storage only – the 2011 ESC is intended to be used to make the case that such disposals are acceptable). Higher stacking (i.e. six high) in the future vaults is quite likely (there is consideration of higher stacking on the eastern side of the future vaults, although this might not be consistent with the use of a gull-wing cap design). • Operationally, it would not be good practice to have six high columns of small packages without ISOs next to them for support (poor stability for smaller packages). Emplacement options for smaller packages that could be used in the future (especially for treatment residues, e.g. ashes from incineration) need to be carefully considered. A 'brick laying' scenario may be envisaged, in which vertical gaps are not aligned between layers (this has implications for emplacement of infill material between packages). • The more complex the emplacement strategy becomes, the greater the requirement will be for storage space at the LLWR. A flexible storage area would be needed at the LLWR as decommissioning sites do not have adequate storage. There may be implications for the required early construction of vaults in order to provide such storage space. • The ISOs may degrade on timescales of the order of 10 years if exposed to the environment. Therefore, long-term storage is not feasible (a temporary weather-proof cover may be possible). New package designs have not been finalised, however, a minimum lifetime for open storage could be specified to allow storage prior to disposal. • Double handling of ISOs or other packages will increase the workload for the LLWR Operations Team and increase health and safety risks. • Packages could potentially be placed next to each other, close enough together so that there is no need for infill. Un-encapsulated soil could also potentially be placed between containers. • The cap design includes an anti-intrusion barrier. Potential enhancements to the design of this layer are outside the scope of the current project. • Operationally, it is easier to place packages at a particular height in a stack rather than to place them at a particular location horizontally. • Activity limits on a vault by vault basis would be more flexible than the current annual limits. The LLWR may propose such limits in the future.

[1] Following the project workshops and completion of the issue 0.1 version of this report, changes to the future vault design and closure engineering were announced. Implications of these changes on the elicitation and assessment are discussed in Appendix 2.

A total of 54 potential emplacement options were put forward at the workshop. Following consultation between NNL and LLWR, these were subsequently distilled into 11 potential strategies that were to be taken forward for further consideration. The full list of 54 options and details of the initial screening process is given in Appendix 1.

The 11 potential emplacement strategies that were taken forward for assessment are listed below.

Potential emplacement strategies	
A	Place packages containing wastes likely to generate significant amounts of radon gas (i.e. those containing significant radium inventories) lower in the waste stacks to reduce the probability that they are disturbed by human intrusion and to provide a longer decay path.
B	Emplace packages or uncontainerised waste in an engineered sub-cell to improve containment. Sub-cell options could include a resistant/impermeable cap to discourage human intrusion and reduce releases in groundwater. The strategy includes consideration of placement of un-containerised waste (e.g. soil and rubble).
C	Disperse packages containing high inventories in order to avoid small volumes of wastes containing relatively high concentrations of key radionuclides and other potential effects associated with the co-location of similar waste types.
D	Separate C-14 containing wastes from other gas producing waste.
E	Consideration of the effects of micro and macro grouting specific wastes, including C-14 bearing waste, Tc-99 in hex cylinders, uranium wastes and secondary wastes. This also needs to take into account the effects of monolithic waste forms on coastal erosion impacts and the potential for using ash as the pulverised fuel ash (PFA) component of grout.
F	Reduce the release of uranium and Tc-99 in the groundwater pathway by providing a local reducing environment, perhaps by co-disposal with directly consigned metal waste.
G	Place leachable wastes in locations where dilution would be relatively high.
H	Place waste containing the highest activities (relating to operational as well as post-closure doses) deeper in the facility and avoiding areas where higher stacking is used and areas closest to the edge of the cap where the cap is thinner.
I	Ensure separation of acidic ashes from wastes where acidity is likely to increase the mobility of contaminants.
J	Use of alternative waste emplacement strategies to improve stack stability, e.g. emplacement of packages in a 'brick wall' configuration and placement of less robust packages higher in the stack.
K	Place selected waste packages in the upper part of the vault where they are less likely to become saturated and less exposed to degradation processes prior to erosion of the site. Target waste packages for this strategy include those containing leachable wastes and those containing higher concentrations of plutonium and americium.

The 11 emplacement strategies were then reviewed, taking into account the following attributes:

- operational considerations and practicality (including logistics, double-handling considerations and implications for consignors);
- inventory considerations (e.g. likely times at which key waste streams will arise);

- health and safety (radiation dose, and conventional health and safety issues);
- pre-closure environmental impacts (radiological and non-radiological);
- post-closure environmental impacts (radiological and non-radiological);
- general impacts (e.g. traffic, noise, dust etc) and stakeholder implications; and
- cost.

An initial review of the strategies was undertaken and discussed at a workshop which was held on 20 January 2010. This second project workshop was again attended by a range of technical specialists from NNL and the LLWR, as follows:

Richard Cummings	LLWR, ESC Project Manager
Amy Huntington	LLWR, Technical Lead for the Emplacement Strategies Project
Andy Baker	LLWR, ESC Technical Integrator
Scott Anderson	LLWR, Head of Programme Delivery, Operations
Paul Blenkinship	LLWR, Operations Team
Martin Walkingshaw	LLWR, Service Development Manager, Consigner Support
David Rossiter	LLWR, Strategy Development Manager
Alan Wareing	NNL, inventory specialist
Andras Paksy	NNL, safety and risk assessment specialist
Candida Lean	NNL, ESC specialist and facilitator
Adam Kennedy	NNL, workshop secretary

The results of the reviews of the performance of each of the 11 emplacement strategies against these attributes are provided in the following sections. The aim of these reviews was to determine whether each strategy would work, what are the main advantages and disadvantages and whether the strategy is worth considering further.

4. Review of Strategy A: Emplacement of packages containing waste likely to generate significant amounts of radon gas low in the waste stacks

Strategy A comprises the emplacement of waste likely to generate significant amounts of radon gas (i.e. those containing a significant radium inventory) lower in the waste stacks so as to reduce the probability that they are disturbed by human intrusion and to provide a longer decay path.

The strategy is aimed at reducing impacts associated with radon (Rn-222). Two cases are of concern:

- The first, and most important, is that intrusion through the cap into the waste could lead to an area of contaminated spoil on which a building might be constructed. In this case, if the spoil contains significant radium content, then radon from the spoil will accumulate in the building leading to doses via inhalation of radon daughters.
- The second case, which is judged to be of lesser concern, is if a building is constructed piercing the cap such that gas from beneath the cap is drawn into the building. This would consist of soil gas with some fraction of gases from degradation of waste and possibly radon. Analysis of this case indicates, however, that gas movement will be limited and transit times from the waste are liable to be substantially longer than the half-life of radon.

Thus, placing waste with a significant radium inventory lower in the waste stacks will directly reduce the probability of intrusion to the depth of the radium wastes. It will also increase the potential migration path for radon in the case of a building piercing the cap to such an extent that any radon gas entry to the building from this source would be negligible.

Over the timescales of interest to the 2011 ESC (a few thousand years up to probable disruption of the site by coastal erosion), the most significant disposed parent radionuclide of Rn-222 is Ra-226, which has a half life of 1,600 years. In the long term, Ra-226 will in-grow from disposed U-234 via Th-230 (half life 77,000 years), but this is only a small contribution to Ra-226 inventory within the time frame of interest.

4.1. Inventory considerations

Table 1 shows the forecast future arisings of Ra-226-contaminated wastes for disposal to the LLWR, extracted from the 2009 LLWR baseline inventory (Lennon, 2009).

Table 1: Future forecast inventory of Ra-226 arisings for LLWR disposal

Stream No.	Description	Total Ra-226 Activity (TBq)	% Ra-226	Stock Volume (m^3)	Arising Volume (m^3)	½ height ISOs (approx)
7S01	Contaminated Soil, Ash & Rubble	1.93	96.27	241	0	16
5C309	Minor Decommissioning LLW Arisings	0.05	2.51	0	767.5	51
2X140	Miscellaneous Demolition Waste	0.008	0.38	0	670	45
6H02	LLW (Minor Users)	0.004	0.21	0	8400	560

It can be seen that the large majority (approximately 96%) of Ra-226 is present in a single MoD waste stream, *7S01: Contaminated Soil, Ash and Rubble*. This waste stream has a high specific activity and a relatively low volume of 241 m^3, resulting in approximately 16 half-height ISO-freight containers for disposal. The waste stream volume for 7S01 exists as a current stock, and therefore it can reasonably be anticipated that this waste would be disposed of within a single year. Operationally, it would therefore be practicable to implement a strategy of placement for these wastes at or towards the bottom of the stacks using temporary buffer storage where necessary.

5C309, which is the second largest contributor of Ra-226, provides only around 2.5% of future forecast arising activity. This waste stream comprises miscellaneous building items from the decommissioning of Harwell research facilities and will provide approximately 51 half-height ISO-freight containers up to 2016.

The remaining two waste streams, 2X140 and 6H02, collectively contribute only around 0.6% of future forecast Ra-226 for LLWR disposal. However, it is noted that the volume of waste associated with the streams at approximately 560 half-height ISO-freight containers is larger than that for the other Ra-226-bearing wastes, and therefore would be relatively more difficult to ensure placement at the bottom of the stacks.

4.2. Operational considerations

Operationally it would not be difficult to ensure that waste streams contributing the greatest amount of Ra-226 activity are emplaced at the bottom of the stacks (e.g. in the bottom two ISOs). There would not be a requirement for new buffer storage in addition to what will be already available on site due to the low volumes of Ra-226 arisings.

A small number of additional movements per package may be required in the use of such storage. This will slightly increase the safety risk to operators and increase costs, but this is not unreasonable, given the low volume of significant waste streams. An additional operational consideration in the use of temporary storage is that of increased record keeping in formal waste tracking. A system is also needed in order to identify relevant waste streams prior to consignment.

4.3. Impacts

Direct intrusion into the waste

Placing waste with a significant radium inventory lower in the waste stacks will reduce the probability of intrusion to the depth of the radium wastes. In particular, it would be desirable to avoid placing containers with high radium content in the topmost layers of containers in the vaults.

It is judged that the most likely intrusion mode that could lead to excavation of large amounts of waste/spoil is a trial pit aimed at determining the suitability of the ground for building or other developments. Such ground investigation pits are generally of depth not greater than about 5 m (Halcrow, 2003), and thus could penetrate to the topmost ISO container, but are unlikely to go deeper. If an investigation is undertaken out of curiosity or for archaeological motives then the investigation may penetrate to or into the topmost ISO container but is unlikely to go deeper, either because the presence of hazardous waste is recognised or because deeper excavation would be problematic and not obviously fruitful.

Damage to and/or a building on the cap

The strategy will also increase the migration path for radon gas in the case of a building piercing the cap. Possible mechanisms for gas transport within the cap have been preliminarily discussed (Sumerling, 2010) and are being assessed within the ESC assessment of the gas pathway (Limer *at al.*, in preparation). The following processes have been identified as potential mechanisms for promoting gas movements or migration of gaseous species within the waste and engineered cap:

- Molecular diffusion – will act, but in still air; the consequent rate of migration is very low and can be shown to be less important than advective mechanisms, see below.

- Entrainment with gases from metal corrosion (principally hydrogen) and degradation of organics (principally carbon dioxide and methane) – the amounts of gas generated have been calculated (Small *et al.*, 2010) and are small relative to the gas movements that can be generated by barometric pressure changes.

- Buoyancy – is a potential modifier to the movements of gases and potentially relevant for bulk amounts of hydrogen and methane.

- Barometric pumping – is the movement of gases due to volume changes of underground gas caused by changes in atmospheric pressure at the ground surface. This can give rise to advection as pressure changes and over cyclic pressure changes, e.g. diurnal pressure variations, leading to a quasi-diffusive or dispersive migration.

Preliminary assessments of these processes indicate that molecular diffusion and entrainment with other gases are insufficient to move radon away from the waste fast enough to avoid decay to trivial levels. Calculations also indicate that pressure variation transmitted through the engineered event vent or a localised area of damaged cap will be dissipated in the cap gas collection layer. Hence, radon gas originating from more than about one or two metres down in the waste container stacks could not be carried to any gas exit zone. In still air, radon will tend to sink on account of its high molecular weight (negative buoyancy).

Hence, placing radium-bearing waste on the lower levels in waste stacks will provide a high degree of confidence that radon from waste will not be able to migrate to any potential exit point through the cap.

4.4. Summary

The majority of future Ra-226 arisings (the main source of radon over the likely lifetime of the facility) are contained in a relatively small volume of waste. Operationally it would not be difficult to ensure that this waste is emplaced lower in the stacks and there would not be a requirement for new buffer storage in addition to what will be already available on site. However, systems would need to be put in place to identify relevant waste streams prior to consignment.

Placing waste with a significant radium inventory lower in the waste stacks will directly reduce the probability of intrusion to the depth of the radium wastes. It will also increase the potential migration path for radon in the case of a building piercing the cap to such an extent that any radon gas entry to the building from this source would be negligible.

There are no significant disadvantages associated with this strategy, although it is noted that the strategy could lead to the creation of small volumes of wastes containing relatively high concentrations of key radionuclides of radium waste (contrary to Strategy C).

5. Review of Strategy B: Emplacement of packages or uncontainerised waste in an engineered sub-cell to improve containment

This strategy considers the emplacement of packages or uncontainerised waste in an engineered sub-cell to improve containment. Sub-cell options could include a resistant/impermeable cap to discourage human intrusion and reduce releases in groundwater.

The strategy potentially covers two different scenarios:

1. Creation of an engineered sub-cell for key waste streams/radionuclides in order to: limit water infiltration; provide a modified local chemical environment; or provide a locally enhanced barrier to reduce the likelihood of human intrusion. A strategy to reduce the outflow of radioactive gas would not be practicable other than in the very short term, however, reduced infiltration could reduce or delay the production of gas (i.e. reduce or delay impacts via C-14 labelled methane and carbon dioxide). It is assumed that these wastes would be containerised.

2. Emplacement of uncontainerised soil and rubble in a sub-cell.

The first scenario is of relevance to the groundwater, gas and human intrusion pathways. The key radionuclides of interest to the groundwater pathway are likely to be uranium, Tc-99, Cl-36 and C-14. Radon and C-14 are the main radionuclides of interest for the gas pathway and radon for human intrusion.

With regard to the second scenario, disposal of uncontainerised soil and rubble is a potential future strategy of interest to the LLWR. However, gaining stakeholder acceptance would be a consideration. On the basis of current practices it was decided not to carry this strategy forward.

5.1. Inventory considerations

As noted above, key radionuclides of potential interest for this strategy include uranium, Tc-99, Ra-226, C-14 and Cl-36.

The majority of future arisings of Tc-99 (~94%) and uranium (~70%) are associated with hex cylinders from Capenhurst. The likelihood of this waste actually arising with an inventory as given in the UK National Inventory is considered very low (prior to disposal the cylinders are likely to be washed out, thereby removing the majority of the activity). The LLWR therefore assumes that this waste stream will not be received for disposal with significant concentrations of uranium and Tc-99. There are no other key future sources of these radionuclides.

The waste streams containing the bulk of radium activity have been presented in Table 1 above. As discussed earlier, the large majority of radium arises from a single waste stream of relatively low volume, which would be anticipated to arise over a short time scale. It would therefore be feasible to segregate this waste for emplacement in an engineered sub-cell.

