Radioactive Waste Management

NDA Report no. DSSC/314/01

Geological Disposal

Generic Operational Safety Assessment
Volume 4 - Criticality Safety Assessment

December 2016

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Preface

Radioactive Waste Management Limited (RWM) has been established as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable programme for the geological disposal of the higher activity radioactive wastes in the UK. As a pioneer of nuclear technology, the UK has accumulated a legacy of higher activity wastes and material from electricity generation, defence activities and other industrial, medical and research activities. Most of this radioactive waste has already arisen and is being stored on an interim basis at nuclear sites across the UK. More will arise in the future from the continued operation and decommissioning of existing facilities and the operation and subsequent decommissioning of future nuclear power stations.

Geological disposal is the UK Government's policy for higher activity radioactive wastes. The principle of geological disposal is to isolate these wastes deep underground inside a suitable rock formation, to ensure that no harmful quantities of radioactivity will reach the surface environment. To achieve this, the wastes will be placed in an engineered underground facility – a geological disposal facility (GDF). The facility design will be based on a multi-barrier concept where natural and man-made barriers work together to isolate and contain the radioactive wastes.

To identify potentially suitable sites where a GDF could be located, the Government has developed a consent-based approach based on working with interested communities that are willing to participate in the siting process. The siting process is on-going and no site has yet been identified for a GDF.

Prior to site identification, RWM is undertaking preparatory studies which consider a number of generic geological host environments and a range of illustrative disposal concepts. As part of this work, RWM maintains a generic Disposal System Safety Case (DSSC). The generic DSSC is an integrated suite of documents which together give confidence that geological disposal can be implemented safely in the UK.

Executive Summary

The principal safety claim (SC) to be demonstrated for the criticality safety assessment is that:

OSC.SC4: All reasonably practicable steps will have been taken to implement design provisions whose function is to prevent or mitigate the consequences of nuclear accidents (i.e. unplanned criticality).

A criticality accident is an unplanned and uncontrolled chain reaction that results in a sudden release of energy and radiation. It can only occur when fissile material is present. A criticality accident can cause structural damage to the waste matrix and the immediate package. As a result, doses of radiation in the immediate vicinity can be harmful if no safety measures are provided to alert workers to the onset of an event and/or reduce the dose to safe levels. As the geological disposal facility (GDF) will contain wastes with fissile material, the safety assessment must demonstrate that the magnitude and likelihood of a criticality accident is less than the regulatory and Radioactive Waste Management Limited (RWM) safety criteria.

At this stage of the GDF programme the focus is on identifying key issues that need to be addressed in developing a criticality safety case. This approach is appropriate where the aim is to demonstrate that the management of significant hazards is possible. The level of assessment is appropriate for the current design development stage of the GDF; it is a feasibility study. The assessment summarises key aspects of criticality safety and presents specific arguments for fault conditions and criticality warning systems. No numerical assessments have been carried out due to the current illustrative nature of the design.

The criticality safety assessment includes emerging capability to identify waste streams that could credibly exceed their safe fissile mass limit. High uncertainty in the package contents is one factor in particular in this assessment. The capability will be developed further, and such packages assessed in greater depth, to ensure that any areas of uncertainty that would affect compliance with the safe fissile mass limits are understood and documented. The safety assessment also considers the Disposability Assessment process, the potential impact of ‘out of specification’ material and the credible faults identified in the preliminary fault schedule.

The assessment covers normal operations and design basis fault conditions. For normal operations, compliance by waste packagers with fissile limits will ensure that a criticality accident within the GDF is highly unlikely. The safety margins within fissile material limits will ensure that ‘out of specification’ waste packages do not pose a risk.

The design basis faults have been reviewed and the conclusions of the assessment are presented below.

Beyond design basis accidents (BDBA) such as rockfall are included in the preliminary fault schedule. Hazard management strategies discussed in Volume 1, will ensure that the facility is ‘passively safe’ in terms of disposal activities. This will include installation of robust rock support systems during construction. The safety argument is supported by all the factors included in setting fissile limits such that the risk is very low in all circumstances.

