LLW Repository Ltd

LLWR Environmental Safety Case

Criticality Assessment for the LLWR 2011 ESC (Extended Disposal Area)

A report prepared by Serco for and on behalf of the Low Level Waste Repository Site Licence Company.

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Prepared for	**LLW Repository Ltd**
Prepared by	**Serco**
Your Reference	**9020/4510275534f**
Our Reference	**TCS/004817/002 Version 1**

27 April 2011

Design | Advise | Integrate | Deliver

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Executive Summary

LLW Repository Limited (LLWR Ltd.) is undertaking a programme of work that will result in the publication of a new Environmental Safety Case by May 2011 (the 2011 ESC). The 2011 ESC will be submitted to the Environment Agency in support of a formal application for re-authorisation of disposal operations.

The 2011 ESC is based on a reference design that assumes five additional vaults will be created in the future (i.e. Vaults 10 to 14) and that the facility will reach volumetric capacity at c. 2080. Predictions of future arisings from the UK nuclear decommissioning programme, however, indicate that this capacity will be insufficient to accommodate all future Low level Waste (LLW) disposal requirements. In addition, there is a strong likelihood that additional LLW will be generated as a result of any future new nuclear build programme.

LLWR Ltd. is therefore considering the disposal of a greater volume of LLW to the facility than is in the reference plan. This variant would involve the creation of further vaults to be used for disposal of the remaining UK LLW arisings in the UK Radioactive Waste Inventory (based on some assumptions about VLLW diversion and waste treatment). The additional vaults are referred to as the Extended Disposal Area (EDA), and the main ESC design as the Reference Disposal Area (RDA).

A safety assessment for the EDA repository will be presented as a variant in the 2011 ESC. The intention is to provide information important to national plans for LLW management.

This document utilises the RDA repository criticality safety assessment (CSA) to demonstrate that the possibility of criticality in the EDA is also so remote that it can be discounted. In instances where the existing CSA does not bound the EDA design, additional assessment is carried out to demonstrate that the probability of criticality would still be negligible.

The Safety Case WAC (SCW) limits will only permit very small quantities of fissile material in waste consignments. In each container (or consignment), the permitted quantity of fissile material will be significantly less than a critical mass.

In the operational phase, it has also been shown that the SCW limits ensure that there is no significant probability of criticality from the hypothetical case of material accumulation being formed by a small group of containers, i.e. if a composite critical mass were envisaged as forming on a common edge or at a common vertex within a group of containers. The EDA waste inventory differs from the RDA inventory in that much greater quantities of graphite are expected to be present. The graphite in the EDA inventory has been assessed and it has also been shown that, even with the expected quantities of graphite, the probability of criticality in the EDA would still be negligible.

During the post-closure phase, the potential relocation of fissile material, for example by groundwater flows, might result in a critical accumulation of fissile material. However the probability of such an event is shown to be negligible in the RDA assessment. The changes required to construct the EDA repository have been assessed and do not alter this conclusion.

This assessment concludes that the candidate SCW (Table 2) proposed in the RDA Criticality Assessment will remain suitable for the proposed LLWR EDA design.

Contents

Glossary of abbreviations and technical terms

The abbreviations and other technical terms used in this report are defined here for convenience

Term	Meaning
Areal density	The ratio of the quantity of a substance in a given body to the area given by the projection of the body onto a reference plane.
Concentration	The mass of a substance, in criticality typically a fissile material or a neutron poison, within a unit volume.
Critical	The exact point (or values) at which criticality becomes possible.
Criticality	The establishment of a self-sustaining nuclear chain reaction in a material or system of materials.
Diluent	In neutronics, a diluent is a material such as the oxygen in uranium dioxide. Diluent atoms increase the spacing between fissile atoms and increase neutron scattering.
EA	The Environment Agency.
EDA	Extended Disposal Area.
ESC	Environmental Safety Case.
Effective moderator	In this report, this term is used to denote a moderator that minimises the number of neutron scattering collisions needed to slow fission neutrons to thermal energies. Hydrogenous materials, for example water, oil and polythene are the most effective moderators and most effectively minimise the critical masses of fissile materials.
Efficient moderator	In this report, this term is used to denote a moderator that minimises the number of neutrons lost by capture events during the scattering collisions needed to slow fission neutrons to thermal energies. Graphite, heavy water and beryllium are the most efficient moderators. Natural uranium can only be made to go critical if it is latticed in an efficient moderator, for example Magnox reactors use graphite, while CANDU reactors use heavy water.
Enrichment	The percentage by mass of ^{235}U in total uranium.
Far Field	The environment beyond the bounds of the near field.
Fissile material	Material capable of sustaining a nuclear chain reaction irrespective of the average energy of the neutrons involved.
Fission	A nuclear reaction in which a nucleus emits nuclear radiation and splits into two smaller nuclei.
GRM	Generalised Repository Model, a computer program that has been used for detailed modelling studies of the near field evolution of the LLWR.
GDF	Geological Disposal Facility - the UK term for a proposed deep repository for ILW and HLW.
HEU	Highly Enriched Uranium, i.e. uranium where the predominant nuclide is ^{235}U.
IAEA	The International Atomic Energy Agency.
ISO	International Standards Organisation.
LEU	Low Enriched Uranium, fissile uranium with more ^{238}U than ^{235}U.
LLW	Low Level Waste.
LLWR	The Low Level Waste Repository in Cumbria.