C-14 labelled gases arise predominantly from wastes having C-14 associated with cellulosic materials that degrade to form C-14-labelled methane and carbon dioxide. It is noted that the large majority (over 95%) of the future C-14 inventory is forecast to arise in graphite from reactor decommissioning, with smaller amounts associated with reactor concrete and stainless steel. These wastes are not expected to contribute significantly to the generation of C-14-labelled gases in the short-term due to the physical nature of the materials and the timescales over which they will degrade. The focus here is therefore given to those wastes having C-14 associated with cellulosic materials.

Table 2 shows the future forecast inventory of waste streams containing C-14 associated with cellulosic materials for LLWR disposal, taken from the 2009 LLWR baseline inventory (Lennon, 2009). It can be seen that around 50% of C-14 activity associated with cellulose arises in just five waste streams, accounting for around 740 half-height ISO freight containers. Moreover, approximately 20% of the C-14 activity in cellulose is represented by a single waste stream, 9H318. It is therefore conceivable that these five waste streams could be segregated for emplacement in a series of engineered sub-cells. The conditions within these sub-cells may be drier than in other parts of the vault and thus less waste will be in contact with water. This would lead to a reduction in the rate of generation of C-14-labelled gases within the cell and potentially result in a reduction in the overall site impact from C-14-labelled gases.

Table 2: Future forecast inventory of C-14 arisings associated with cellulosic materials for LLWR disposal

Stream No.	Description	Total C-14 Activity in cellulose (TBq)	% C-14 in cellulose	Stock Cellulosic Volume (m3)	Arising Cellulosic Volume (m3)	½ height ISOs (approx)
9H318	Final Dismantling & Site Clearance : Secondary Wastes LLW	0.035	33	0	817	54
2C920	Care and Maintenance Preparation (Reactor LLW)	0.011	10	0	5,349	357
2C921	Care and Maintenance Preparation Ponds LLW	0.008	8	0	4,198	280
5F307	WAGR Decommissioning	0.006	5	0	1,617	108
Remaining wastes with C-14 associated with cellulosic materials		0.068	44	593	80,235	5,349

Table 3 shows the waste streams forecast for LLWR disposal which have the highest concentrations of C-14 (total inventory) and Cl-36.

Table 3: Future forecast waste streams for LLWR disposal with significant concentrations of key radionuclides up to 2055

Radio-nuclide	Waste Stream	Description	Stock (m^3)	2009 – 2030 (m^3)	2031 – 2055 (m^3)	Activity (TBq)	% total Activity
C-14	7D39/C	LLW Submarine Ion Exchange Resin	2.8	91.8	0	4.14E-01	20.0
	5F307	WAGR Decommissioning	0	3,351	0	3.78E-01	18.3
	9E958	Oldbury C&M Preparations	0	3,893	0	2.73E-01	13.2
	5F302	B14 Operational Waste	0	36	0	2.05E-01	9.9
	3S06	Spent Resins	84.2	272.8	136.1	1.08E-01	5.3

Radio-nuclide	Waste Stream	Description	Stock (m^3)	2009 – 2030 (m^3)	2031 – 2055 (m^3)	Activity (TBq)	% total Activity
	2C920	Chapelcross C&M Preparations	0	34,326	0	6.87E-02	3.3
	Remainder of C-14-bearing wastes		2,217	209,979	141,607	6.19E-01	30.0
Cl-36	9C911	Care & Maintenance Preparation: Reactor and Boiler Systems LLW	0	2438	0	2.76E-02	17
	9H923	Care & Maintenance Preparation: Concrete (Non-reactor) LLW	0	3935.3	0	2.68E-02	16.5
	5G301	SGHWR Decommissioning LLW	0	2902.5	2902.5	1.86E-02	11.5

Over 70% of C-14 activity in future forecast waste for LLWR disposal up to 2055 is accounted for in six waste streams, arising predominantly before 2030. Ignoring 2C920, approximately 67% of this activity is contained within 7600 m^3. However, only 45% of future Cl-36 is contained within three waste streams (~9,000 m^3). The large volumes associated with these waste streams would make it less easy to segregate the key contaminants for groundwater pathway impacts within an engineered sub-cell.

5.2. Operational considerations

Key waste streams that might be considered for disposal within an engineered sub-cell include those associated with significant activities of Ra-226, C-14 and Cl-36. Forecast arising volumes for some of these wastes, in particular C-14, are significant and occur over an extended time period; therefore an engineered sub-cell designed to contain such waste types would need to be of large capacity and be available for use over a number of years (unless a subset of these waste streams is chosen). It is anticipated therefore that a single cell would not suffice, and thus a number of cells would be constructed sequentially in line with the larger vault construction programme. It is likely that additional procedures and operations would be required in the emplacement of wastes within the engineered sub-cells, although the extent of these would be dependent upon the design. The access areas to the sub-cells would need to be kept clear, reducing the handling and emplacement space for regular consignments. To avoid the need for buffer storage, construction of the engineered sub-cells would need to be planned such that disposal capacity for key waste streams is always available. Alternatively, such wastes could be disposed of to the regular waste stacks in a retrievable position and moved at a later date when engineered sub-cell capacity becomes available. This option would involve the double-handling of containers in the main disposal areas. Another option would be to require consignors to store waste until the LLWR is ready to accept it.

In the use of temporary or buffer storage, increased record keeping will be needed to ensure formal waste tracking. A system would also be needed in order to identify relevant waste streams prior to consignment.

Engineered sub-cells provide additional shielding, and as such could improve operational radiological safety. However, construction of additional cells will increase conventional safety risks associated with construction activities, including, for example, working in confined space. However, the risks can be controlled through use of appropriate controls and procedures.

5.3. Impacts

This strategy is aimed at reducing post-closure impacts by means of improved containment and therefore reduced releases via the groundwater and human intrusion pathways. There may be some impact for the gas pathway as well, although it is likely that sufficient water will always be available for gas generation from humidity even if infiltration rates are reduced. There is some confidence that the desired aim could be achieved for timescales of up to a few hundred years. For timescales beyond this (up to a few thousand years), the impact is less certain due to uncertainties associated with degradation of engineered barriers and their impact on flows. In addition, it is noted that construction of engineered sub-cells within the vaults increases the complexity of the closure system, and as such increases the uncertainties associated with the future evolution of the system as a whole. Important considerations in this respect include:

- the impact on waste settlement (additional walls could act as hard points thereby increasing differential settlement and negatively affecting cap performance);
- the impact on near-field flows (additional barriers would increase the complexity of the flow field and increase uncertainties associated with near-field flows); and
- the impact on the saturation of the vaults (sub-cells may cause the remainder of the vault to saturate more quickly, or the sub-cells themselves to fill with water).

For containerised waste, the purpose of this strategy is to:

- limit water infiltration;
- provide a modified local chemical environment; and
- provide a locally enhanced barrier to reduce the likelihood of human intrusion.

These are discussed below in turn, with regard to the potential effect to impacts via the gas, groundwater and human intrusion pathways.

It is noted that barriers put in place to create a sub-cell will not be gas tight. Gas would still be released, albeit over a longer time period. The impact of such a potential time delay on the release of C-14 labelled gases is considered insignificant due to the long half-life of C-14 (5730 years).

<u>Water infiltration</u>

The primary impact of the strategy is reduced inflows of water over a period of time for which the barriers are performing effectively. Reduced inflows would lead to reduced rates of release from the source term. In effect the releases would be spread over a longer time and peaks reduced, leading to lower impacts.

Both the 2002 PCSC and the 2008 Engineering Performance Assessment (EPA) (BNFL, 2002a, and Paksy, 2008) have considered the impact of engineered barriers on local flows. In both cases there is a marked difference in the performance of barriers depending on the materials used. Only barriers made of natural materials (clay and bentonite) were credited with some certainty in terms of their impact on flows. In comparison, concrete barriers (e.g. vault walls) were found to have a smaller impact on flows. Therefore, the potential impact of an engineered sub-cell will depend on the materials used, with natural materials expected to provide a longer lasting impact.

In addition to the materials and the consequent performance of the barrier, near field water flows are also influenced by climate and changes in local hydrological conditions (water levels in the Upper groundwater). Analysis of the evolution of the engineered system in the 2002 PCSC and the 2008 EPA and its impact on near-field flows has demonstrated that engineered barriers could have a significant influence on localised flows (several orders of magnitude), but the time of this influence is limited to a few hundred years. In order to have an impact, the sub-cells should be of high specification (e.g. use of combination of natural materials, including clay or bentonite). For a localised sub-cell, a typical scenario may be an increase in hydraulic gradients over time across the sub-cell wall, as the surrounding area of the vault fills up with water. Under such circumstances, it is likely that the additional barriers will reduce water infiltration into the sub-cell for about a few hundred years at most.

This could have an impact on overall release rates due to the effect of spreading releases over a longer time. The degree of this impact would depend on the rate of release from the source (and its evolution over time) relative to the time history of near-field flows as affected by the effectiveness of the barrier. Source release is controlled by a number of processes (half life, sorption or solubility) and could be coupled to near-field flows depending on the nature of the controlling process. Given the complexity of these processes and uncertainty associated with these, it is difficult to assess the potential impact of the strategy on releases.

Modified chemical environment

Drier conditions may arise within the vaults, at least for a limited length of time. Drier conditions are normally associated with a higher (oxidising) Eh. Under these conditions, the degradation of organic materials is more likely to produce CO_2 rather than CH_4. This would have important implications for the release of C-14 from cellulosic wastes via the gas pathway, with CO_2 being more reactive and therefore less mobile than CH_4.

The overall geochemical impact of additional materials (bentonite, clay or cement) used to construct the sub-cells is assumed to be negligible when compared with the amount of these materials already present in the vaults. However, at the level of the individual sub-cells, the impact on radionuclides could be more important. For example, additional grout material within the sub-cell would act as an effective sink for C-14 in the gas pathway, particularly, as described above, when predominantly present as CO_2. Grout and bentonite would also provide additional sorption capacity and therefore retard the release of radionuclides in the aqueous phase. Additionally, it would be possible, if the waste was sufficiently segregated, to design each sub-cell with material specifically to target the specific radionuclides within the waste. This could include specific sorbents or material to influence the prevailing biogeochemical conditions, to induce anaerobic conditions, for example.

Reduce the likelihood of human intrusion

Additional engineered barriers could be used to reduce the potential for human intrusion into the LLWR. There are two aspects of additional barriers that need consideration in order to assess impacts: the depth of the barrier to intrusion, and the material used that could potentially reduce the likelihood of intrusion.

With regard to depth, changes in the geometry of the design (cap profile or the profile of the wastes) are not considered. Therefore, the depth to intrusion will not change, only the type of material would change from example from cap infill (soil) to an additional clay layer. Therefore, unless additional barriers involve changes in the overall geometry of the design, likelihood of human intrusion will not be affected by increased barrier depth.

With regard to the effect of materials used, it is possible to use materials that may be considered to have deterrent effect on intrusion (for example, ceramic tiles or high quality concrete). However, any credit claimed for such barriers in a safety case is difficult to defend, due to uncertainties regarding their impact on future human actions. In addition, it is noted that application of such materials would be very expensive.

5.4. Summary

Overall it may be concluded that the proposed strategy could reduce infiltration into the vaults in the short and medium term (for a few hundred years approximately). This could reduce the rate of release of radionuclides via the groundwater pathway due to spreading releases over a longer time period. The degree of this impact would depend on the relative time histories of source release and reduction in near-field flows due to the additional barrier..

Operationally, there are difficulties in implementing this scenario due to the potentially large volumes of waste should it be implemented for all key wastes. The construction of an engineered sub-cell could require construction of buffer storage or the requirement for consignors to store waste on site until the LLWR are ready for its disposal.

Overall, based on current waste practices, it is considered that the net benefits of this strategy are outweighed by the disadvantages. However, this strategy could have potential benefits in the future for different waste disposal strategies.

6. Review of Strategy C: Disperse contaminants to avoid small volumes of wastes containing relatively high concentrations of key radionuclides

This strategy involves the dispersal of packages containing high inventories in order to avoid small volumes of wastes containing relatively high concentrations of key radionuclides and other potential effects associated with the co-location of similar waste types.

Small volumes of wastes containing relatively high concentrations of key radionuclides will not be of concern for situations where concentrations of radionuclides in the accessible environment do not depend on concentration variations in the facility (e.g. the groundwater pathway) or where exposure group habits mean that any variations are averaged out. The key pathway of concern is therefore the human intrusion pathway and the key radionuclide of concern is Ra-226.

6.1. Inventory considerations

Inventory considerations for Ra-226 are discussed in Section 4.1; the majority of future arisings of Ra-226 are associated with a single waste stream (7S01), which is predicted to be only 241 m^3 in volume.

6.2. Operational considerations

Given the low volume of key future Ra-226 arisings, dispersal of these wastes would not be too a complex a strategy and there would not be a requirement for new buffer storage.

A small number of additional movements per package may be required in the use of such storage. This will slightly increase the safety risk to operators and increase costs, but this is not unreasonable, given the low volume of significant waste streams. An additional operational consideration in the use of temporary storage is that of increased record keeping in formal waste tracking. A system is also needed in order to identify relevant waste streams prior to consignment.

6.3. Impacts

This strategy is designed to reduce post-closure impacts through avoidance of small volumes of wastes containing relatively high concentrations of key radionuclides associated with waste streams containing relatively high concentrations of the same radionuclides in close proximity. The groundwater and gas pathways are ruled out on the basis that, for these pathways, concentrations of radionuclides in the accessible environment do not depend on concentration variations in the facility, or the nature of the correlation is too uncertain to base a strategy on it. In case of the groundwater pathway this is due the effects of mixing within the facility and uncertainties of near-field flows. In case of the gas pathway discharges will be focussed on the vent and local imperfections in the cap (location unknown) and as such heterogeneity of the waste is less of a concern. The coastal erosion methodology is not sufficiently developed to understand if concentrations of activity would be significant.

Therefore, the key pathway of concern is the human intrusion pathway. The key radionuclide of concern is likely to be Ra-226 as doses may arise via radon. Other dose contributing radionuclides via human intrusion include Cl-36, Tc-99 and Cs-137. However, the 2008 Requirement 2 performance calculations indicated that doses associated with these radionuclides are significantly below the relevant dose constraints (see Galais and Fowler, 2008), although this conclusion may need to be revisited when the 2011 ESC assessment calculations have been completed. The reduction of impacts associated with the disposal of Ra-226 is discussed under Strategy A, including both the human intrusion and gas pathways. It is considered that Strategy A is more effective for reducing impacts from Ra-226 than Strategy C could be. In conclusion, given that the main pathway and radionuclide of interest is already covered, it is considered that potential impact of this strategy would be marginal.

6.4. Summary

Operationally, the dispersal of Ra-226 to avoid small volumes of wastes containing relatively high concentrations of key radionuclides would not be very difficult to undertake due to the small volume of waste. However, it is considered that impacts associated with disposal of Ra-226 are best covered under Strategy A. The 2008 performance calculations indicated that impacts associated with other key radionuclides associated with the human intrusion pathway are significantly below the relevant dose criteria (see Galais and Fowler, 2008), although this conclusion may need to be revisited when the 2011 assessment calculations have been completed.