Low Heat Generating Waste

For Intermediate Level Waste (ILW), the fissile concentration in most of the conditioned waste is typically well below the level where criticality risk is a concern. Uncertainty and variability in the wasteform is accounted for when safety limits are set, by making conservative assumptions. The Disposability Assessment process provides the mechanism for checking that appropriate criticality controls are proposed and applied. Waste producers are required to develop criticality compliance assurance documentation that demonstrates how their procedures ensure the safe fissile masses will not be exceeded (now or in the future). Auditing of the waste producers' systems and procedures for the control of the fissile material content of waste packages is an integral part of demonstrating that the risk will be low.

Criticality in a single waste package is not possible during the operational period of the GDF due to the following factors:

- limits set on fissile package contents
- waste contains fissile nuclides distributed at low concentration with other non-fissile materials, so there would be very little neutron interaction between packages
- fissile limits are set assuming that the packages will be stored in arrays in the worst configuration. This means that any actual emplacement of the waste in large arrays within the GDF will not lead to a criticality

Dropping a waste package from a height much greater than its withstand capability could lead to failure of the package and a change of geometry, including redistribution of the contents. This will lead to a decrease in reactivity. Even if there was accumulation of fissile material in a single location this will still not exceed the criticality safety criterion.

The assessment has shown that the following sequence of events would result in the greatest criticality risk:

1. Failure to package waste in accordance with waste acceptance criteria, and
2. Failure to identify the deviation from waste acceptance criteria, and
3. Shipment of the 'out of specification' package, and
4. Emplacement with other 'out of specification' packages, and/or
5. Addition of moderator

More generally, two unlikely, independent, concurrent changes in the conditions essential to criticality safety are required for a criticality risk to occur (the 'double contingency' principle) and hence the likelihood is very low. Following the production of the procedures and processes at the waste producers' plants and at the GDF, the criticality safety arguments will be fully developed and a safety justification produced.

High Heat Generating Waste

High Level Waste (HLW) contains insufficient fissile material to present a criticality safety concern as the fission products have been separated from re-usable fissile material. In addition to the well mixed and passive nature of the vitrified wasteform, the concentration of fissile material per package is very low.

For spent fuel, the fissile concentration in the wasteform will be significantly higher than that found in ILW. However, there are other features of the wasteform and package design which contribute significantly to criticality safety:

- the wasteform will normally contain significant amounts of neutron absorbers and diluents in the form of U-238 and fission products
- packaging, storage and transport of spent fuel are mature technologies supported by safety assessment methodologies based on many decades of industrial experience at reactor sites and reprocessing centres
- the wasteform is well defined with less variability and uncertainty than ILW
- packaging arrangements could include, for example, the presence of fixed neutron absorbers in the container and internal furniture to maintain sub-critical configurations during GDF operation

- the robust wasteform and waste package prevent rearrangement of fissile material into an unsafe arrangement

For separated plutonium residues and highly enriched uranium, the wasteform will be engineered to provide a well-defined and stable material and where necessary, will include neutron absorbing material. The processed waste within the disposal container will be designed to be passively safe under any credible accident conditions that may occur during on-site storage, transport or emplacement at the GDF. The potential for post-event distribution and accumulation of spent fuel, for example on filters and sumps, has not been assessed at this stage.

For the majority of spent fuel, a major disruptive event leading to a change in geometry and the addition of water is required for a criticality accident. For fresh or low burn-up fuels, a criticality accident would require failure of the disposal container combined with loss of a system preventing flooding. Both of these examples meet the double contingency principle, ie, the independent and unlikely events of rockfall and an inrush of water would both have to occur concurrently for a criticality event to take place.

Dounreay Prototype Fast Reactor fuel is a potential exception as it has higher enrichment and therefore the potential to create a criticality without addition of a moderator. This fuel will require specific consideration as the waste package design is developed. It should be noted that the amount of fuel in a package will be limited to meet other requirements, for example to limit heat output and ensure post-closure safety.

Criticality warning systems

The illustrative criticality safety assessment has included an initial review of the requirements for the provision of a criticality warning system in line with regulatory guidance and the Nuclear Operational Safety Manual (NOSM). The initial assessment concluded that a criticality warning system including a criticality incident detection and alarm system will not be required in the GDF. The nature of the packaged waste material is inherently unfavourable for criticality and a control failure on waste packaging will not result in a critical configuration. Normal operations in the GDF will not result in a change of configuration from sub-critical to critical, mainly due to the immobility of waste inside most packages and the robustness of the packages themselves. This conclusion will be kept under review as the design develops.