Term	Meaning
Low Level Waste	Radioactive waste with a radioactive content not exceeding four gigabecquerels per tonne (GBq/te) of alpha or 12 GBq/te of beta/gamma activity.
k-effective	The effective neutron multiplication factor, i.e. the ratio of the rate of neutron production to the rate of neutron loss. k-effective is used as a criticality safety index - a value of 1 indicates a critical system and a value of 0.95 or less indicates an acceptably safe system.
Moderation	The process by which neutrons lose energy as a result of successive collision with atomic nuclei.
Moderator	Material with which neutrons collide and thereby lose energy.
NDA	Nuclear Decommissioning Authority.
NS-GRA	The UK Environment Agency document “Near-surface Disposal Facilities on Land for Solid Radioactive Wastes, Guidance on Requirements for Authorisation”.
Near Field	The environment in and around the repository, including any ground disturbed by its construction.
Neutron absorber	A material with the ability to absorb neutrons.
Neutron leakage	The escape of neutrons beyond the boundaries of a fissile system.
Neutron poison	A neutron absorber used to prevent criticality.
Neutron scattering	Collision events between neutrons and nuclei from which the neutrons rebound with changed energy and direction.
RDA	Reference Disposal Area
SCW	Safety Case WAC waste acceptance criteria – candidate fissile limits based on the latest operational criticality safety assessments for the LLWR.
Safety Factor	The ratio of a safe limit to the maximum predicted system value. For example, if an aqueous system can reach a maximum fissile concentration of 0.5 g/litre under fault conditions and the safety limit is 10 g/litre, the safety factor is (10 / 0.5) = 20.
VLLW	Very Low Level Waste.
WAC	Waste Acceptance Criteria. In this report, these refer to the current operating limits, as published by LLWR Ltd.

1 Introduction

1.1 Purpose

LLW Repository Limited (LLWR Ltd) is undertaking a programme of work that will result in the publication of a new Environmental Safety Case by May 2011 (the 2011 ESC). The 2011 ESC will be submitted to the Environment Agency in support of a formal application for re-authorisation of disposal operations.

The 2011 ESC is based on a reference design that assumes five additional vaults will be created in the future (i.e. Vaults 10 to 14) [1] and that the facility will reach volumetric capacity at c. 2080 [1]. Predictions of future arisings from the UK nuclear decommissioning programme, however, indicate that this capacity will be insufficient to accommodate all future Low level Waste (LLW) disposal requirements [2]. In addition, there is a strong likelihood that additional LLW will be generated as a result of any future new nuclear build programme.

LLWR Ltd is therefore considering the disposal of a greater volume of LLW to the facility than is in the reference plan. This variant would involve the creation of further vaults to be used for disposal of the remaining UK LLW arisings in the UK Radioactive Waste Inventory (based on some assumptions about VLLW diversion and waste treatment). The additional vaults are referred to as the Extended Disposal Area (EDA), and the main ESC design as the Reference Disposal Area (RDA).

A safety assessment for the EDA repository will be presented as a variant in the 2011 ESC. The intention is to provide information important to national plans for LLW management.

This document utilises the RDA repository Criticality Assessment [3] to demonstrate that the possibility of criticality in the EDA is also so remote that it can be discounted. In instances where the existing criticality assessment does not bound the EDA design, additional assessment is carried out in order to demonstrate that the probability of criticality would still be negligible.

1.2 Environment Agency requirements for near surface LLW repositories

The EA requirements for near-surface repositories are given in the ‘NS-GRA’ [4], and the interpretation of these for criticality safety is discussed in the RDA Criticality Assessment [3].

At the LLWR, the Waste Acceptance Criteria (WAC) [5] only permit small quantities of fissile material (i.e. much less than a critical mass) to be present within waste consignments sent for disposal. Compliance with these criteria ensures that the probability of a criticality event in the LLWR will be negligible.

2 Description of the LLWR

2.1 Overview

A detailed description of the LLWR, up to the extent of the RDA, is provided in the 2011 ESC Engineering Design Report [1] and is summarised in the RDA Criticality Assessment [3]. This assessment considers the EDA, which compromises a series of further vaults that may be constructed on the southern perimeter of the RDA.

2.2 The Extended Disposal Area

2.2.1 Inventory

Assumptions regarding the additional volumetric disposal capacity likely to be required for the EDA are fundamental to the present study. Four main inventory cases [2] have been developed for this. A summary of these is provided below.

- Case A is a baseline case based on the declared UK Radioactive Waste Inventory and assumes that all identified LLW will be consigned to the LLWR, apart from wastes with known alternative disposal routes (e.g. to the Dounreay LLWR) and certain high-volume, low activity waste streams including Sellafield contaminated land).
- Case B is based on Case A, but includes additional volumes to represent wastes that might arise as a result of a future new build programme.
- Case C is based on Case A but examines the implications of introducing additional sorting and segregation measures, leading to reduced volumes (e.g. through more waste treatment or additional diversion of VLLW).
- Case D is based on Case A but takes into account the possibility that no wastes arising from contaminated land at NDA sites are routed to LLWR.