7. Review of Strategy D: Separation of C-14 containing waste from other gas producing waste

This strategy focuses on the separation of C-14 associated with non-cellulosic waste from cellulosic waste and other gas producing waste. Cellulosic materials will degrade over time to produce landfill gases, which could act as a carrier for C-14-labelled gases, reducing the timescales by which C-14 would reach the biosphere. The strategy, through limiting the association of C-14 with landfill gases, is therefore primarily aimed at reducing the migration of C-14-labelled carbon dioxide and methane and thus the reduction of impacts associated with C-14 via the gas pathway.

7.1. Inventory considerations

Future forecast C-14 activity designated for LLWR disposal arises predominantly from graphite, concrete and metal wastes from reactor decommissioning. The majority of these wastes are not forecast to arise before 2075, which may mean they are not disposed to the LLWR. In addition, their physical nature is such that release of C-14 would take place over a timescale beyond that associated with the degradation of cellulosic material. It is sensible, therefore, to focus on those C-14-bearing wastes arising up to 2055, the calculated date for the end of LLWR operations (Wareing *et al.*, 2008). An assessment of the radiological impact of C-14-labelled gases (Ball *et al*., 2008) was undertaken. One of the conclusions from this study was that cellulosic materials not contaminated with C-14 could degrade to produce landfill gases that could act as a carrier for C-14-labelled gases, reducing the timescales by which these would reach the biosphere. It is therefore important to examine the quantity and timing of arisings of cellulosic materials in relation to those for C-14-contaminated wastes. However, it should be noted that a lot of the cellulosics wastes might be incinerated in future.

The quantities and profile of arisings of wastes accounting for over 70% of future forecast C-14 activity up to 2055 are presented against the quantities and profile of arisings of cellulosic wastes up to 2055 in Table 4, as taken from the LLWR 2009 baseline inventory (Lennon, 2009). The quantities and profile of all LLW arisings forecast for LLW disposal are shown to provide an indication of the proportions of waste involved.

Table 4: Future forecast inventory of C-14-contaminated and cellulosic wastes for LLWR disposal up to 2055

Waste Type	Stock (m^3)	2009 – 2020 (m^3)	2021 – 2030 (m^3)	2031 – 2040 (m^3)	2041 – 2050 (m^3)	2051 - 2055 (m^3)
Cellulosic-bearing wastes (total volume)	0	103,982	63,484	47,074	34,696	10,421
Cellulosic-bearing wastes (cellulose volume)	0	36,425	17,887	11,383	9,671	2,993
C-14-bearing wastes (total volume)[1]	87	24,642	17,329	124	0	0
Total LLW arisings	8,050	243,619	206,372	91,389	58,292	33,236

[1] These wastes are associated with six waste streams (see Table 3) and account for over 70% of the total activity of C-14.

It can be seen that the C-14-bearing wastes arise predominantly in the period 2009 to 2030, which corresponds closely to the period of time having the greater proportion of cellulosic wastes. As these wastes are forecast to arise over similar time periods, it would be necessary to employ an active emplacement strategy to ensure separation.

Table 4 shows that the proportions of both cellulosic materials and C-14-bearing wastes in comparison to total LLW arisings are reasonably low; each generally representing 15% or less of the total. It is therefore considered that segregation of these wastes within the disposal vaults is achievable.

7.2. Operational considerations

This strategy is likely to require active management; inventory studies show that C-14-bearing wastes and cellulosic materials, which are those most associated with landfill gas generation, arise over similar time periods and therefore will be disposed together in the same vaults. Volumetrically, the proportions of cellulosic and C-14-bearing wastes are small compared with total arisings (generally representing less than 15%); therefore it should be possible to dispose containers of C-14-bearing wastes amongst containers holding waste forms other than cellulosics.

Such a strategy may require more than one stack to be in active operation, and it is considered that either buffer storage or double-handling of containers would be required. Alternatively, consignors could be required to store waste until the LLWR is ready to receive it.

Double handling will correspondingly increase the conventional health and safety risk to operatives; however, risks can be controlled through use of appropriate controls and procedures. Furthermore, the integrity of ISOs may degrade on timescales of the order of 10 years if exposed to the environment. Should packages be moved after they have started to degrade, exposure of workers to contaminated material (e.g. dust) could occur, in particular if damage occurs during the movement or emplacement. In addition, there may be the potential for increased worker dose from exposure via irradiation to stored waste compared with waste in the vaults. These doses are likely to be low compared with annual limits; however, monitoring will be required.

This waste could be separated by the consignors; however, the LLWR operations team would also need to ensure separation on emplacement. In the use of temporary or buffer storage, increased record keeping will be needed to ensure formal waste tracking. A system would also be needed in order to identify relevant waste streams prior to consignment.

7.3. Impacts

This strategy is designed to reduce post-closure impacts via the gas pathway from C-14 by reducing / preventing release of C-14 entrained by landfill gases. This has been postulated as being the most important release mechanism for C-14 labelled gases (Ball *et al*., 2008; Sumerling, 2009b). Landfill gases (e.g. carbon-dioxide and methane) are generated mostly by the degradation of cellulosic materials, such as wood, paper and cotton. Therefore, it follows that by separating C-14 bearing waste from waste that contains cellulosic materials, the rate of release of C-14 via the gas pathway may be reduced.

The strategy depends on the assumption that entrainment of C-14 by landfill gases is the most important release mechanism for C-14, with the effectiveness depending on its potential to reduce the proportion of C-14 incorporated into landfill gases (termed the Gas Release Fraction or GRF, Ball *et al*., 2008). If this assumption was robust, the lower limit is set by the amount of cellulosic material that is associated with C-14, as the separation of this would require a more intrusive strategy. Current studies show that around 13% of the future forecast volume for C-14-bearing wastes is associated with cellulosic material (Wareing, 2009). Thus the maximum impact of the strategy would be about an eightfold decrease in dose from C-14. However, when practical limitations of placing the waste packages within a vault and incorporation of C-14 into landfill gas that is generated in a separate waste package is factored in, a more realistic maximum impact may be estimated as between about a factor of 2 to 5. As such the potential effect of the strategy is assessed as low to medium, depending on the practicability of separating C-14 bearing waste from cellulosic waste.

However, due to the physical nature of the waste form, release of C-14 is likely to take place over a timescale that is longer than the timescale associated with degradation of cellulosic material. Therefore, mechanisms other than entrainment in landfill gases should also be considered for the release of C-14 labelled gases from the LLWR. These include molecular diffusion and pressure driven gas flow (as discussed under Strategy A, Section 4.3, for radon gas).

The key C-14 waste streams are grouted (see Section 8.1) and it likely that such encapsulation of C-14 wastes would generally be of benefit in isolating the C-14 wastes from transport in groundwater and gas, either by limiting contact with infiltrating groundwater or lowering gaseous exchange rates by processes of molecular diffusion and barometric pumping. In terms of gas diffusion, the presence of water in the microporosity of cement grout, such as initially present after curing, may slow gas transport rates. However, given the relatively long half-life of C-14 (5730 years), it may be considered that most C-14 gas generated will reach the accessible environment prior to decay (the times of peak impacts may be delayed, but the peaks will not be significantly reduced), apart from the retardation association with the sorption of CO_2 onto grout.

7.4. Summary

There is no confidence that this strategy would be able to significantly reduce impacts over the lifetime of the LLWR, and it would be operationally complex to undertake. It is therefore concluded that the disadvantages of this strategy outweigh the potential benefits.

8. Review of Strategy E: Grouting of specific wastes

This strategy involves consideration of the effects of grouting specific wastes, including C-14 bearing waste, Tc-99 in hex cylinders, uranium wastes and secondary wastes.

This strategy considers both micro and macro grouting. Micro grouting relates to grouting inside the container, whilst macro grouting relates to grouting outside the container.

This strategy is aimed at reducing impacts via the groundwater pathway by reducing the migration potential of key radionuclides (e.g. uranium, Tc-99 and C-14). Micro grouting is currently undertaken for the majority of waste streams, although it is possible that the amount of grout used might be decreased (Paulley *et al*., 2009). Large items that are too big to fit into ISOs are macro grouted into the vaults.

8.1. Inventory considerations

The key radionuclides of interest to the groundwater pathway are likely to be Tc-99, uranium, Cl-36 and C-14. However, as discussed in Section 5.1, the majority of future arisings of Tc-99 and uranium are associated with hex cylinders from Capenhurst, which are assumed not to be received for disposal with significant concentrations of uranium and Tc-99. There are no other key future sources of these radionuclides. Radon and C-14 are the main radionuclides of interest for the gas pathway.

The majority (over 70%) of C-14 activity in future forecast waste for LLWR disposal up to 2055 is accounted for by just six waste streams, arising predominantly before 2030, as shown in Table 3.

In terms of activity, the top-contributing waste stream, 7D39/C, comprises ion exchange resins from submarine decommissioning. It is stated in Poyry (2008) that this waste will undergo pre-treatment (MODULOX) to remove the majority of C-14, following which it will be encapsulated in cement within 200 litre drums which will then be placed in half-height ISO freight containers for disposal.

The waste stream 5F307 contains C-14 within activated concrete and stainless steel from reactor decommissioning. Poyry (2008) states that this waste is planned for grouting within half-height ISO freight containers, and that inaccessible voidage is expected; however, this is anticipated to be less than 10% of the waste volume. With a total arising volume of 3,351 m^3, approximately 215 half-height ISO freight containers would be generated for this waste stream.

9E958 has C-14 present as graphite dust associated with a small amount of cellulosic material. As it is present as a dust then the graphite may be subject to microbial attack. C-14-labelled CH_4 and CO_2 could potentially be released from this waste; therefore a significant benefit could be gained by employing the micro-grouting strategy.

5F302 was listed in the 2007 UK Radioactive Waste Inventory as an ILW stream (Poyry, 2008). However, this has since been declared in the NDA Waste Accountancy Templates as LLW. The waste stream comprises activated graphite blocks (99%) and aluminium from Windscale Piles 1 and 2. No information on how this waste would be treated as LLW is available.

3S06 contains trace quantities of C-14 adsorbed onto resin beads. There is potential for C-14 to be released via the gas and groundwater pathways if water were allowed to infiltrate the waste. Similarly to 7D39/C, the planned treatment for this waste stream is encapsulation in 200 litre drums followed by disposal to LLWR in half-height ISO freight containers. No voidage is anticipated.

8.2. Operational considerations

It is considered that current planned treatments are in line with the micro grouting strategy.

Large items are directly grouted into the vaults and there are no plans to discontinue this practice. However, initiation of procedures for macro grouting between packages would have an effect on LLWR operations, cost and space, probably including construction of a grouting plant.

New operating procedures would need to be in place for macro grouting between packages. This could lead to additional health and safety risks to operators, although these can be managed through management controls.

8.3. Impacts

Given the expected future inventory, C-14 is of prime interest to this strategy. Micro grouting with an Ordinary Portland Cement (OPC) based grout may be effective in retarding the migration of C-14 in inorganic forms, such as CO_2 gas or dissolved carbonate, through precipitation as calcium carbonate. C-14 in organic form, such as CH_4 gas or as carboxylic acids formed by the biogeochemical processes related to the anaerobic degradation processes has little or no potential to react and be retarded by the cement grout. The chemical form of C-14 is therefore key to evaluating the effectiveness of the strategy, and is influenced by the following:

- the nature of C-14 in the primary waste materials; and
- the biogeochemical processes in the near field, which may affect the speciation of C-14 as it is affected by the processes affecting stable carbon behaviour.

The majority of C-14 in future arisings is in the form of activation products in irradiated metal, concrete and graphite, or is present in ion exchange resins. The form of C-14 in resins is assumed to be carbonate recovered from reactor cooling effluents. In irradiated metals, C-14 may be present associated with carbides, which on contact with water might generate methane and other organic forms. C-14 in graphite may yield either organic or inorganic forms. C-14 in concrete is perhaps more likely to be inorganic and will be bound to the material in carbonate phases.

Following the primary release from the above waste materials, C-14 will be subject to biogeochemical processes, which will be driven by degradation of cellulosic wastes. Methane generation may also occur from carbonate reduction by microbes which utilise hydrogen generated by anaerobic corrosion. It is assumed that C-14 will be affected by the same processes that affect stable carbon and that its chemical form and chemical reactivity with grout will be increased where it forms carbonate of CO_2. In this respect, Strategy D (separation of C-14 wastes from gas producing wastes) is linked, but the effect of cellulose and metal in determining the chemical form of C-14 was not considered under Strategy D (Section 7).

Initial GRM modelling of C-14 generation in the LLWR near field (Small *et al*., 2009a) indicates that the dominant form of C-14 that is released from the both gas and groundwater is organic (methane and carboxylic acids). GRM simulates the reaction of inorganic C-14 with cement grout and also the formation of $FeCO_3$ as an anaerobic corrosion product, which is an important sink of C-14 in the trenches. GRM results indicate that CH_4 is the dominant gas produced from the vaults as any CO2 reacts with cement grout. In the trenches, the inventory of C-14 is significantly lower than that estimated for the future vaults, and GRM results show that a greater proportion of CO_2 is generated. These GRM simulations are consistent with the results of 10 year large-scale experiments of gas generation from cellulosic wastes (Small *et al.,* 2008) and are also consistent with the low generation of CH_4 from the trenches and the association of C-14 with CH_4 (Poulton and Rushbrook, 1990; Clayton, 1993; Ball *et al.*, 2008). On-going monitoring of the trenches for C-14 gas generation should provide further relevant data.

Micro grouting of vault waste will be effective in limiting release of C-14 in its inorganic form (CO_2 in both gas and dissolved phases), principally through being retained by reaction with grout. Organic forms will not, however, be influenced by the presence of grout. Where C-14 is in primary inorganic form there may be benefit in limiting the migration of C-14 as carbonate, such as by encapsulation in cement. In the case of ion exchange resins it is noted that the current CFA of waste at the LLWR specify that such materials are encapsulated in cement. For irradiated concrete, in which C-14 may be in inorganic form, there would be little benefit in adding further cementitious material.

In addition to the chemical effects that micro grouting provides, it likely that such encapsulation of C-14 wastes would generally be of benefit in isolating the C-14 wastes from transport in groundwater and gas, either by limiting contact with infiltrating groundwater or lowering gaseous exchange rates by processes of molecular diffusion and barometric pumping. In terms of gas diffusion, the presence of water in the microporosity of cement grout, such as initially present after curing, may slow gas transport rates. Additionally, current grouting practices provide a means by which voidage within ISOs is reduced, therefore reducing the probability of settlement due to waste degradation and limiting potential preferential pathways within the waste.

In terms of other radionuclides, micro grouting of wastes has the benefit of providing surfaces with strong sorption potential, thus reducing the migration of these radionuclides via the groundwater pathway.

8.4. Summary

Continued micro grouting of C-14 wastes is likely to bring a benefit in terms of reducing the flux of C-14 via the groundwater and gas pathways. No disadvantages are associated with continuing this practice.

Large items are presently grouted directly into the vaults and this process is expected to continue. No benefits are identified for the macro grouting of the current ISO disposals.