Concluding remarks

The extent to which the principal safety claim (OSC.SC4) has been demonstrated is summarised below.

The illustrative criticality safety assessment presents evidence related to the process that has been followed, the scope of the assessment, nature of hazards identified requiring design provisions, regulatory expectation related to their control, and hazard management strategies that will need to be adopted to prevent or minimise the consequences of criticality accidents.

The nature of the waste material is inherently unfavourable to criticality and the failure of controls on waste packaging would not result in a critical configuration, either in individual packages or in combination. Normal operations at the GDF would not result in a change of configuration from sub-critical to critical.

Fissile mass limits for waste packages and the criticality assessments that underpin the derivation of any limits are based on conservative assumptions. As a result, there is a significant safety margin between the fissile mass limits and the minimum critical masses required for a criticality. Normal GDF operations cannot give rise to a criticality incident provided the safety margin is maintained to ensure that there are no cliff edge effects.

Design basis fault scenarios have been reviewed and the double contingency approach applies; for a criticality event to occur, two unlikely and independent failures would have to occur concurrently. The likelihood of this is very low. The assessment also indicates that a criticality warning system is unlikely to be required on this basis. Following the detailed definition of the procedures and processes at the waste packagers' plants and at the GDF, the criticality safety arguments will be fully developed and a full assessment undertaken.

RWM recognises its responsibility to reduce the likelihood of criticality at the GDF to meet relevant criteria and standards and to reduce the likelihood of criticality accidents to a level that is tolerable and as low as reasonably practicable (ALARP). No significant obstacles to making future claims for compliance with targets for tolerability of risk or the ALARP principle have been identified. Areas that require further work to fully underpin the principal claim are related to design development, including the design of waste packages and detailed package-specific criticality safety assessment and the resolution of the forward action plans.

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1 Introduction

1.1 The generic Disposal System Safety Case

RWM has been established as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable programme for geological disposal of the UK's higher activity radioactive waste. Information on the approach of the UK Government and devolved administrations of Wales and Northern Ireland[1] to implementing geological disposal, and RWM's role in the process, is included in an overview of the generic Disposal System Safety Case (the Overview) [1].

A geological disposal facility (GDF) will be a highly-engineered facility, located deep underground, where the waste will be isolated within a multi-barrier system of engineered and natural barriers designed to prevent the release of harmful quantities of radioactivity and non-radioactive contaminants to the surface environment. To identify potentially suitable sites where a GDF could be located, the Government is developing a consent-based approach based on working with interested communities that are willing to participate in the siting process [2]. Development of the siting process is ongoing and no site has yet been identified for a GDF.

In order to progress the programme for geological disposal while potential disposal sites are being sought, RWM has developed illustrative disposal concepts for three types of host rock. These host rocks are typical of those being considered in other countries, and have been chosen because they represent the range that may need to be addressed when developing a GDF in the UK. The host rocks considered are:

- higher strength rock, for example, granite
- lower strength sedimentary rock, for example, clay
- evaporite rock, for example, halite

The inventory for disposal in the GDF is defined in the Government White Paper on implementing geological disposal [2]. The inventory includes the higher activity radioactive wastes and nuclear materials that could, potentially, be declared as wastes in the future. For the purposes of developing disposal concepts, these wastes have been grouped as follows:

- High heat generating wastes (HHGW): that is, spent fuel from existing and future power stations and High Level Waste (HLW) from spent fuel reprocessing. High fissile activity wastes, that is, plutonium (Pu) and highly enriched uranium (HEU), are also included in this group. These have similar disposal requirements, even though they do not generate significant amounts of heat.
- Low heat generating wastes (LHGW): that is, Intermediate Level Waste (ILW) arising from the operation and decommissioning of reactors and other nuclear facilities, together with a small amount of Low Level Waste (LLW) unsuitable for near surface disposal, and stocks of depleted, natural and low-enriched uranium (DNLEU).

RWM has developed six illustrative disposal concepts, comprising separate concepts for HHGW and LHGW for each of the three host rock types. Designs and safety assessments for the GDF are based on these illustrative disposal concepts.

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[1] Hereafter, references to Government mean the UK Government including the devolved administrations of Wales and Northern Ireland. Scottish Government policy is that the long term management of higher activity radioactive waste should be in near-surface facilities and that these should be located as near as possible to the site where the waste is produced.