The inventory that could be consigned to the EDA represents an increase of approximately 50% over the total vault waste volume assumed in the reference design for the 2011 ESC. The EDA wastes also differ from the RDA wastes in that some waste streams will include potentially significant volumes of graphite from final reactor decommissioning. Graphite is a potential concern as it would exhibit very low neutron absorption, compared to a typical waste matrix.

The total waste volume in the EDA could amount to an additional 573,000 m^3 of total disposal volume beyond that assigned to Vaults 8 - 14 by the Case A inventory. Taking into account potential arisings from new build (Case B), this could rise to an additional total disposal volume of 730,000 m^3 above that assigned to Vaults 8 - 14 by the Case A inventory .

Performance assessment calculations for the main ESC examine the implications of all four inventory cases. In providing illustrative assessments of impacts that might arise from disposals to an EDA, it is considered that investigation of Cases A and B (assuming complete disposal of all relevant waste streams) is sufficient for the intended purpose. The EDA vault capacities are listed in Table 1.

Table 1 - Air-space capacities of additional vaults

	Inventory Case A (m^3)	Inventory Case B (m^3)
Vault 15	153000	202000
Vault 16	98000	148000
Vault 17	122000	136000
Vault 18	72000	83000
Vault 19	67000	83000
Vault 20	61000	78000
Total	573000	730000

The Radiological Assessment [6] lists the forward inventories by vault using data supplied in [2]. These inventory data are listed in Table 3 in Appendix A1. The EDA forward inventory predictions for Vaults 15 - 20 are bound, in terms of effective ^{235}U mass and effective ^{235}U enrichment values by the RDA forward inventories for Vaults 8 - 14. This comparison is presented graphically in Figure 3 in Appendix A1.

2.2.1.1 Graphite

One potentially significant difference between the inventory of the RDA and the EDA is the presence of much greater quantities of graphite within the EDA inventory (see Figure 4, taken from [7]). Such quantities could reduce safe fissile masses, as graphite can be a more efficient neutron reflector than water due to its low neutron absorption. Note that water remains a bounding moderator under these circumstances [8].

The total graphite inventory for the EDA is anticipated to be approximately 11,000 m^3, i.e. 3.7% of the total waste by volume. Most of the graphite will be consigned from a small number of decommissioning projects at reactor sites. Hence it is likely that this volume may be disposed of in a number of dedicated waste containers, with a quantity of about 10 m^3 per container and that these waste streams will not be associated with large fissile inventories.

2.2.2 Waste Acceptance Criteria

The methodology adopted in the RDA Criticality Assessment [3] is to assess the vaults on the basis that all containers can be loaded up to the declared fissile limits, as opposed to using container loadings predicted from the forecast fissile inventory. As a result, the RDA Criticality Assessment [3] demonstrates criticality safety on the basis of fissile limits in a candidate Safety Case WAC (SCW) as presented in Table 2.

Table 2 - Safety Case WAC (SCW) for fissile material

The fissile inventory of a LLW consignment* shall be:

(a) less than 0.15 kg (U235 + U233** + Pu),
or
(b) less than 0.3 kg U235 if the uranium enrichment does not exceed 5% U235 w.r.t. U,
or
(c) less than 1.0 kg U235 if the uranium enrichment does not exceed 1.6% U235 w.r.t. U,
or
(d) unrestricted if the uranium enrichment does not exceed 0.93% U235 w.r.t. U.

Categories (b), (c) and (d) above may also contain up to 0.015 kg of (U233 + Pu).

* A ‘LLW consignment’ in this context applies to any ISO freight container filled with waste. For non-containerised wastes, the above limits can be applied pro-rata per 20 m^3 of waste.

** The specific restriction on U233 only applies where the waste is derived from a plant or process which handled separated U233.

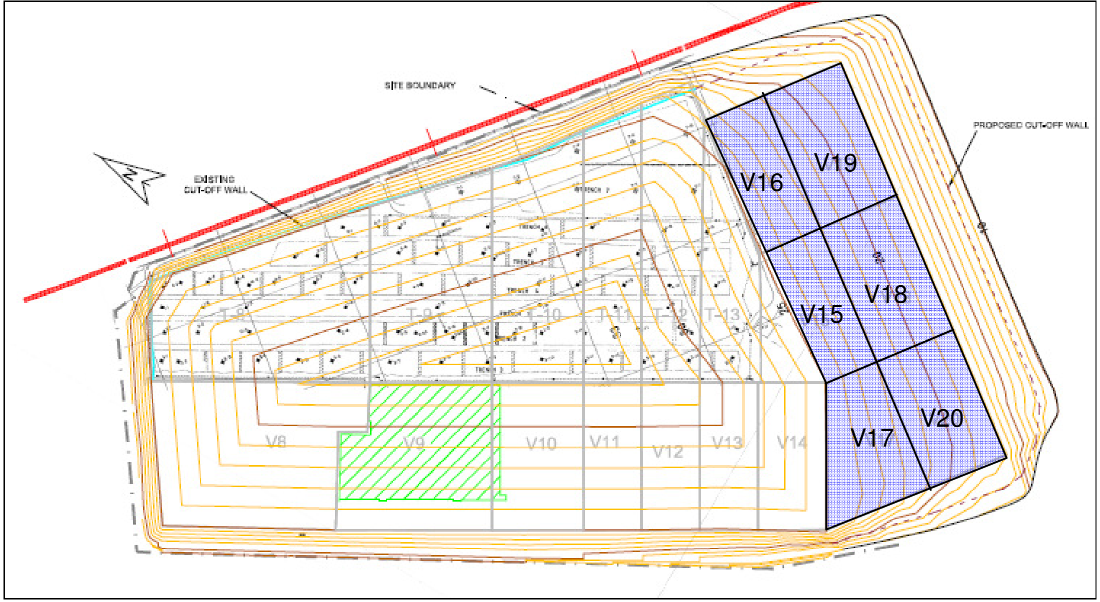
Note that fissile nuclides shall also be restricted as required by applicable activity limits.