9. Review of Strategy F: Reduce the release of uranium and Tc-99 in the groundwater pathway by providing a local reducing environment

This strategy involves reducing the release of uranium and Tc-99 (and also C-14) in the groundwater pathway by providing a local reducing environment, perhaps by co-disposal with directly consigned metal waste. Anaerobic conditions will reduce the solubility of uranium and Tc-99 and therefore reduce the impacts via the groundwater pathway. The majority of future uranium and Tc-99 arisings will be associated with hex cylinders, which are also the largest single contribution to metal in the future inventory. Anaerobic conditions may also lower the release of C-14 from waste metal due to reduced corrosion rates.

9.1. Inventory considerations

As discussed previously, the Capenhurst hex cylinders (2B03) which contain the majority of future arisings of uranium and Tc-99 will not be received at the LLWR with an inventory as given in the UK National Inventory. No other key future sources of these radionuclides have been identified.

It is expected that, in the continuance of use of steel ISO freight disposal containers, a reducing environment would develop across the majority of the disposal areas. However, future disposal packages could, potentially, use materials other than metals. In this situation, a locally reducing environment would need to be provided by ensuring a high proportion of metallic wastes are placed in the area.

Table 5 shows those waste streams forecast to provide the majority of metals in future arisings up to 2055, as taken from the LLWR 2009 baseline inventory (Lennon, 2009). It can be seen that the waste stream contributing the single largest proportion of metal (21.8%) is 2B03, which will not be received at the LLWR in its currently declared form. The other key waste stream is 2D109 (Sellafield miscellaneous plants initial/interim decommissioning waste) which is estimated at contributing 17.6% of future metal arisings. It is anticipated that these waste streams will contribute to reducing conditions in the areas in which they are disposed without additional measures needing to be taken.

Table 5: Future forecast inventory of metal-bearing wastes for LLWR disposal up to 2055

Waste Stream	Description	Stock (m^3)	2009 – 2030 (m^3)	2031 – 2055 (m^3)	Total Metal Volume (m^3)	% Total Metal
2B03	Empty Uranium Hexafluoride Containers	57.2	57,870	0	57,870	21.8
2D109	Sellafield Miscellaneous Plants Initial/Interim Decommissioning	0	20,646	44,164	46,575	17.6
2C920	Chapelcross Miscellaneous Plants Initial/Interim Decommissioning	0	34,326	0	25,822	9.7
2D123	Sellafield Miscellaneous Plants Final Decommissioning	0	8,058	34,789	11,321	4.3
3S301	Sizewell B Decommissioning: Mild Steel	0	0	8,131	8,131	3.1

Waste Stream	Description	Stock (m^3)	2009 – 2030 (m^3)	2031 – 2055 (m^3)	Total Metal Volume (m^3)	% Total Metal
2F20	Thorp Decommissioning: Mild Steel	0	6,781	0	6,633	2.5
2D42	Magnox Pond Furniture	0	4,800	0	4,800	1.8
2X20	Magnox Ponds West Mild Steel	0	7,744	0	4,552	1.8

As shown in Table 3, over 70% of future forecast activity of C-14 up to 2055 is accounted for in six waste streams, arising predominantly before 2030. These are associated with relatively large volumes of waste (~42,000 m^3).

9.2. *Operational considerations*

Anaerobic conditions will reduce the mobility of radionuclides such as uranium and Tc-99 and a potential emplacement strategy would involve the engineering of these conditions. The production of a locally reducing environment can be achieved by increased mixing with metallic waste or by the introduction of iron filings. Future disposals of Tc-99 and uranium are low, although significant volumes are associated with C-14 wastes. However, as discussed in Section 9.1, there is probably enough metal within the disposal system (associated with consigned waste and containers) to ensure a reducing environment without adopting a particular emplacement strategy.

However, should future waste streams arise that include higher levels of uranium or Tc-99 or lower volumes of metal, this emplacement strategy may need to be reconsidered. To ensure that this is captured, there is a need to monitor the metal inventory in order to assess how changes could affect the near field and identify whether additional controls could be required in the future.

9.3. *Impacts*

Reducing environmental conditions brought upon or enhanced by this strategy are conducive to anaerobic (as opposed to aerobic) corrosion of metals. Small *et al*. (2009b) describes the coupling that exists between the processes of anaerobic metal corrosion and leaching of cement grout. Under these conditions, radionuclide release is dominated by the effects of corrosion of the primary waste with secondary effects of sorption onto corrosion products and grout. Thus, the effects of the strategy for the release and near-field transport of key radionuclides are as follows:

- reduced release of C-14 from metal waste due to passivation and reduced corrosion rates. However, strongly anaerobic conditions could lead to methanogenesis and therefore potentially lead to increased release of C-14 in the gas phase;
- reduced mobility of Tc-99 due to the establishment of a Tc(IV) solubility control by the anaerobic corrosion of the metal waste with which it is associated; and
- reduced solubility of uranium under sulphate reducing conditions (due to H_2 generated from anaerobic corrosion together with sulphate in the grout).

However, the overall impact of these effects on post-closure performance is likely to be limited based on findings by Small *et al*. (2009a) and also Paulley *et al*. (2009). In addition, it is noted that the steps that could practically be taken in support of this strategy can only reinforce existing factors (ISO containers are already present in the vault waste form in large quantities together with bulk metallic waste) and conditions.

Overall it is considered that the strategy will have no significant benefits, given that uranium and Tc-99 are managed by other means. The effects relating to C-14 are considered to be minimal. However, the strategy should be reconsidered, should the LLWR need to receive new waste streams containing significant inventories of Tc-99 or uranium. This can be managed using future controls, e.g. internal trigger levels.

9.4. Summary

No significant benefits are currently associated with this strategy, although there is a need for further management procedures to monitor the metal inventory in order to assess how changes could affect the near field and identify whether additional controls could be required in the future.

10. Review of Strategy G: Enhance dilution of leachate

This strategy involves placing waste in locations where subsequent dilution in the geosphere and biosphere will be enhanced. Dilution will occur if the leachate volume flux is mixed with a relatively high volume of uncontaminated water from another source. For example this may involve placing waste in a part of the repository associated with low inflows of groundwater, or areas where subsequent dilution in groundwater is high (i.e. part of the repository where it is thought that discharge to the aquifer is likely).

The strategy is applicable to waste packages containing high inventories of key radionuclides for the groundwater pathway (C-14, Cl-36, Tc-99 and uranium), particularly in cases where the inventory is easily leachable). Leachable wastes are assumed to be those where infiltration of water will significantly increase the release of radionuclide and material contaminants, both on the outer surfaces and within the structure of the waste, to the groundwater pathway through dissolution. These wastes generally include soft, low-density organics, such as cellulosics, plastics and rubber, and soil.

10.1. Inventory considerations

Table 6 shows the volumes of soft organics and soils together with the total volume of LLW forecast to arise for LLWR disposal up to 2055, as taken from the LLWR 2009 baseline inventory (Lennon, 2009).

Table 6: Future forecast inventory of soft organics and soil for LLWR disposal up to 2055

Waste Type	Stock (m^3)	2009 – 2020 (m^3)	2021 – 2030 (m^3)	2031 - 2040 (m^3)	2041 – 2050 (m^3)	2051 – 2055 (m^3)
Soft Organics	1,339	107,689	55,601	32,087	21,795	7,786
Soil	115	5,465	3,937	7,277	4,326	79
Total LLW arisings	8,050	243,619	206,372	91,389	58,292	33,236

It can be seen that soft organics make up between around a quarter to a half of total LLW arisings, whilst soil also accounts for a significant, albeit smaller, proportion of the waste. Placing leachable wastes lower in the stack would increase the likelihood of saturation and hence leaching of contaminants. Given the relative volumes of the leachable wastes, the small amount of soil forecast to arise could easily be disposed of at the bottom of the stacks, whilst only a proportion of the soft organics could be placed lower down.

10.2. Operational considerations

Operationally, it would be straightforward to employ a strategy where soil disposals are placed in a specific part of the stacks, using buffer storage where necessary until an appropriate disposal position becomes available. For soft organics it would be more difficult to guarantee placement of containers in a specific part of the disposal areas: the relatively large volumes associated with such waste would rule out the use of buffer storage and, to ensure uninterrupted operations, containers would need to be placed wherever space was available. Therefore, this strategy would be extremely difficult to manage operationally.

Double handling of packages will correspondingly increase the conventional health and safety risk to operatives, however, this can be controlled through use of appropriate controls and procedures. The integrity of ISOs may degrade on timescales of the order of 10 years if exposed to the environment. Should packages be moved after they have started to degrade, exposure of workers to contaminated material (e.g. dust) could occur, in particular if damage occurs during the movement or emplacement. In addition, there may be the potential for increased worker dose from exposure via irradiation to stored waste compared with waste in vaults. These doses are likely to be low compared with annual limits, although monitoring will be required.

10.3. Impacts

The proposed strategy aims to reduce post-closure environmental impacts via the groundwater pathway by maximising dilution of leachate released from the facility in the geosphere or the biosphere.

Results from the analysis undertaken to support the 2008 Requirement 2 submission (Paksy and Henderson, 2008) suggest that leachate from contaminants placed at different locations within the facility will be subject to varying degrees of dilution as they enter the geosphere due to the existence of a number of potential near field – geosphere pathways. Thus, for example, contaminants from the trenches are released into the superficial deposits below the trenches, while contaminants from the vaults could either be released to the superficial deposits or to the sandstone via the vertical pathway. The amount of dilution in these aquifers differs by about a factor of 3 to 6 (higher in the sandstone), depending on the source release location (see Table 7).

Table 7: Dilution in the sandstone aquifer and the superficial deposits for source release locations considered in Paksy and Henderson (2008)

	Trenches	**Vault 8**	**Vault 9**	**Future vaults**
Groundwater flux in superficial deposits (m^3 d^{-1})	188	116	193	205
Groundwater flux in sandstone (m^3 d^{-1})	682	682	682	682
Dilution ratio (sandstone / superficial deposits)	3.6	5.9	3.5	3.3

The impact of the strategy is assessed via the analysis of a possible scenario of achieving enhanced dilution. This is based on the assumption that contaminants from waste placed closer to the vertical drains[2] and higher up in the vaults are more likely to be released via

[2] Note that the analysis is based on a design concept that has been superseded. The currently proposed design no longer includes a vertical drain (Appendix B). Nevertheless the analysis remains relevant as it supports the conclusion of this section which is considered unaffected by the design change.

the vertical drains to the sandstone aquifer, and therefore are subject to higher dilution in the geosphere. However, it should be noted that this assumption is conditional on the presence of vertical drains and also on a release scenario in which there is significant flow through the vertical drains due to the bathtubbing of the vaults. If these assumptions are not true (i.e. no vertical drain and no bathtubbing), contaminants from the vaults will also be released to the superficial deposits and thus diluted by the same factor irrespective of location.

The proportion of contaminants routed to the vertical drain and to the superficial deposits from the vaults is highly uncertain and depends on the wider hydrological conditions and the performance of near-field engineering. An additional factor to note is that the pathway via the vertical drain is unlikely to be operational until after a few hundred years after site closure (if at all). Therefore, the strategy can only affect contaminants that are present at the facility after a few hundred years.

The example detailed above highlights that it is extremely difficult to determine those areas where dilution is likely to be greatest; there will be significant variations in groundwater flux through the vaults. Without a thorough understanding of the variation of flux within the vaults, which would be difficult to obtain, it is not possible to determine the benefits or disadvantages of the strategy in terms of impacts.

10.4. Summary

This strategy involves placing waste in locations where subsequent dilution in the geosphere and biosphere will be enhanced. However, it would be difficult to identify robustly regions of the repository where such high dilution would occur. In addition, operationally, this strategy would be extremely difficult to manage. Therefore it is considered that the disadvantages of this strategy outweigh any potential benefits.

11. Review of Strategy H: Emplacement of higher activity waste deeper in the facility

This strategy involves the emplacement of waste containing the highest activities (relating to operational as well as post-closure doses) deeper in the facility and avoiding areas where higher stacking is used and areas closest to the edge of the cap where the cap is thinner. The focus of this strategy is operational doses (for which Co-60 is the key radionuclide) and human intrusion (for which the key radionuclide is Ra-226). The 2008 Requirement 2 performance calculations indicated that doses from other key radionuclides associated with human intrusion are below the relevant dose criteria (Galais and Fowler, 2008), although this conclusion may need to be revisited when the 2011 ESC assessment calculations have been completed.

With regard to coastal erosion, there might be a need to disperse key radionuclides (e.g. Am-241 and Pu-241) to reduce impacts rather than emplace wastes in a specific location. This is discussed under Strategy C (although coastal erosion is not seen as one of the key pathways for this strategy). It is noted that, as discussed in Section 14.1, these radionuclides are already associated with relatively large volumes of arisings from Sellafield, which potentially may be consigned with other waste streams thereby increasing the dilution.

11.1. Inventory considerations

Future arisings of Ra-226 are dominated by one relatively low volume future waste stream (see Section 4.1). Table 8 shows the volumes and total activities of waste streams contributing the largest proportions of activities for future disposals of Co-60, as taken from the LLWR 2009 baseline inventory (Lennon, 2009).

Table 8: Volumes and total activities of waste streams contributing the largest proportions of activities for future disposals of Co-60 to the LLWR

Radio-nuclide	Stream	Description	Stock (m^3)	2009-2020 (m^3)	2021-2030 (m^3)	2031-2040 (m^3)	2041-2050 (m^3)	2051-2055 (m^3)	Total Stream Activity (TBq)	% of Total Activity
Co-60	3S301	Decommissioning: Mild Steel	0	0	0	0	7517	614	8.13E+01	61.5
	3S305	Decommissioning: Stainless Steel	0	0	0	0	687	87	1.55E+01	11.7
	5H304	JET Decommissioning Tritiated Activated	0	1793	0	0	0	0	1.38E+01	10.4
	2F20	LWR Pond Furniture (Racks and Frames)	0	6771	10	0	0	0	8.14E+00	6.2

Strategy H should be straightforward to implement for low-volume wastes. Over 70% of Co-60 activity is contributed by two waste streams comprising steel from Sizewell B decommissioning and which arise after 2040. Much of the remaining Co-60 activity arises in the early period up to 2020 and, being contributed by waste streams with relatively low activity concentrations, is represented in a significant volume (~9,000 m^3). It is considered that the waste volumes, whilst large, are low enough to enable specific placing of containers in the vault areas.

11.2. Operational considerations

The assessment of volumes of key waste streams (see inventory considerations) has shown that significant volumes are associated with key waste streams associated with operational and human intrusion doses. Buffer storage may be required where stacks are being operated close to the edges of the cap, or where the next available disposal spaces are in the upper sections of the stack.

Ungrouted containers must comply with the Transport Regulations, which will ensure that doses from, for example, Co-60 are acceptable. Occasional one-off consignments may need shielding after grouting (e.g. uncontainerised waste that is grouted against the vault wall); these items will meet the CFA but will not fit in an ISO. There would be a benefit in keeping doses from activities on the top of the stack to a minimum in order to protect the workforce involved in the final cap construction. However, the key issue here is contamination as opposed to activity.

Placing packages containing the highest concentrations of key radionuclides in the base of the stack will increase self-shielding and thereby reduce off-site radiation dose due to shine. However, doses to workers could potentially be increased. Associated impacts are considered to be comparatively small; however, monitoring will be required.

To implement this strategy, it is probable that temporary storage of packages/ISOs will be required to ensure that relevant waste streams are disposed in the correct part of the disposal facility. Such double handling will correspondingly increase the conventional health and safety risk to operatives, however, risks can be controlled through use of appropriate controls and procedures. Alternatively, consignors could be required to store waste until space at the LLWR becomes available.

In the use of temporary or buffer storage, increased record keeping will be needed to ensure formal waste tracking. A system would also be needed in order to identify relevant waste streams prior to consignment.

The integrity of ISOs may degrade on timescales of the order of 10 years if exposed to the environment. Should packages be moved after they have started to degrade, exposure of workers to contaminated material (e.g. dust) could occur, in particular if damage occurs during the movement or emplacement.

11.3. Impacts

The 2008 human intrusion assessment calculations indicated that the most important radionuclide is Ra-226 (Galais and Fowler, 2008). Assuming that waste packages containing high concentrations of this radionuclide can be identified at the time of placement and thus placed at an appropriate location within the vaults, the impact of this strategy is considered to be medium to high (around an order of magnitude reduction in risk or higher). This strategy would also result in a reduced probability of an intrusion event affecting the most active waste materials.

Reduction of doses associated with Ra-226 is also discussed under Strategy A. The 2008 assessment calculations showed that doses from other key radionuclides associated with human intrusion were significantly below the relevant dose criteria (Section 6.3). In this situation, activity concentrations of these radionuclides could be managed using limits in the new Authorisation, as opposed to initiating a specific emplacement strategy.

However, this conclusion may need to be revisited when the 2011 ESC human intrusion assessment calculations have been completed.

11.4. Summary

Given that a reduction in impacts associated with radon is covered under Strategy A and assuming that doses from other key radionuclides associated with human intrusion are significantly below the relevant dose criteria, no significant benefits are associated with this strategy. However, this conclusion may need to be revisited when the 2011 ESC human intrusion assessment calculations have been completed. This strategy would be complex operationally to undertake.

12. Review of Strategy I: Separate acidic ashes from wastes where acidity is likely to increase the mobility of contaminants.

This strategy involves the separation of acidic ashes from wastes where acidity is likely to increase the mobility of contaminants. Metallic wastes are amongst those most susceptible to acidic corrosion and hence potentially enhanced contaminant release. However, the dissolution rate of metal oxides was likely to be relatively low.

This strategy is aimed at reducing impacts via the groundwater pathway, with key radionuclides such as C-14, Tc-99 and uranium becoming more mobile in an acidic environment.

12.1. Inventory considerations

Currently very few waste streams are incinerated prior to LLWR disposal; however, as additional treatment methods to reduce disposal volumes become more commonplace, it is anticipated that greater amounts of ash may be generated. For the purposes of this study it is assumed that all soft organics will be incinerated prior to disposal with a volume reduction factor of around 50 (LLWR, 2009). Table 9 shows the forecast arisings of soft organics for LLWR disposal up to 2055 and the equivalent volume of ash this would produce, as taken from the LLWR 2009 baseline inventory (Lennon, 2009).

Table 9: Future forecast inventory of soft organics for LLWR disposal up to 2055

Waste Type	Stock (m^3)	2009 – 2020 (m^3)	2021 – 2030 (m^3)	2031 - 2040 (m^3)	2041 – 2050 (m^3)	2051 – 2055 (m^3)
Soft Organics (Raw)	1,339	107,689	55,601	32,087	21,795	7,786
Soft Organics (Ash)	27	2154	1112	642	436	156

It can be seen from Table 9 that, even with the assumption that all incinerable wastes are incinerated, the volumes of ash to be produced would be relatively small compared to the total volumes of LLW for disposal (see Table 4 for total volumes).

It is assumed that metallic wastes would be amongst those most susceptible to acidic conditions in terms of corrosion and hence contaminant release; therefore it is worth examining the quantities and timings of metallic waste arisings against those for ash given in Table 12. Volumes of key metallic waste streams up to 2055 are presented in Table 5. It can be seen that the key metallic arisings are predicted to occur in relatively similar volumes between 2009-2030 and 2031-2055, however, as noted previously, there is doubt over whether waste stream 2B03, which accounts for around 20% of future metal disposals up to 2055 and is scheduled for disposal in the period 2009-2030, will be disposed to the LLWR. Nevertheless, metallic arisings occur in line with the forecasts for the majority of ash arisings as shown in Table 9, therefore the separating of key metallic disposals from disposals of ash would require active management.

In summary, the amount of ash declared in the UK National Inventory is very low. Even if all incinerable wastes were incinerated, the total volumes of ash will be too low to have a significant effect on impacts (~2% of original volume). Similarly, volumes of metal waste arising from metal melting would be very low (~5% of original volume).

12.2. Operational considerations

Active management to separate consignments of metallic waste streams from ash would be required, possibly including the use of buffer storage and/or double-handling of containers. Alternatively, consignors could be required to store waste until space at the LLWR becomes available.

Double handling will correspondingly increase the conventional health and safety risk to operatives, however, risks can be controlled through use of appropriate controls and procedures. The integrity of ISOs may degrade on timescales of the order of 10 years if exposed to the environment. Should packages be moved after they have started to degrade, exposure of workers to contaminated material (e.g. dust) could occur, in particular if damage occurs during the movement or emplacement.

In addition, there may be the potential for increased worker dose from exposure via external irradiation to stored waste compared with waste in vaults. These doses are likely to be low compared with annual limits, however, monitoring will be required.

In the use of temporary or buffer storage, increased record keeping will be needed to ensure formal waste tracking. A system would also be needed in order to identify relevant waste streams prior to consignment.

The CFA are compatible with the acceptance of ashes (assuming correct packaging), although no ash has been received to date. In the use of temporary or buffer storage, increased record keeping will be needed to ensure formal waste tracking. A system would also be needed in order to identify relevant waste streams prior to consignment.

12.3. Impacts

Out of the key radionuclides, uranium, C-14 and Tc-99 are sensitive to pH either in terms of release from the waste or mobility within the near field. However, as already described for other strategies (see Strategies E and F), although changes in pH will affect the release and transport of these radionuclides, it does not significantly change peak risks. In addition, as discussed in Section 6.1, uranium and Tc-99 are not likely to be disposed in significant concentrations in the future vaults.

It is noted that the geochemical impact of this strategy on the near field as a whole would depend on the amount of acidic ashes disposed. For the purpose of this assessment, only a localised impact was assumed, given the likely amount of such wastes and the buffering effect of cementitious grout. In addition, the ashes may be alkaline or acidic in nature. Therefore the overall impact of this strategy on post-closure safety is considered to be minimal.

12.4. Summary

The effects on this strategy on impacts are likely to be minimal and it would be operationally complex to implement.

13. Review of Strategy J: Use of alternative waste placement strategies to improve stability

This strategy involves the use of alternative waste placement strategies to improve the stability of waste package stacks, e.g. brick wall stacking and placement of less robust packages higher in the stack.

This strategy is principally aimed at reducing the likelihood of a sudden collapse in the waste stack. However, this is a hypothetical situation that is highly unlikely to occur, even when the packages/ISOs are degraded as the integrity of packages/ISOs is less important than voidage in terms of settlement. Localised subsidence is accounted for in the cap design, and the LLWR are actively challenging consignors to meet the required voidage requirement.

13.1. Inventory considerations

The inventory of disposals is not considered to impact on this strategy.

13.2. Operational considerations

Placement of less-robust packages higher in the stack may require the use of buffer storage to hold such wastes until a suitable position within the stack becomes available. Alternatively, consignors could be required to store waste until suitable space becomes available at the LLWR. However, the operations team already routinely emplace packages with lower stability on top of the ISOs. A recommendation to cover new packages to avoid excessive localised failures is required.

The use of a 'brick wall' stacking strategy (i.e. overlapping of containers on successive rows) would necessitate the filling of the vaults on a row-by-row basis rather than the current stack-by-stack basis, to enable the overlaps to be made. However, this could facilitate employment of a number of the other emplacement strategies discussed in this report, such as dispersal of wastes containing key contaminants to avoid hot spots (Strategy C).

Brick wall stacking would involve changes to normal working practices. There is a potential that the new placement method required to achieve 'brick wall stacking' would lead to an additional hazard to workers. It is assumed that management controls will be in place to mitigate these hazards due to the additional work activities and that the strategy utilises existing safety procedures and trained and experienced personnel.

There may be a requirement to temporarily store waste on the site prior to emplacement. In this situation, there may be the potential for increased worker dose from exposure via external irradiation from stored waste compared with waste in the vaults. These doses are likely to be low compared with annual limits; however, monitoring will be required.

In the use of temporary or buffer storage, increased record keeping will be needed to ensure formal waste tracking. A system would also be needed in order to identify relevant waste streams prior to consignment.

The integrity of ISOs may degrade on timescales of the order of 10 years if exposed to the environment. Should packages be moved after they have started to degrade, exposure of workers to contaminated material (e.g. dust) could occur, in particular if damage occurs during the movement or emplacement.

13.3. Impacts

The physical stability of the waste in the facility is important for post-closure safety as it affects cap performance (collapse of waste stacks would cause differential settlement). The proposed future cap is designed to withstand an anticipated waste settlement of around 800 mm for the future vaults (Belton, 2007). Larger settlement than this would cause a stepwise change in cap performance, increased infiltration and gas release and potentially lead to increased releases via the groundwater and gas pathways.

The proposed strategy is aimed at reducing the likelihood of a sudden collapse rather than improving long term settlement performance[3], although it could have a minor beneficial impact on the latter. However, a sudden collapse is considered to be a hypothetical situation that is highly unlikely to occur, even when the packages/ISOs are degraded as the integrity of packages/ISOs is less important than voidage in terms of settlement. Localised subsidence is accounted for in the cap design, and the LLWR are actively challenging consignors to meet the required voidage requirement. It is therefore considered that this strategy will have a negligible effect on impacts.

Brick wall stacking would have no net benefit in reducing impacts via radon through increasing the length of the migration pathway.

13.4. Summary

The effects of this strategy on impacts will be minimal and it could be operationally complex to implement. Furthermore, the operations team already routinely emplace packages with lower stability on top of the ISOs.

[3] Waste settlement was originally estimated (Paksy, 2003) by consideration of gradual changes over time due waste degradation and overburden placed on the wastes. Sudden collapse of waste package stacks as a consequence of stack instability was not considered.

14. Review of Strategy K: Emplacement of selected waste packages in the upper part of the vaults where they are less likely to become saturated

This strategy involves the emplacement of selected waste packages in the upper part of the vault where they are less likely to become saturated and less exposed to degradation processes prior to erosion of the site. Target waste packages for this strategy include those containing leachable wastes and those containing higher concentrations of plutonium and americium.

This strategy is aimed at reducing impacts via the groundwater pathway, with key radionuclides including C-14, Tc-99, Np-237 and uranium (it is effectively the opposite of Strategy G). It is also aimed at reducing coastal erosion impacts arising from Am-241 and Pu-241; the highest risks via this pathway are associated with degradation which could cause these radionuclides to become associated with fine particles such as bottom crud, slime and corrosion products and hence pose a greater risk through inadvertent ingestion and inhalation.

14.1. Inventory considerations

Future forecast arisings of leachable wastes (i.e. soft organics and soil) are given in Table 6. It can be seen that soft organics make up between around a quarter to a half of total LLW arisings, whilst soil accounts for a significant, albeit smaller, smaller proportion of the waste. Placing leachable wastes higher in the stack would decrease the likelihood of saturation and hence leaching of contaminants. Given the relative volumes of the leachable wastes it is considered that the small amount of soil forecast to arise could easily be disposed at the top of the stacks, whilst only a proportion of the soft organics could be placed higher up. Those waste streams comprising soft organics with the highest concentrations of key contaminants should therefore be prioritised.

A summary of future waste streams contributing to the largest activities of plutonium and americium is given in Table 10, as taken from the LLWR 2009 baseline inventory (Lennon, 2009). Approximately 50% of americium arisings occurs in four waste streams (~14,000 m^3), whilst 70% of plutonium arisings occurs in three waste streams (~100,000 m^3).

Table 10: Future forecast inventory of waste streams contributing the largest activities of plutonium and americium for LLWR disposal up to 2055

Radio-nuclide	Stream No	Description	Stock (m^3)	2009 – 2030 (m^3)	2031 – 2055 (m^3)	Total Activity (TBq)	% of total Activity
Am	2X80	Railways Monitoring & Decontamination Facilities LLW	0	1,610	893.2	2.28E-01	14.6
	1A03	LLW Non-Compactable Non-Drummable	0	1,335	720	2.26-01	14.5
	5C303	Radiochemical Building Decommissioning LLW	0	2,023	0	1.85E-01	11.8
	2X20	Magnox Storage Pond and Decanning Facility	0	7,744	0	1.34E-01	8.6

Radio-nuclide	Stream No	Description	Stock (m^3)	2009 – 2030 (m^3)	2031 – 2055 (m^3)	Total Activity (TBq)	% of total Activity
Pu	7A27	Operational LLW Suitable for Disposal at the LLWR - Plutonium	0	11,705	4,450	1.89E+01	53.0
	2X68	Analytical Services Facilities	0	11,500	10,300	4.22E+00	11.8
	2D109	Miscellaneous Plants Initial/Interim Decommissioning	0	20,645	44,164	1.84E+00	5.2

Sellafield LLW streams are often disposed to the LLWR as mixed consignments. Routinely, three or four different waste streams may be present in a single container. It should therefore be noted that the key Sellafield waste streams containing significant proportions of the future forecast americium and plutonium inventory (i.e. 2X80, 2X20 and 2X68) could be consigned with other waste streams, significantly increasing the volumes to be considered. This would be difficult from an operational perspective, although the LLWR could require the consignor to ensure that individual waste streams are separated prior to disposal.

14.2. Operational considerations

This strategy considers placing selected waste packages (e.g. leachable wastes) in the upper part of the vault where they are less likely to become saturated and less exposed to degradation processes prior to erosion of the site. This is essentially the opposite of Strategy G. As discussed under Strategy G, leachable waste streams include soft, low-density organics and soil.

An assessment of the inventory has shown that there is a small amount of soil forecast to arise for future LLWR disposal, whilst soft organics make up around half of waste arisings in the near future. Operationally, it would therefore be straightforward to employ a strategy where soil disposals are placed near to or at the top of the stacks, using buffer storage where necessary until an appropriate disposal position becomes available. For soft organics it would be more difficult to guarantee placement of containers in the upper regions of the disposal areas: the very large volumes would rule out the use of buffer storage and, to ensure uninterrupted operations, containers would need to be placed wherever space was available. It is anticipated therefore that the strategy would be preferentially used for those waste streams comprising soft organics with the highest concentrations of key radionuclides.

To implement this strategy, it is possible that temporary storage of packages/ISOs will be required to ensure that relevant waste streams are disposed in the correct part of the disposal facility. Such double handling will correspondingly increase the conventional health and safety risk to operatives, however, risks can be controlled through use of appropriate controls and procedures.

In the use of temporary or buffer storage, increased record keeping will be needed to ensure formal waste tracking. A system would also be needed in order to identify relevant waste streams prior to consignment.

The integrity of ISOs may degrade on timescales of the order of 10 years if exposed to the environment. Should packages be moved after they have started to degrade, exposure of workers to contaminated material (e.g. dust) could occur, in particular if damage occurs during the movement or emplacement.