2.2.3 Location

The proposed location and layout of the EDA is presented in Figure 1. It shows six additional vaults (15 to 20) to the south of the RDA as determined in the Engineering Design Optimisation Study [9].

Figure 1 - Schematic layout showing additional EDA vaults

(Vaults 15 to 20 are labelled as items V15 to V20 below)



2.2.4 Design

The Engineering Design Optimisation Study [9] reaches the following conclusions regarding the design of the EDA vaults:

- The basic features of the design for any additional vaults should be consistent with the 2011 ESC reference design.
- The vault bases and underlying passive drainage features should be at the same level as for vault 14, consistent with site topography.
- The vault bases should be appropriately sloped to facilitate active leachate management via a system of sumps. Operational leachate from the southern end of the trenches should be collected separately and pumped directly to the marine holding tank.
- The maximum cap dome height for the reference design should be retained, with the profile of the cap extended to the south to accommodate any additional vaults. The different disposal volumes required for different inventory cases (with and without new nuclear build) can be addressed by minor changes to the profile slope with a broadly similar overall footprint.
- The cut-off wall should be implemented to a depth of two metres deeper than in the reference design around the south and east perimeters of the additional vaults, in order to provide confidence against lateral inflows.

3 Observations from the RDA criticality assessment

The RDA criticality assessment [3] demonstrates that criticality safety of the LLWR depends on the following observations:

- The wastes at the LLWR are only permitted to contain limited quantities of fissile materials (i.e. enriched uranium and/or plutonium).

- As emplaced, the fissile material will be dispersed throughout the wastes, which may include much greater quantities of non-fissile uranium. The other waste materials will dilute the fissile material so that criticality is physically impossible.
- The post-closure design features of the LLWR will passively control the emplaced fissile materials and reduce water infiltration rates into the repository. Only very gradual changes will take place post-closure and groundwater flows will not lead to criticality.
- Groundwater and geochemical modelling studies have predicted the chemical reactions that will take place as the wastes degrade and interact with the groundwater. The results from these studies show that, in general, the solubility of the fissile material will remain at very low values for hundreds or even thousands of years. Hence the long-term transport of fissile material within the repository and from the repository to the underlying far field geology will be limited to quantities too small to give any significant possibility of criticality.
- In the vaults, the general conditions in the near field will be predominantly alkaline, so fissile material movements caused by localised evolutions of oxidising conditions will not result in large scale accumulations of fissile material. The alkaline background will be the result of the cement materials used in the grout backfill in waste containers and the concrete structures of the vaults. The equilibration of cement materials with groundwater will establish alkaline conditions through the dissolution of alkali metal hydroxides, including calcium hydroxide from the cement. These alkaline conditions will provide chemical containment of the fissile materials by means of solubility limitation, which will provide an upper limit to the dissolved concentration of the fissile materials in the groundwater. The alkaline conditions will also favour precipitation, co-precipitation and sorption, which will remove fissile materials from solution and hence reduce their migration both within and from the repository.

These observations will remain unaffected by the presence of the EDA and so will remain valid for the RDA design. The safety arguments for the RDA vaults are therefore applicable to the proposed EDA vaults. This is discussed in further detail in Sections 4 and 5 below.

4 Operational Assessment of the EDA

The criticality safety of Vaults 8 - 14 is demonstrated on the basis of the fissile limits that will be applied to each waste consignment [3]. The majority of consignments will be grouted waste containers, but items too big to fit into containers, for example redundant transport flasks, can also be disposed of to the vaults. The chosen safe mass limits ensure the safety of single containers, arrays of containers and provide sufficient safety margin to ensure safety under abnormal conditions.

This assessment follows the same approach; the sub-sections below extend the applicability of the RDA CSA [3] to the EDA.

4.1 Assessment for single disposal containers

Single disposal containers are assessed and shown safe in [3], [10] and [11]. These assessments provide a bounding case for all containers and show that there is a large safety margin associated with the SCW limits. However, the potential for wastes with a significant graphite content (e.g. several cubic metres of graphite per container) is not assessed and hence is discussed below.

Although graphite is one of the few very efficient moderators that can be used to manufacture a nuclear reactor fuelled by natural uranium [12], the critical and safe masses of enriched uranium and plutonium are much less with water moderation than with graphite moderation [8], [13]. For example, the bare minimum critical masses of ^{235}U are 1.3kg with water moderation and 5.3 kg with graphite moderation. Hence any potential effects of graphite as a moderator are bounded by the assumption of water moderation in [3].

The safe and critical fissile mass data in the RDA CSA [3] assume neutron reflection by either water or repository materials, for example soil and grout. In order to provide an estimate of the potential reductions in safe and critical fissile masses, data from [14] and [15] were used to evaluate the effects of graphite reflection. These references indicate that critical and safe masses would reduce by between 27% and 40% as a result of a change from water to graphite reflection.