In addition, there may be the potential for increased worker dose from exposure via external irradiation to stored waste compared with waste in vaults. These doses are likely to be low compared with annual limits, however, monitoring will be required.

14.3. Impacts

The benefits of this strategy depend on the following factors:

- the likelihood and timing of waste saturation in the vaults as a function of depth; and
- the impact of water saturation on the degradation of waste packages and hence on release via the groundwater and coastal erosion pathways.

The first factor is a pre-condition for this strategy: there is no benefit either if the vaults are not saturated at any time, or if the vaults are saturated quickly to full depth. Therefore, this strategy is only worth considering for scenarios in which the vaults are saturating at a very low rate over time, or if they get saturated to a certain depth only. The likelihood of these scenarios is very difficult to judge and highly uncertain. It is noted that ongoing optimisation work is addressing the effect of stratification within the vaults, e.g. in the case of bathtubbing, water may only leach contaminants from the upper levels of the stacks. There also could be the situation when only the lower part of the stacks is saturated.

The impact of water saturation (the second factor above) is also very difficult to assess. The timing of vault saturation (assuming it occurs) may be assumed to be after a few hundred years after closure (Paksy, 2008). This leaves sufficient time for the effects of water saturation to take place before erosion of the site. From a geochemical viewpoint, full saturation could be important for increased availability of water and for the development (or quicker development) of anaerobic conditions.

The availability of water is unlikely to be a limiting factor in the future geochemical evolution of the vaults even if the system is unsaturated, because water will be available throughout the vaults due to other processes (e.g. capillary action, condensation and localised flows). It is also considered that anaerobic conditions are likely to develop within the vaults whether saturated or not. Therefore, given the large uncertainties associated with geochemical evolution of a complex system such as the vaults, it is concluded that full water saturation (as compared with a generally wet system) is unlikely to make a significant impact in terms of increased waste degradation and consequent release.

The strategy is also aimed at potentially reducing impacts associated with Pu-241 and Am-241 via coastal erosion; the highest risks are associated with these radionuclides and degradation could cause Pu-241 and Am-241 to become associated with fine particulates which poses a greater hazard via inhalation and inadvertent ingestion. However, it was unclear how corrosion rates could vary with stack height, thereby affecting the availability of these radionuclides.

Overall, it was considered to be difficult to quantify the benefits or disadvantages of this strategy in terms of impacts.

14.4. Summary

The effect of this strategy on impacts is highly uncertain and the strategy would be difficult to implement operationally.

15. Summary and conclusions

In support of the 2011 ESC, there is a need to demonstrate that all potential waste emplacement strategies for significant waste streams and types had been identified and assessed in terms of impacts on site operations, operational safety, environmental impacts (pre- and post-closure) and costs.

In developing potential emplacement strategies, we have considered a number of significant waste types, including those that are most likely to give rise to the most significant pre- and post-closure impacts:

- Waste containing high concentrations of the radionuclides that are most likely to be the key contributors to post-closure radiological impact (e.g. C-14, Cl-36, Tc-99, I-129, Ra-226, Th-232, uranium isotopes, plutonium isotopes and Am-241).
- High activity packages that could give rise to operational constraints (e.g. containing Co-60).
- Waste containing materials or chemicals that may have a direct impact on safety (e.g. toxic metals, organics and asbestos).
- Waste containing materials that may influence the future evolution of the disposed waste matrix. These include:
    - metals, which contribute to reducing conditions;
    - concrete, which contributes to high pH conditions; and
    - soil, which may act as a substrate for sorption of radionuclides.
- Large volume (probably low activity LLW) waste, e.g. soil and rubble.
- Materials that, due to their physical size and shape (e.g. very large items such as hex cylinders and redundant flasks), require packaging and disposal methods different to the majority of routine waste streams.
- Wastes that are subject to alternative treatment options (e.g. incineration, metal melting and chemical or physical decontamination).
- Wastes that are subject to different types of packaging and conditioning.

Taking into account these key waste types, a total of 11 potential strategies for the emplacement of waste in the future vaults at the LLWR (Vault 9 onwards) were elicited. These were:

A Place packages containing wastes likely to generate significant amounts of radon gas (i.e. those containing a significant radium inventory) lower in the waste stacks to reduce the probability that they are disturbed by human intrusion and to provide a longer decay path.

B Emplace packages or uncontainerised waste in an engineered sub-cell to improve containment. Sub-cell options could include a resistant/impermeable cap to discourage human intrusion and reduce releases in groundwater.

C Disperse packages containing high inventories in order to avoid small volumes of wastes containing relatively high concentrations of key radionuclides and other potential effects associated with the co-location of similar waste types.

D Separate C-14 containing wastes from other gas producing waste.

E Consideration of the effects of micro and macro grouting specific wastes, including C-14 bearing waste, Tc-99 in hex cylinders, uranium wastes and secondary wastes.

F Reduce release of uranium and Tc-99 in the groundwater pathway by providing a local reducing environment, perhaps by co-disposal with directly consigned metal waste.

G Place leachable wastes in locations where dilution would be relatively high.

H Place waste containing the highest activities (relating to operational as well as post-closure doses) deeper in the facility and avoiding areas where higher stacking is used and areas closest to the edge of the cap where the cap is thinner.

I Ensure separation of acidic ashes from wastes where acidity is likely to increase the mobility of contaminants.

J Use of alternative waste emplacement strategies to improve stack stability, e.g. emplacement of packages in a 'brick wall' configuration, and placement of less robust packages higher in the stack.

K Place selected waste packages in the upper part of the vault where they are less likely to become saturated and less exposed to degradation processes prior to erosion of the site.

These strategies were then assessed in terms of impacts on site operations, operational safety, environmental impacts (pre- and post-closure) and costs, with the aim of determining whether each strategy would work, what are the main benefits and disadvantages/costs and whether the strategy is worth considering further.

Previous assessments at the LLWR have shown that two key radionuclides for the groundwater pathway are uranium and Tc-99 (e.g. BNFL, 2002b). The majority of future arisings of both these radionuclides are associated with hex cylinders from Capenhurst. However, due to treatment, the LLWR now assumes that this waste stream will not be received for disposal with significant concentrations of either uranium or Tc-99. There are no other key future sources of these radionuclides.

For many of the strategies considered, it was difficult to identify or be confident of clear improvements in performance. For the majority of strategies, it was also concluded that the disadvantages outweigh any potential advantages. This was generally because no significant benefits were ascertained.

However, one strategy, Strategy A (emplacement of packages containing wastes likely to generate significant amounts of radon gas lower in the waste stacks), offers a real potential for reducing post-closure impacts, with a minimal effect on site operations. This is because the majority of future Ra-226 arisings (the main source of radon over the likely lifetime of the facility) are contained in a relatively small volume of waste. Operationally it would not be difficult to ensure that this waste is emplaced at the bottom of the stacks (i.e. in the bottom two ISOs) and there would not be a requirement for new buffer storage in addition to what will be already available on site. However, systems would need to be put in place to identify relevant waste streams prior to consignment in order to track waste held in temporary storage. The net effect of this strategy would be to directly reduce the probability of intrusion to the depth of the radium wastes. It will also increase the potential migration path for radon in the case of a building piercing the cap to such an extent that any radon gas entry to the building from this source would be negligible. No significant disadvantages were associated with this strategy.

It was also concluded that continued micro grouting of key waste streams (i.e. grouting within waste containers, in line with Strategy E), in particular wastes with a significant C-14 inventory, is likely to bring a benefit in terms of reducing releases via the groundwater and gas pathways. No significant disadvantages are associated with continuing this practice. Macro grouting is currently undertaken for large items that are directly grouted into the vaults, however, based on the current package design, the introduction of grouting between containers would have operational and cost implications and it was concluded that the disadvantages of this strategy outweighed any potential advantages.

In addition to the requirement to put systems in place to identify relevant Ra-226 bearing waste streams prior to consignment, there is a need for further management procedures to monitor future waste streams in order to identify changes that might result in additional controls being required. In particular, there is a requirement to monitor the metal inventory and assess how changes could affect the near field (metallic waste contributes to the creation of anaerobic conditions which reduce the mobility of key radionuclides such as Tc-99 and uranium).

Subsequent to the elicitation and assessment of potential emplacement strategies as described in Sections 3 to 14, changes to the design of the future vaults and closure engineering were proposed. The key design changes affect the cap design (allowing for higher stacking of ISOs), the heights of the internal vault walls and replacement of vertical drains by a vault under-drainage blanket. These changes have an effect on the elicited performance of some of the emplacement strategies, as detailed in Appendix 2. Most significantly, the potential greater depth of waste could further increase the effectiveness of Strategy A.

It is likely that the design change would alter near-field flow regimes by reducing the potential for bathtubbing and by encouraging horizontal flows within the vaults over 1 m depth of leachate towards the eastern and western edges. In addition, the lower internal vault walls and the vault under-drainage blanket are designed to allow only the lowermost ISO to saturate. However, although saturation conditions and the near-field flow regime influence the effectiveness of a number of the strategies including B, D, E, F, G, I and K, it is considered that these effects would not be significant within the bounds of the associated uncertainties.

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Appendix 1: Potential Emplacement Strategies elicited at the First Project Workshop of 17 November 2009

A list of potential emplacement strategies that were elicited at the first project workshop of 17 November 2009 is provided below. The strategies were classified according to potential exposure pathway and to waste type (as discussed in Section 2 of this report), with reference to radionuclides of significance to the 2011 ESC.

A summary is provided at the end of the list of strategies, along with an initial screening of which strategies are considered feasible for further consideration.

Gas pathway

Radon and C-14 are the most important gaseous radionuclides.

1. Place packages containing wastes likely to generate significant amounts of radon (Rn) gas (i.e. those containing radium (Ra-226) contamination) lower in the waste stacks to provide a longer decay path. Due to the short half life of Rn, the longer the pathway, the longer the time needed for gas to reach the accessible environment and the lower the associated environmental impacts. Rn migration is principally driven by pressure variations. [A specific commitment has been given by the LLWR to the Environment Agency to consider this issue.]

2. 'Brick wall' stacking of containers above Ra-containing wastes could increase the migration pathway length.

3. Place all Ra-containing wastes in a localised area and use a capping layer (e.g. clay) to reduce/remove gas flow. It was noted that a large volume of the Ra-containing wastes will arise from a MOD waste stream, which may not arise.

4. Separate Ra-containing wastes from other gas producing waste. This would be important if Rn migration is affected by landfill gas (however, it is considered that the pressure variations are much more significant).

5. Disperse Ra-containing wastes as much as possible to dilute Rn (would be most important if diffusion is an important transport mechanism).

6. Place packages containing wastes likely to generate significant amounts of C-14 gas lower in the waste stacks to provide a longer decay path. Due to the relatively long half life of C-14 (~5730 years) this will not be effective over the expected lifetime of the LLWR. In the longer-term, this could also increase the potential for dissolution of C-14 in groundwater (C-14 is a significant radionuclide for the well water extraction case).

7. 'Brick wall' stacking of containers above C-14 containing wastes could increase the migration pathway length. As discussed under (6), this will not be effective.

8. Place all C-14 containing wastes in a localised area and use a capping layer (e.g. clay) to reduce/remove gas flow. Any capping would need to completely encapsulate the wastes as C-14 can dissolve and migrate in groundwater. The

main sources of C-14 waste are waste streams from Winfrith and Windscale which will arise over the next few years and graphite, which is not expected until after 2100 and may not be consigned to the LLWR at all. However, even without the latter waste stream, the expected arisings of C-14 will be significant in terms of future impacts.

9. Separate C-14 containing wastes from other gas producing waste, in particular cellulosic wastes. C-14 is entrained by landfill gas (e.g. carbon dioxide and methane) and this is a significant influence on migration, as well as pressure variations.

It should be noted that incineration of C-14 generating waste types such as cellulosic material would remove at source the potential to generate C-14.

10. Disperse C-14 containing wastes as much as possible to dilute C-14 (would be most important if diffusion is an important transport mechanism).

11. An effective cementitious barrier could be used to prevent/reduce migration in the gas phase as cement reacts with gaseous C-14 to entrap it. Therefore, inclusion of as much cement grout in the package and container as possible and ensuring that materials are well mixed (micro grouting) and/or grouting between containers (macro grouting) could be beneficial. Could also place C-14 bearing wastes next to cementitious wastes.

Groundwater pathway

C-14, Cl-36 and Tc-99 are the most important radionuclides for the groundwater pathway over the next few thousand years (the expected lifetime of the LLWR). Most of the Tc-99 (and Np-237) is associated with hex cylinders from Capenhurst. There is an uncertainty about whether this exists as Tc-99 concentrations are based on a pessimistic estimate; Tc-99 is associated with residues inside the cylinders and could be cleaned out prior to consignment to LLWR.

12. Hex cylinders could be macro grouted. This would reduce voidage as well as have a positive effect on mobility.

13. Release of Tc-99 in the groundwater pathway is redox sensitive. Release could be reduced by providing a local reducing environment (partly provided by steel).

14. Place leachable wastes in the upper part of the vault where they are less likely to become saturated, and hence decrease the potential to leach into the regional groundwater. However, this could result in key radionuclides being preferentially leached into near-surface groundwater pathways and into the local streams, which could increase environmental impacts.

15. Place leachable wastes as far away from the coast as possible in order to increase the pathway to the marine environment and increase the potential for dilution. It was considered that, on the scale of the vaults, this would have a minimum effect.

16. Place leachable wastes in a location where dilution would be increased, potentially close to the vertical drains.

17. Distribute leachable wastes as evenly as possible throughout the vaults to reduce small volumes of wastes containing relatively high concentrations of key radionuclides. This may be difficult to arrange over more than one vault.

18. Use a less permeable engineered sub-cell to contain key waste streams.

19. Continue to grout uranium-bearing waste, which is redox sensitive. There is also a potential to create a local redox environment, e.g. using iron filings. Macro encapsulation of uranium-bearing wastes could also be used. There is currently a great uncertainty about the magnitude of the future uranium inventory.

20. Emplace peat mixed with soil under uranium-bearing waste, effectively forming a permeable reactive barrier.

Human intrusion

The key contributor to human intrusion doses/risks is Rn associated with a residential scenario. Emplacement strategies relating to Ra-bearing wastes are discussed under the gas pathway (items 1 to 5). Occupational scenarios tend to give rise to relatively low doses.

21. Disperse wastes to avoid small volumes of wastes containing relatively high concentrations of key radionuclides.

22. Place waste containing the highest activities deeper in the facility and avoiding areas where higher stacking is used and areas closest to the edge of the cap where the cap is thinner.

23. Place sealed sources in the centre of ISOs (encapsulated in cement).

24. Localised capping of selected waste to discourage intrusion.

Coastal erosion

Key radionuclides for coastal erosion include plutonium and americium. Rn is also an issue in terms of assessment of impacts to a user of a beach hut (a 'what if' scenario).

25. Emplace key wastes in eastern part of vaults. This will delay impacts occurring but will not significantly reduce their magnitude as peak doses/risks are associated with longer-lived radionuclides. There is also uncertainty regarding the direction of erosion.

26. Have as little monolithic waste as possible (i.e. minimise grouting) in order to increase dispersion when erosion is occurring.

27. Place packages containing higher concentrations of plutonium and americium higher in the stacks so that there is less of an opportunity for degradation of the waste form prior to erosion (plutonium and americium contamination is mainly associated with surface contamination).