It should be noted that this is a theoretical comparison based on pure metal spheres with either pure water or pure graphite reflection. Furthermore, large volumes of contiguous graphite would be required to provide full neutron reflection (e.g. volumes of at least 1 m^3 around a fissile accumulation) and any impurities or interstitial materials (e.g. grout infill) would act as neutron absorbers and reduce the potential for efficient neutron reflection.

In order to assess the significance of the graphite within the EDA waste, the reduction in critical fissile mass discussed above can be used. If a 40% reduction is applied to the ^{239}Pu critical mass (i.e. reducing it from 0.51 kg to 0.30 kg) then the SCW limit of 0.15 kg ^{239}Pu corresponds to 49% of a critical mass. Hence, for single containers, the SCW limits will safely bound the potential presence of significant graphite volumes in these wastes.

4.2 Assessment for arrays of disposal containers

In both the RDA and EDA, containers will be emplaced as a close-packed stack, up to nine containers high. Hence a formal assessment is required for the effects of neutron interactions between adjacent containers.

In any given container, any fissile material will be dispersed throughout a waste matrix that will be a mixture of materials such as paper, cardboard, wood, plastic sheeting, protective clothing, scrap metal, redundant equipment, process wastes, filters, resins, bricks, slag, ash, concrete and excavated soil.

Also, as far as is possible, any void space is filled with grout after the receipt of containers at the LLWR site. All of the waste materials and the grout will act to scatter neutrons, thus providing some moderation effects, but will also act as casual neutron poisons. So the expectation is that the k-effective value for arrays of containers loaded up to the customer WAC limit would be very low.

The RDA Criticality Assessment [3] assesses arrays of disposal containers under the assumption that, under normal conditions, the fissile material will be dispersed throughout the waste. Criticality safety is demonstrated on the basis of limiting surface density and safe infinite sea calculations.

The limiting surface density calculations in [3] demonstrate significant safety margins under conditions of concrete reflection. These results therefore suggest that a safety demonstration would also be possible for a waste matrix of graphite grouted into waste containers but, in the absence of specific data for such systems, cannot be claimed as formal proof of this. [13] shows that the critical infinite sea concentrations of ^{235}U and ^{239}Pu in pure graphite are 0.15 kg/m^3 and 0.1 kg/m^3. From these data, using the safety factor of 0.85 as discussed in [3], a safe waste container fissile limit for either ^{235}U or ^{239}Pu would be 0.85 kg if the container volumes are conservatively modelled as 10m^3.

It follows that, in the EDA, even if arrays of waste containers only contained pure graphite and fissile material, the SCW limits will ensure their safety. Furthermore, this safety justification will be valid for cases where the fissile material is distributed throughout the waste and for cases where the fissile material is in local accumulations.

4.3 Assessment for abnormal conditions

As ongoing container handling operations will be required to fill the EDA vaults, it is also appropriate to consider if potential fault conditions could affect the criticality safety of the disposal containers.

A hazard analysis for these operations was carried out within [10] and identified the following potential abnormal conditions for the disposal container emplacement operations:

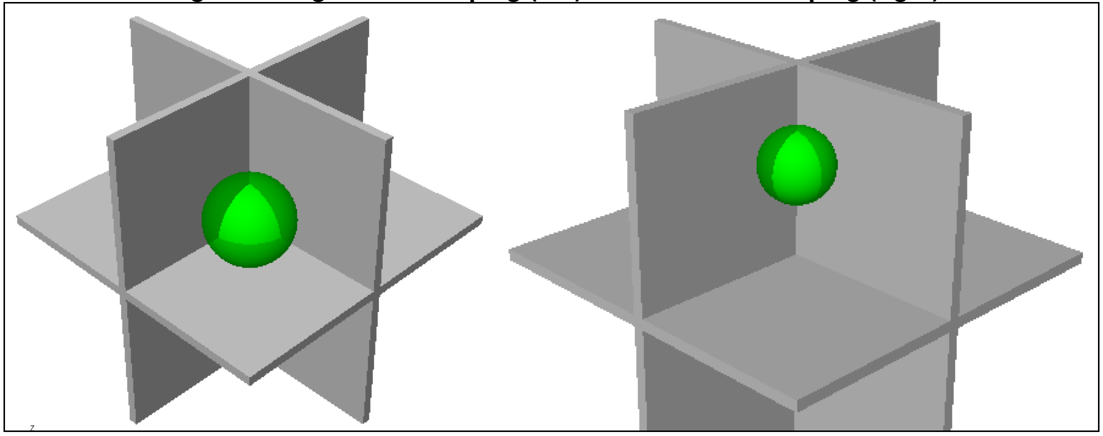
(a) Increased interaction
(b) High fissile inventory
(c) Inhomogeneity
(d) Improved moderation
(e) Over-stacking
(f) Manual handling accidents and spillage of LLW
(g) Migration during long term storage
(h) Fire/explosion, fire fighting and flooding

The RDA Criticality Assessment [3] provides a safety demonstration for each of these potential fault conditions. In summary, the hazards above do not challenge criticality safety on the basis that the normal conditions assessment uses conservative assumptions and methodology to bound abnormal conditions. These arguments are equally applicable to the EDA with the exception of the combination of increased interaction and inhomogeneity, as the potential effects of graphite reflection need to be considered for the EDA.

In the RDA Criticality Assessment [3] the SCW limits are intended to assure deterministic safety in the event of 'four unit clumping' (see Figure 2). This is where the reactivity of groups of four containers is maximised by co-locating all of their fissile material along a common edge, to form a composite sphere, so that neutron interactions are maximised and neutron leakage is minimised. Safety is demonstrated on the basis that SCW limits are effectively based on a quarter of a safe mass.

A more reactive case would be 'eight unit clumping', where all the fissile material from eight containers is co-located around their common vertex. It is shown in the RDA Criticality Assessment [3] that the probability of eight unit clumping (see Figure 2) is small enough to not require deterministic safety analysis.

Figure 2 - Eight unit clumping (left) and four unit clumping (right)



For the EDA, the presence of significant quantities of graphite means that the SCW limits are theoretically greater than a quarter of a safe mass and so if four unit clumping was considered possible, safety could not be assured.

However, the probability of four unit clumping in the RDA is to be estimated 1.5×10^{-7} [3] for the RDA at its maximum projected capacity of 63,000 containers. The EDA would increase the LLWR capacity by a further 36,000 containers to a total of 99,000. On this basis the estimated overall probability of a four unit clump might increase to 2.4 $\times 10^{-7}$. Then if the number of containers containing bulk graphite is approximately 1100 from the total of 99,000, it follows that the likelihood of a four unit clump involving one or more of the graphite containers will be approximately 2.6 $\times 10^{-9}$. This estimate indicates that the possibility is tolerably remote and suggests that reductions from the SCW limits should not be needed for containers containing graphite.

4.4 Inventory considerations

Although this assessment and the RDA Criticality Assessment [3] are based on packages containing fissile material at the SCW limit, it is helpful to consider the anticipated vault inventories in order to demonstrate an additional safety factor.

Table 3 in Appendix A1 lists the projected inventories for Vaults 15 - 20 (the EDA) and Vaults 8 - 14 (the RDA) for comparison. The inventories are listed for both case A and case B inventory scenarios. The information is also presented graphically in Figure 3. They show that the EDA anticipated inventories are bounded, both in terms of fissile mass and effective enrichment by the RDA inventories. Both RDA and EDA inventories are significantly below the assessed model, i.e. in which every package would be loaded to the SCW limit.

4.5 Operational assessment summary

In summary, the EDA vaults have been shown to be safe on the same basis as the RDA vaults from the following factors:

- The concentration of fissile material is very low within the overall waste volumes. Hence, the other materials in the waste will provide more than sufficient neutron absorption to prevent a critical chain reaction.
- A disposal container inventory limit of one quarter of a safe mass per package will ensure safety in the event of “four-unit clumping” on the basis that the probability of a criticality event would be tolerably remote.
- A simple probabilistic analysis has shown that the likelihood of “eight unit clumping” is negligible. Hence there is no need to limit disposal container inventories to one eighth of a safe mass as a safeguard against this eventuality.

The main difference from the RDA Criticality Assessment [3] is that the safety justification for the abnormal condition of ‘four unit clumping’ is based on the likelihood of such a scenario being tolerably remote for containers loaded with graphite.

5 Post-closure assessment of the EDA

5.1 Post-closure introduction

The RDA Criticality Assessment provides a post-closure criticality assessment for the vaults. In summary, four main potential routes have been identified that could lead to criticality post-closure [3]:

- Transport and accumulation of dissolved fissile material;
- Transport and accumulation of colloidal fissile material;
- Transport and accumulation of particulate fissile material;
- Concentration of fissile material due to repository slumping.

Whilst any of the above mechanisms can provide a potential risk of criticality, the degree of accumulation required for a criticality event is shown to lead to a negligible probability of criticality from any of these mechanisms [3]. The analysis in [3] shows that the low probability of criticality is a function of both the ratio of the typical accumulation volume needed for criticality relative to the overall waste volume and the number of container inventories that would need to accumulate before a critical event could occur.

One of the most important design features that reduces the probability of criticality is the grout infill used in the disposal containers. This will retard potential movements of fissile material from the containers in the vaults, so that the fissile material remains widely dispersed and critical accumulations will not form. This is achieved because:

- the chemical nature of the grout will promote an alkaline, low solubility environment;
- the physical nature of the grout will favour sorption and precipitation within the overall waste volume, as opposed to concentration in any particular part of each vault and;
- the neutronic properties of the grout make it reasonably effective as a diluent and as a casual neutron poison.
- the physical properties of the grout make it an effective void filler, so it is not likely that there would be water filled void spaces that could be good potential accumulation sites for criticality.
- the structural properties of the grout will also resist waste slumping.

The supporting geochemical modelling has shown that outflows of fissile material from the vaults to the far field will be at very low concentrations. No direct relationship has been observed between the container fissile limits and the outflow concentrations, so the post-closure assessment for the far field does not require any changes to the SCW limits set by [10].

5.2 Post-closure for the EDA

The differences in design between the RDA and the EDA are summarised in Section 2.2.4 and in more detail in the EDA Design Optimisation document [9]. From these observations, it is concluded that the criticality safety arguments presented in the RDA Criticality Assessment [3] are also applicable to the EDA repository. This view is also supported by the EDA GRM Near-Field Modelling [16], which finds that the chemical evolution of the EDA is similar to that of the RDA.