28. Disperse wastes to avoid small volumes of wastes containing relatively high concentrations of key radionuclides.

Operational period

Co-60 is the radionuclide of significance in terms of operational dose. Rn is also a potential issue as it is observed in some buildings on site.

29. Place higher dose packages in the centre of the stack, avoiding the area of higher stacking. Such packages could also be placed next to the vault wall for self-shielding.

30. Place packages with greatest voidage potential higher in the stacks to maintain cap stability for as long as possible.

31. Place Rn-generating wastes in more exposed areas of the vaults (prior to capping) to allow dispersion of Rn, rather than potential accumulation in buildings on site.

Hazardous materials

Although radionuclides are likely to be the key differentiator with regard to consideration of emplacement strategies, chemical hazards also need to be considered. Significant quantities of asbestos arisings are anticipated. The hazard could be reduced by heat treating or encapsulation (prior to disposal).

32. Disperse wastes containing chemical contaminants to avoid small volumes of wastes containing relatively high concentrations of key contaminants.

33. Consider potential conflicts between chemical contaminants and radionuclides, in particular on the package scale.

Material that may influence the future evolution of the disposal system

This includes concrete, soil and metals, which are found in large volumes in the future inventory.

34. Crush concrete wastes to increase the surface area and hence the pH and sorption potential. It was noted that it might be difficult to convince consignors to do this.

35. Consider the mixing of waste from different consignors within single ISOs, e.g. C-14 bearing wastes with cement waste, Tc-99 and uranium with metallic waste and waste containing radionuclides that are likely to be highly sorbing with soils.

36. Keep waste dry. This could reduce the mobility of radionuclides, for example, non-gaseous radionuclides could not enter the groundwater pathway from dry waste. However, in the case of unsaturated (i.e. not fully saturated) waste, there is limited evidence on the impact of the unsaturation on release.

37. Avoid placing large volumes of these materials together. For example, large volumes of cellulosic materials could lead to voidage issues, whilst large volumes of metals could lead to heave after oxidation due to a volume increase during corrosion.

Large items

It was noted that large items such as heat exchangers and flasks would generally be cut up prior to reaching the LLWR (unless this is shown not to be the BPEO).

38. Concentrations of such large items could create hard spots, thereby increasing the potential for differential settlement to occur. This could be dealt with by dispersing waste or by macro encapsulation. A reinforced area of the cap could be used.

Alternative waste treatments

It was noted that some consignors sent waste that has been treated and encapsulated prior to arrival at the LLWR, e.g. Devonport resin catch tanks and grouted waste from WAGR. There was also a query as to whether ash is acceptable under the current CFA (the CFA will be subject to future revision). Secondary wastes are likely to be more stable than primary wastes, with the exception of residues from metal decontamination. They are also likely to contain higher concentrations of radionuclides. Ash leachate is likely to be acidic.

39. Alternative treatments for waste could provide more opportunity for mixing of wastes, e.g. ash from different consignors is unlikely to be separated prior to disposal. This gives the LLWR the opportunity to request more homogenisation of material from the treatment plants.

40. Graphite could be disposed uncontainerised in the LLWR as C-14 does not dissolve easily from graphite. There are no post-closure benefits in terms of stability or impacts of grouting such wastes. However, the material is likely to be very dusty and there is uncertainty as to whether graphite will be disposed at the LLWR. This strategy would contravene the current CFA.

41. Conditioning of ash, resins and sludges with grout may be needed.

42. Mix ash with alkaline waste streams or, potentially, use it as the PFA component of grout.

43. Place all ashes in a single engineered sub-vault to increase containment, although this may concentrate activity.

44. Ensure separation of acidic ashes from wastes where acidity is likely to increase the mobility of contaminants, e.g. uranium-bearing wastes.

45. Supercompaction will be less effective if alternative treatment methods are to be used. It is envisaged that most compactable wastes will in the future go to incineration (more efficient volume reduction).

46. Disperse high end LLW secondary wastes to avoid small volumes of wastes containing relatively high concentrations of key radionuclides.

High volume wastes

These wastes include soil and rubble and are likely to be low end LLW. There is no perceived benefit from containerising and grouting these wastes.

47. Use an engineered sub-cell to emplace un-containerised waste.

48. Emplace these wastes in gaps between ISOs.

49. Use these wastes to improve packaging efficiencies within ISOs (this is currently done using VLLW wastes).

50. Use LLW soil in a triangular area at the edges of the cap next to the areas of higher stacking (this is currently envisaged for VLLW).

Alternative packaging strategies

It was noted that package considerations are relatively unimportant with regard to post-closure impacts, however, they are of importance operationally. In future, ISOs may be reusable, with just the liners being disposed. Packages for secondary wastes could be smaller, although the design is yet to be finalised (it is unlikely that packages substantially smaller than the current ISOs will be introduced as disposal packages). There is a need to improve packing efficiency where possible.

51. Dispose waste in ISO liners (probably mild steel) as opposed to entire ISOs. It was noted that that such liners would need to maintain integrity over the operational lifetime of the LLWR in order to ensure that the leachate management system is not compromised.

52. Emplace containers next to each other (new design allowing emplacement of metal to metal) to avoid use of grout or other infill material between containers.

53. 'Brick laying' emplacement strategy for smaller packages.

54. Emplacement of more robust packages at base of stack to enhance stability.

Summary

Although a large number of potential strategies were identified at the workshop, there is a substantial amount of overlap between strategies for each waste type / pathway. Furthermore, from the discussions on the day, a number of potential strategies can be ruled out from further consideration.

Table 11 provides a summary of the strategies elicited and the reasoning for taking the topic forward for further consideration (or not). Following the table, a list is given of topics to be taken forward for assessment. These topics comprise future emplacement strategies that are considered to have a potential for reducing impacts (pre- and post-closure). It is noted that some potential strategies are mutually exclusive (e.g. the strategies involving dispersal versus containment of specific wastes).

Table 11: Summary of strategies elicited at the first project workshop and the reasoning for taking the topic forward (or not)

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
1	Place packages containing wastes likely to generate significant amounts of radon gas (i.e. those containing radium contamination) lower in the waste stacks to provide a longer decay path.	✓	A	It is considered that this strategy could significantly reduce impacts associated with radon. Furthermore a specific commitment has been given to the Environment Agency to consider this issue. This strategy will be taken forward for further consideration.
2	'Brick wall' stacking of containers above Ra-containing wastes to increase the migration pathway length.	✕		The increased migration pathway between containers caused by brick wall stacking is considered to be less significant than the effect of an increased pathway caused by disposing relevant waste deeper in the facility (see strategy 1).
3	Place all Ra-226 containing wastes in a localised area and use a capping layer (e.g. clay) to reduce/remove gas flow.	✓	B	This strategy will be taken forward under the engineered sub-cell option.
4	Separate Ra-containing wastes from other gas producing waste.	✕		Given that radon is not entrained in landfill gas (unlike C-14), this strategy is unlikely to provide significant benefit.
5	Disperse Ra-containing wastes as much as possible to dilute radon.	✓	C	This strategy will be taken forward under the dispersal of waste option.

Strategy number	**Strategy description**	**Consider further?**	**Included in topic**	**Reasoning**
6	Place packages containing wastes likely to generate significant amounts of C-14 gas lower in the waste stacks to provide a longer decay path.	✕		Due to the relatively long half-life of C-14 (5730 years), disposing of C-14 bearing waste streams deeper in the facility will not provide any significant benefit.
7	‘Brick wall’ stacking of containers above C-14 containing wastes could increase the migration pathway length.	✕		As discussed under strategy 2 for radon and strategy 6 for emplacement of C-14 wastes deeper in the stacks, this strategy will not provide any significant benefit.
8	Place all C-14 containing wastes in a localised area and use a capping layer (e.g. clay) to reduce/remove gas flow.	✓	B	This strategy will be taken forward under the engineered sub-cell option.
9	Separate C-14 containing wastes from other gas producing waste, in particular cellulosic wastes.	✓	D	The separation of C-14 waste from landfill gas generating waste will be taken forward for further consideration.
10	Disperse C-14 containing wastes as much as possible to dilute C-14.	✓	C	This strategy will be taken forward under the dispersal of waste option.
11	Use of a cementitious barrier to prevent/reduce migration of gaseous C-14.	✓	E	This strategy will be taken forward under the grouting option.

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
12	Hex cylinders could be macro grouted to reduce voidage and mobility of uranium and Tc-99.	✕	E	The treatment of hex cylinders is considered under a separate LLWR optimisation study (LLWR, 2008). They are unlikely to be received in their current form at the LLWR.
13	Reduce release of Tc-99 by providing a local reducing environment.	✓	F	This strategy will be taken forward under consideration of the effects of providing a local reducing environment.
14	Place leachable wastes in the upper part of the vault where they are less likely to become saturated.	✓	K	This strategy will be taken forward under consideration of the emplacement of leachable wastes in the upper parts of the future vaults.
15	Place leachable wastes as far away as possible from the coast in order to increase the pathway to the marine environment and increase the potential for dilution.	✕		On the scale of the vaults, this is unlikely to provide a significant benefit.
16	Place leachable wastes in a location where dilution would be increased.	✓	G	This strategy will be taken forward under consideration of enhanced leaching of wastes.
17	Distribute leachable wastes as evenly as possible throughout vaults to reduce small volumes of wastes containing relatively high concentrations of key radionuclides.	✓	C	This strategy will be taken forward under the dispersal of waste option.

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
18	Use a less permeable engineered sub-cell to contain key waste streams.	✓	B	This strategy will be taken forward under the engineered sub-cell option.
19	Continue to grout uranium-bearing waste, which is redox sensitive / create a local redox environment, e.g. using iron filings.	✓	E, F	This strategy will be taken forward under the grouting option and the creation of a redox environment.
20	Emplace peat mixed with soil under uranium-bearing waste, effectively forming a permeable reactive barrier.	✕		This option would be difficult to engineer and it is not a proven technology, therefore assessment of potential benefits would be extremely difficult. It is considered that use of novel technologies would not be suitable.
21	Disperse wastes to avoid small volumes of wastes containing relatively high concentrations of key radionuclides.	✓	C	This strategy will be taken forward under the dispersal of waste option.
22	Place waste containing the highest activities deeper in the facility and avoiding areas where higher stacking is used and areas closest to the edge of the cap where the cap is thinner.	✓	H	This strategy will be taken forward under the emplacement of key waste streams to minimise future human contact.

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
23	Place sealed sources in the centre of ISOs (encapsulated in cement).	✕		It is considered that there would be no long-term benefit for the coastal erosion or human intrusion pathways from this strategy. Furthermore, cement encapsulation is already used to minimise potential future contact.
24	Localised capping of selected waste to discourage intrusion.	✓	B	This strategy will be taken forward under the engineered sub-cell option.
25	Emplace key wastes in eastern part of vaults.	✕		This will delay impacts from coastal erosion occurring but will not significantly reduce their magnitude as peak doses/risks are associated with longer-lived radionuclides. There is also uncertainty regarding the direction of erosion. Therefore, this option is not likely to have a significant effect on overall impacts.
26	Have as little monolithic waste as possible (i.e. minimise grouting) in order to increase dispersion when erosion is occurring.	✓	E	This strategy will be taken forward under the grouting option.
27	Place packages containing higher concentrations of plutonium and americium higher in the stacks so that there is less of an opportunity for degradation of the waste form prior to erosion.	✓	K	This strategy will be taken forward under consideration of the emplacement of leachable wastes in the upper parts of the future vaults.

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
28	Disperse wastes to avoid small volumes of wastes containing relatively high concentrations of key radionuclides.	✓	C	This strategy will be taken forward under the dispersal of waste option.
29	Place higher dose packages in the centre of the stack, avoiding the area of higher stacking	✓	H	This strategy will be taken forward under the emplacement of key waste streams to minimise future human contact.
30	Place packages with greatest voidage potential higher in the stacks to maintain cap stability for as long as possible.	✕		Localised subsidence is accounted for in the cap design, and the LLWR are actively challenging consignors to meet the required voidage requirement. Relevant issues are covered under topic J.
31	Place radon-generating wastes in more exposed areas of the vaults (prior to capping) to allow dispersion of radon.	✕		The focus of this strategy is to prevent radon accumulation in buildings on site. However, this is not associated with significant impacts and could result in increased post-closure impacts.
32	Disperse wastes containing chemical contaminants to avoid small volumes of wastes containing relatively high concentrations of key contaminants.	✕		The dispersal of waste to avoid small volumes of wastes containing relatively high concentrations of key contaminants is considered under topic C. Asbestos is likely to be the most significant non-radioactive contaminant, which will be present in a large number of decommissioning waste streams.

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
33	Consider potential conflicts between chemical contaminants and radionuclides, in particular on the package scale	✕		Although not considered as a topic in its own right the effect of non-radioactive substances is considered under topics D, E and F.
34	Crush concrete wastes to increase the surface area and hence the pH and sorption potential.	✕		It is noted that this is a conditioning strategy as opposed to an emplacement strategy. Relevant issues are covered under topic E (grouting option).
35	Consider the mixing of waste from different consignors within single ISOs.	✕		Examples of mixing could include C-14 bearing wastes with cement waste, Tc-99 and uranium with metallic waste and waste containing radionuclides that are likely to be highly sorbing with soils. However, this would be operationally difficult to achieve. Relevant issues are covered under topics E and F.
36	Keep waste dry.	✓	K	Keeping waste dry could reduce the mobility of radionuclides, for example, non-gaseous radionuclides could not enter the groundwater pathway from dry waste. However, in the case of unsaturated (i.e. not fully saturated) waste, there is limited evidence on the impact of the unsaturation on release. The effect of keeping leachable wastes in the upper parts of the future vaults is considered under topic K.
37	Avoid placing large volumes of materials that may influence the evolution of the disposal system together	✓	C	Relevant materials include cellulosic materials, which could lead to voidage issues, and metals could lead to heave after oxidation due to a volume increase during corrosion. This strategy will be taken forward under the dispersal of waste option.

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
38	Avoid concentrations of large items which could create hard spots, thereby increasing the potential for differential settlement to occur	✕		This effect could be dealt with by dispersing waste or by macro encapsulation, which is covered under topic E. Cap design issues are outside the scope of this project.
39	Alternative treatments for waste could provide more opportunity for mixing of wastes.	✕		It was considered that this strategy relates to treatment options as opposed to providing an emplacement strategy and hence is outwith the scope of the current project.
40	Disposal of uncontainerised graphite.	✓	E	This strategy will be taken forward under the grouting option, whilst noting that this strategy contravenes the current CFA.
41	Conditioning of ash, resins and sludges with grout.	✓	E	This strategy will be taken forward under the grouting option.
42	Mix ash with alkaline waste streams or, potentially, use it as the PFA component of grout.	✓	E	This strategy will be taken forward under the grouting option.
43	Place ashes in a single engineered sub-vault to increase containment.	✓	B	This strategy will be taken forward under the engineered sub-cell option.
44	Ensure separation of acidic ashes from wastes where acidity is likely to increase mobility of contaminants.	✓	I	This strategy will be taken forward under the separation of acidic ashes from wastes where acidity is likely to increase the mobility of contaminants option.

Strategy number	Strategy description	Consider further?	Included in topic	Reasoning
45	Incineration of compactable waste.	✕		This strategy relates to treatment of waste rather than an emplacement strategy, and hence is outwith the scope of the current project.
46	Disperse high end LLW secondary wastes to avoid small volumes of wastes containing relatively high concentrations of key radionuclides.	✓	C	This strategy will be taken forward under the dispersal of waste option.
47	Use an engineered sub-cell to emplace un-containerised waste.	✕		This option contravenes the current CFA, however, it is discussed further under topic B).
48	Emplace high volume, low activity wastes in gaps between ISOs.	✕		A large gap would be needed to emplace high volume wastes in gaps between containers, contradicting the drive to place ISOs more closely together. As noted under strategy 47, un-containerised disposal is outside the scope of the current project.
49	Use high volume, low activity wastes to improve packaging efficiencies within ISOs.	✕		This is not considered an emplacement strategy (this is currently done using VLLW wastes).
50	Use LLW soil in a triangular area at the edges of the cap next to the areas of higher stacking.	✕		This strategy relates to cap design and hence is outside the scope of this project.

Strategy number	**Strategy description**	**Consider further?**	**Included in topic**	**Reasoning**
51	Dispose waste in ISO liners (probably mild steel) as opposed to entire ISOs.	✕		This strategy is considered a packaging issue as opposed to an emplacement strategy. It would have a minimal effect anticipated in terms of post-operational impacts, given that no credit is taken for the effects of containers in the post-closure period.
52	Emplace containers next to each other to avoid use of grout or other infill material between containers.	✕		The effect of grout is considered under the grouting option (topic E).
53	'Brick laying' emplacement strategy for smaller packages.	✓	J	This strategy will be taken forward under the use of emplacement strategies to improve stability.
54	Emplacement of more robust packages at base of stack to enhance stability.	✓	J	This strategy will be taken forward under the use of emplacement strategies to improve stability.

The options (topics) taken forward for further assessment were:

A Place packages containing wastes likely to generate significant amounts of radon gas (i.e. those containing a significant radium inventory) lower in the waste stacks to reduce the probability that they are disturbed by human intrusion and to provide a longer decay path.

B Emplace packages or uncontainerised waste in an engineered sub-cell to improve containment. Sub-cell options could include a resistant/impermeable cap to discourage human intrusion and reduce releases in groundwater. This strategy includes placement of uncontainerised soil and rubble.

C Disperse packages containing high inventories in order to avoid 'areas of higher concentration', and other potential effects associated with the co-location of similar waste types.

D Separate C-14 containing wastes from other gas producing waste.

E Consideration of the effects of micro and macro grouting specific wastes, including C-14 bearing waste, Tc-99 in hex cylinders, uranium wastes and secondary wastes. This also needs to take into account the effects of monolithic waste forms on coastal erosion impacts and the potential for using ash as the PFA component of grout.

F Reduce release of uranium and Tc-99 in the groundwater pathway by providing a local reducing environment, perhaps by co-disposal with directly consigned metal waste.

G Place leachable wastes in locations where dilution would be relatively high.

H Place waste containing the highest activities (relating to operational as well as post-closure doses) deeper in the facility and avoiding areas where higher stacking is used and areas closest to the edge of the cap where the cap is thinner.

I Ensure separation of acidic ashes from wastes where acidity is likely to increase the mobility of contaminants.

J Use of alternative waste placement strategies to improve stability, e.g. brick wall stacking and placement of less robust packages higher in the stack.

K Place selected waste packages in the upper part of the vault where they are less likely to become saturated and less exposed to degradation processes prior to erosion of the site. Target waste packages for this strategy include those containing leachable wastes and those containing higher concentrations of plutonium and americium.

Appendix 2: Assessment of the implications of future vault and closure engineering design changes

The design of the post-closure engineering system is subject to ongoing optimisation. Since the completion of Issue 0.1 of this report, the design concept has been updated as a result of this process. This appendix is concerned with the impact of the design update on the emplacement strategies described in the body of this report. A summary of the proposed changes to the design of the future vaults and closure engineering is provided in Egan (2010).

Design changes

In the new concept, a single dome cap replaces the gull wing design considered previously. Waste would be stacked into the space under the cap. Due to an increased cap elevation at the centre of the single dome as compared with the previous gull-wing design, there is a potential for higher stacking of waste packages. The new design considers higher stacking and profiling of waste stacks according to the available space under the cap and includes up to nine high stacking of half-height ISO containers in the vaults. This should be compared with a maximum of six high stacking considered in the gull wing cap design.

The heights of the internal vault walls to the east and west sides are reduced to 1 m above the base (in the previous design they were equal to, or higher than, the waste depth). This is to ensure that saturation over the depth of the waste column is precluded by overflow of leachate within each vault to the sides over the 1 m height walls.

The vertical drain is replaced by a vault under-drainage blanket, consisting of a continuous layer of drainage material installed under the basal liner. The vault base will now comprise concrete over geomembrane over bentonite enhanced soil (BES). The vault base is surrounded by free-draining materials providing a hydraulic link between the leachate in the vaults above 1 m waste and the vault under-drainage blanket. As a result, routing of leachate within the vaults and discharge to the geosphere differs significantly to that which may occur in the case of a vault design using a vertical drain.

The new design considers a reduced height of 1 m for the vault walls as compared with the ‘full height’ (i.e. equivalent to or higher than the waste depth) walls considered previously. This is to ensure that saturation over the depth of the waste column is precluded by overflow of leachate within each vault over the sides of the 1 m high walls.

There are also changes to the design of the cut-off wall, but these are not relevant for the consideration of emplacement strategies.

The implications of each of these aspects for potential emplacement strategies are discussed in the sub-sections below. Given that the latter two design features (i.e. the reduced height of the vault walls and the use of a vault under-drainage blanket) are both likely to influence saturation and flow regimes within the vaults, the implications of these are discussed under the same heading. The implications of the new design on the evolution of the near field are discussed in a subsequent section.

Higher stacking in the vaults

The implications of higher stacking of ISOs in the vaults include: increased importance of stack collapse, increased loads on the vault base and also on the bottom containers and a greater depth of waste in the vaults.

Increased waste depth in vaults

It is considered that the most important of these issues is the increased waste depth, combined with the fact that the depth of waste is not uniform. This will have implications for radon gas release and human intrusion; for areas of higher stacking the effectiveness and importance of Strategy A (place packages containing wastes likely to generate significant amounts of radon gas lower in the waste stacks) will be increased both to allow a longer decay path and to reduce the probability of human intrusion. This is simply because of the increased contrast between placing radium-bearing waste lower versus higher in the waste stack.

The effectiveness of Strategy H (emplacement of higher activity waste deeper in the facility) would also be increased for a similar reason, but this would not affect the overall conclusion regarding the significance of this strategy.

The higher stacking may also have a marginal effect on Strategy K; the use of higher stacking will allow emplacement of selected waste packages higher in the stacks where, it was postulated, they are less likely to become saturated. However, as discussed in Section 14, the effect of Strategy K on impacts is highly uncertain (as well as being difficult to implement operationally) and that conclusion remains in the case of higher stacking.

There could also, potentially, be a marginal effect on Strategy C (dispersal of contaminants to avoid small volumes of wastes containing relatively high concentrations of key radionuclides), whereby the increased depth of waste due to higher stacking could result in a more concentrated leachate load on to the vault base, assuming predominantly vertical transport along the stack of ISO containers.

Stack collapse

Stack collapse is mainly an issue for cap design optimisation and, potentially, for waste form development. However, it is also of relevance to Strategy J (use of alternative waste placement strategies to improve stability). Considerations for emplacement include:

- profiling should ensure maximum stability of stacks (e.g. consideration of gaps between stacks, steps between neighbouring stacks);
- there will be an increased importance of the structural integrity and load bearing capacity of the bottom containers (checking of integrity before use, monitoring of container condition during operations); and
- there will be an increased importance of precise placement of waste packages for stability of stacks (operational methods and procedures).

Under the new design, the waste containers on the very bottom of the vaults would be under increased stress due to an increased load and increased exposure to saturated conditions. The increased load will mostly be an issue for the operational period and during cap placement. It may be considered that either a specific container design is selected or otherwise management practices are put in place to ensure that the condition of the lowermost containers is maintained during the operational period up to the time of cap placement. As noted in Section 13, the operations team already routinely emplace packages with lower stability at the top of the ISO stacks.

Due to higher stacking, some of the cap refill material will be replaced with waste packages. Therefore, after cap placement, stresses on the bottom container will slightly differ from those in the case of the previous design (even assuming the same overall cap elevation) as a result of the difference between the densities of the cap profiling fill compared with the vault waste form density. This, however, is not considered to have a major impact on the structural integrity of the container and its evolution over time.

Reduced height of vault walls and the use of a vault under-drainage system as opposed to a vertical drain

One of the effects of a reduction in the height of the vault walls to the east and west sides combined with the use of vault under-drainage is that the containers at the bottom of the stacks are now much more likely to be exposed to saturated conditions compared with the others. It is thus likely that the design change would alter near-field flow regimes by reducing the potential for bathtubbing and by encouraging horizontal flows within the vaults over 1 m depth of leachate towards the eastern and western edges. This is different from likely dominant flow regimes under the previous design (vertical drain and higher walls), where horizontal flows were less significant due to higher vault walls. Also, in case of overtopping of the vault walls (in the old design), flows would be predominantly towards the trenches as opposed to towards both edges of the vaults. However, the most important difference is the likely lower saturation depth in the new design.

Changes in near-field flow regimes and saturation conditions directly affect Strategy K (emplacement of selected waste packages in the upper part of the vaults where they are less likely to become saturated). In addition, flow path changes within the vaults could affect the locations considered optimal for dilution (i.e. placement at the eastern edge may not be preferred as compared to placement at the western edge). Strategy G (emplacement of leachable wastes in locations where dilution would be relatively high) is affected by this issue. However, as discussed in Sections 10 and 14 respectively, the effects of both Strategies G and K on impacts were considered highly uncertain and both would be difficult to implement operationally. This conclusion is not altered by the new design.

Implications on the biogeochemical evolution of the near field

The proposed changes to the design of the future vaults and to the design of the closure engineering have the potential to influence the biogeochemical evolution of the near field and thus impact on the emplacement strategies described in this document.

The implications of the proposed changes, summarised above, for potential emplacement strategies, from the perspective of the biogeochemical evolution of the system, are described below.

Higher stacking of ISOs in the vaults, for example within the cap profile, may lead to the higher ISOs within each stack being more oxidised than the lower ISOs in the stack. This may promote oxidation of C-14 wastes, leading to lower releases as methane and thus an increase in release as carbonate. As discussed earlier, C-14 in the form of carbonate is subject to retention processes, such as carbonation of the grout, and thus slower release from the near field. There is a potential implication for Strategy D (separation of C-14 containing wastes from other gas producing waste) in that the separated C-14 waste could be placed higher in the stack, away from other gas producing waste to reduce the rate of release of C-14 through enhanced retention due to carbonation and lower incidence of landfill carrier gases. However, the same reservations associated with this strategy would remain, with the added factor of reduced pathlengths if C-14 was placed high in each stack.

As described above, a reduction in the height of the vault walls and the use of vault under-drainage would mean that the containers at the bottom of the stacks are now more likely to be exposed to saturated conditions as compared with the others. Therefore, the base layer would be expected to be more strongly reducing than other containers, with consequent lower mobility for many radionuclides through solubility controls or slower release of activation products from metals through lower corrosion rates. This has a direct implication on Strategy F, which is aimed at providing a locally reducing environment to lower the mobility and release of uranium and technetium.

Assessment of impacts on strategies

A summary of the overall impacts of the engineering design changes on the elicited potential emplacement strategies is presented in Table 12.

Table 12: Assessment of the impact of design changes on potential emplacement strategies

Strategy	Issue	Assessment	Impact on effectiveness of strategy due to design change
A	waste depth	Strategy could be more effective given the greater depth of waste.	Increased effectiveness
B	near-field flow regime	The effectiveness of this strategy for the groundwater pathway is dependent on the impact of engineered barriers on near-field flows. Changes in the near-field flow regime will therefore influence the effectiveness of the strategy. However, due to the complexity of processes controlling source release and near-field flows and uncertainties associated with these, it is not possible to come to a clear conclusion as to the impact of design change on the effectiveness of the strategy.	Not significant within the bounds of uncertainties
C	none identified	Not affected by design changes.	No impact
D	waste depth, waste saturation	Separated C-14 waste could be placed higher in the stack, away from other gas producing waste to reduce the rate of release of C-14 through enhanced retention due to carbonation and lower incidence of landfill carrier gases. However, the same reservations associated with this strategy would remain, with the added factor of reduced pathlengths if C-14 was placed high in each stack.	Unlikely to be significant within the bounds of uncertainties; will also reduce C-14 migration path length to surface
E	waste depth, waste saturation	The effectiveness of this strategy is dependent on the geochemistry of the system. Changes in waste saturation and waste depth influence geochemical conditions and therefore the effectiveness of the strategy. However, the uncertainties concerning the relationship between depth and redox conditions, and state of water saturation and redox conditions (Eh) are large. Therefore it is not possible to come to a clear conclusion as to the impact of design changes on the effectiveness of the strategy.	Not significant within the bounds of uncertainties

Strategy	**Issue**	**Assessment**	**Impact on effectiveness of strategy due to design change**
F	waste saturation	The strategy is based on providing a reducing environment. Changes in waste saturation influence redox conditions, and therefore the effectiveness of the strategy. However, the uncertainties concerning the relationship between the state of water saturation in the vaults and redox conditions are large. Therefore it is not possible to come to a clear conclusion as to the impact of the design change on the effectiveness of the strategy.	Not significant within the bounds of uncertainties
G	near-field flow regime	The strategy is based on the emplacement of waste at locations where subsequent dilution in the geosphere and biosphere will be enhanced. These locations are dependent on near-field flows. Changes in the near-field flow regime will therefore influence the effectiveness of the strategy. However, due to the complexity of processes controlling source release and near-field flows and uncertainties associated with these, it is not possible to come to a clear conclusion as to the impact of design changes on the effectiveness of the strategy.	Not significant within the bounds of uncertainties
H	waste depth	The strategy could be more effective given the greater depth. However, this issue is already covered under Strategy A. Given the greater significance of Strategy A, the impact is assessed as not significant.	Some impact (increased effectiveness), but not significant, as already covered by Strategy A.
I	waste saturation	Waste saturation will affect the effectiveness of this strategy due to the influence on redox potential. However, this impact is assessed as minimal and uncertain.	Not significant within the bounds of uncertainties
J	stack stability	Higher stacking could potentially increase the likelihood of sudden stack collapse, and this increases the importance of this strategy in the case of the new design. It is however assessed that this impact will be limited due to the application of appropriate procedures during operations.	Some impact, but of low significance, as stack collapse still assessed as of low likelihood.
K	waste depth waste saturation	The strategy is based on emplacement of waste packages higher up in the stacks where there are more likely to be unsaturated conditions. Given that the design changes influence saturation conditions and also that higher stacking increases the number of waste packages that could be placed higher up, this suggests that the effectiveness of the strategy would be increased by the design changes. It is noted, however, that the overall effectiveness of the strategy was assessed as difficult to quantify due to uncertainties, and thus the significance of increased effectiveness is doubtful (assessed as low).	Some impact (increased effectiveness), but of low significance

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