Hydrogeological modelling has been carried out for the EDA design [17]. Comparison of the RDA and EDA designs find that ground water flow rates are not sufficiently different to invalidate the findings in the RDA Criticality Assessment [3].

6 Discussion and conclusions

This assessment has considered the criticality safety of the LLWR EDA vaults, both for future operations and post-closure. The safety justifications presented in the RDA Criticality Assessment [3] have been shown to be mostly applicable to the EDA and where differences exist further justification has been provided.

During the operational phase, it been determined that the SCW limits are very conservative; hence, grouted waste containers do not pose any significant probability of criticality. The possibility of significant quantities of graphite in the EDA inventory has been considered and shown not to significantly increase the probability of criticality.

During the post-closure phase, vaults will contain fissile inventories sufficient to give the potential for criticality. The probability of a criticality event is, however, negligible on account of the repository design features and the low fissile limits on each container.

This assessment concludes that the candidate SCW (Table 2) proposed in the RDA Criticality Assessment [3] should remain suitable for the proposed LLWR EDA design.

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Appendix A I
Inventory Data

Table 3 - RDA and EDA vault inventories for case A and B scenarios

(Inventory Case) Vault	Mass (g)				Fissile Mass (g)	Effective Fissile (U235) Inventory (g)	Effective U235 Enrichment (U+1.56Pu) (%)	Volume (m^3)	Area (m^2)	Average Fissile Conc. (g/litre)	Average Fissile Areal Density (g/cm^2)
	U235	U238	Pu239	Pu240							
(A) 8	9.30E+04	4.67E+06	8.37E+02	2.71E+01	9.38E+04	9.43E+04	2.0	3.09E+05	111275	3.06E-04	8.48E-05
(A) 9	5.12E+05	5.11E+07	1.20E+03	4.50E+01	5.13E+05	5.14E+05	1.0	2.70E+05	100368	1.90E-03	5.12E-04
(A) 10	7.06E+05	1.05E+08	6.07E+02	1.87E+01	7.07E+05	7.07E+05	0.7	1.71E+05	54045	4.14E-03	1.31E-03
(A) 11	3.26E+05	4.84E+07	2.94E+02	7.20E+00	3.26E+05	3.26E+05	0.7	1.20E+05	38370	2.72E-03	8.50E-04
(A) 12	1.51E+04	6.28E+05	4.60E+02	1.15E+01	1.56E+04	1.58E+04	2.5	1.25E+05	42004	1.27E-04	3.77E-05
(A) 13	4.98E+04	1.62E+06	7.38E+02	2.69E+01	5.06E+04	5.10E+04	3.0	1.41E+05	28722	3.62E-04	1.78E-04
(A) 14	3.49E+04	8.27E+05	4.27E+01	4.21E+00	3.50E+04	3.50E+04	4.1	1.62E+05	30326	2.16E-04	1.15E-04
(A) 15	1.48E+04	8.59E+05	1.19E+01	1.92E+00	1.49E+04	1.49E+04	1.7	1.53E+05	28722	9.72E-05	5.18E-05
(A) 16	8.07E+03	4.91E+05	6.77E+00	1.08E+00	8.08E+03	8.09E+03	1.6	9.80E+04	28722	8.25E-05	2.82E-05
(A) 17	3.02E+03	7.83E+04	3.73E+00	4.28E-01	3.02E+03	3.03E+03	3.7	1.22E+05	28722	2.48E-05	1.05E-05
(A) 18	1.10E+03	5.20E+04	1.82E+00	2.96E-01	1.10E+03	1.10E+03	2.1	7.20E+04	28722	1.53E-05	3.83E-06
(A) 19	9.22E+02	4.37E+04	1.42E+00	2.40E-01	9.24E+02	9.25E+02	2.1	6.70E+04	28722	1.38E-05	3.22E-06
(A) 20	1.39E+03	6.46E+04	1.91E+00	3.49E-01	1.39E+03	1.39E+03	2.1	6.10E+04	28722	2.28E-05	4.83E-06
(B) 8	9.30E+04	4.67E+06	8.37E+02	2.71E+01	9.38E+04	9.43E+04	2.0	3.09E+05	111275	3.06E-04	8.48E-05
(B) 9	5.12E+05	5.10E+07	1.20E+03	4.50E+01	5.13E+05	5.14E+05	1.0	2.70E+05	100368	1.90E-03	5.12E-04
(B) 10	7.05E+05	1.05E+08	6.07E+02	1.86E+01	7.06E+05	7.06E+05	0.7	1.71E+05	54045	4.14E-03	1.31E-03
(B) 11	3.27E+05	4.86E+07	2.94E+02	7.20E+00	3.27E+05	3.27E+05	0.7	1.20E+05	38370	2.73E-03	8.53E-04
(B) 12	1.46E+04	6.12E+05	4.47E+02	1.11E+01	1.51E+04	1.53E+04	2.4	1.25E+05	42004	1.23E-04	3.65E-05
(B) 13	4.93E+04	1.61E+06	7.51E+02	2.71E+01	5.01E+04	5.05E+04	3.0	1.41E+05	28722	3.58E-04	1.76E-04
(B) 14	3.52E+04	8.27E+05	4.47E+01	4.32E+00	3.52E+04	3.53E+04	4.1	1.62E+05	30326	2.17E-04	1.16E-04
(B) 15	1.72E+04	1.04E+06	1.38E+01	2.30E+00	1.72E+04	1.72E+04	1.6	2.02E+05	28722	8.54E-05	6.00E-05
(B) 16	8.20E+03	3.63E+05	7.03E+00	9.09E-01	8.21E+03	8.21E+03	2.2	1.48E+05	28722	5.55E-05	2.86E-05
(B) 17	1.43E+03	6.09E+04	2.38E+00	3.56E-01	1.44E+03	1.44E+03	2.3	1.36E+05	28722	1.06E-05	5.01E-06
(B) 18	1.08E+03	5.13E+04	1.81E+00	2.91E-01	1.08E+03	1.08E+03	2.1	8.30E+04	28722	1.31E-05	3.77E-06
(B) 19	9.25E+02	4.37E+04	1.37E+00	2.38E-01	9.26E+02	9.27E+02	2.1	8.30E+04	28722	1.12E-05	3.23E-06
(B) 20	1.19E+03	5.56E+04	1.64E+00	3.01E-01	1.19E+03	1.20E+03	2.1	7.80E+04	28722	1.53E-05	4.16E-06

Figure 3 - Scatter plot for comparison of V8-14 (RDA) and V15-20 (EDA) inventories

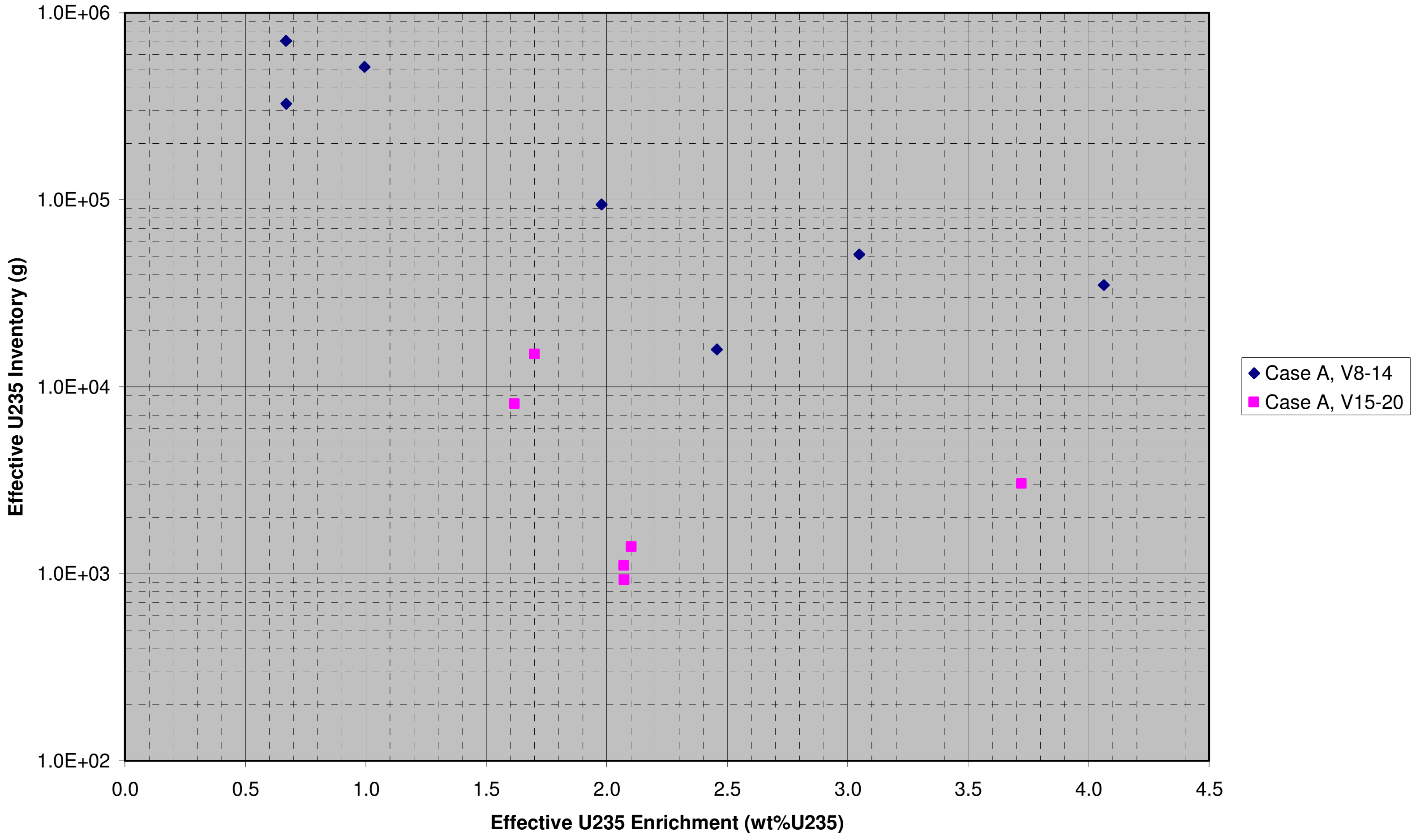

Figure 4 - Anticipated graphite inventory per year