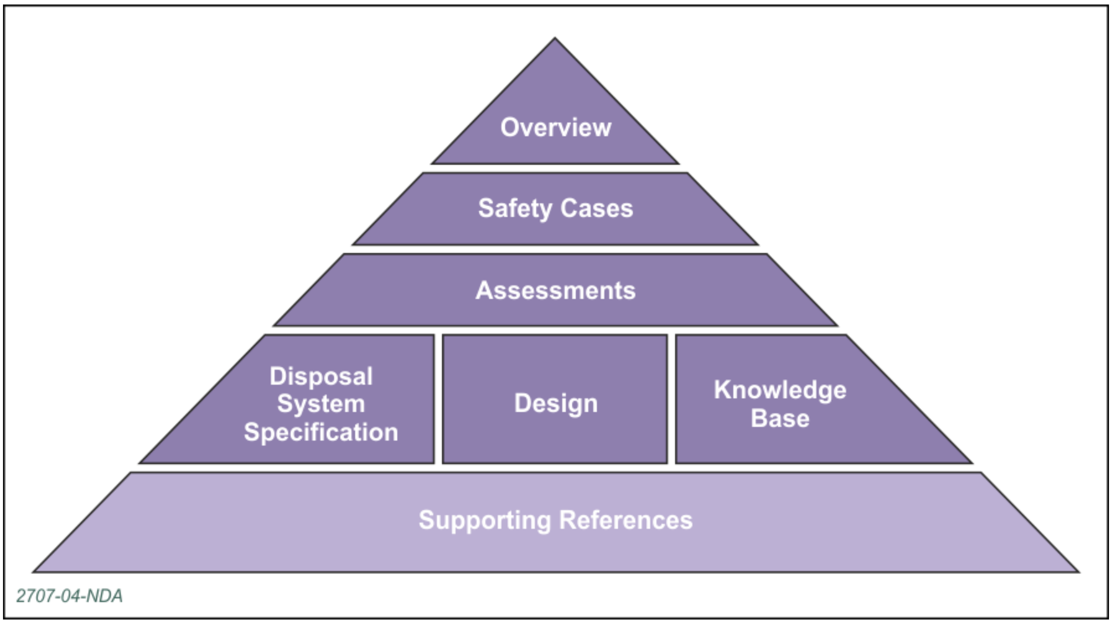
High level information on the inventory for disposal, the illustrative disposal concepts and other aspects of the disposal system is collated in a technical background document (the Technical Background) [3] that supports this generic Disposal System Safety Case.

The generic Disposal System Safety Case (DSSC) plays a key role in the iterative development of a geological disposal system. This iterative development process starts with the identification of the requirements for the disposal system, from which a disposal system specification is developed. Designs, based on the illustrative disposal concepts, are developed to meet these requirements, which are then assessed for safety and environmental impacts. An ongoing programme of research and development informs these activities. Conclusions from the safety and environmental assessments identify where further research is needed, and these advances in understanding feed back into the disposal system specification and facility designs.

The generic DSSC provides a demonstration that geological disposal can be implemented safely. The generic DSSC also forms a benchmark against which RWM provides advice to waste producers on the packaging of wastes for disposal.

Document types that make up the generic DSSC are shown in Figure 1. The Overview provides a point of entry to the suite of DSSC documents and presents an overview of the safety arguments that support geological disposal. The safety cases present the safety arguments for the transportation of radioactive wastes to the GDF, for the operation of the facility, and for long-term safety following facility closure. The assessments support the safety cases and also address non-radiological, health and socio-economic considerations. The disposal system specification, design and knowledge base provide the basis for these assessments. Underpinning these documents is an extensive set of supporting references. A full list of the documents that make up the generic DSSC, together with details of the flow of information between them, is given in the Overview.

Figure 1 Structure of the generic DSSC



1.2 Introduction to the Operational Safety Assessment: Volume 4 - Criticality Safety Assessment

This report is the criticality safety assessment of the operational period of the GDF and is one of 4 volumes that, together with a summary report, make up the Operational Safety Case (OSC).

The generic DSSC was previously published in 2010. There are now a number of drivers for updating the safety case as an entire suite of documents, most notably the availability of an updated inventory for disposal.

A criticality accident is an unplanned and uncontrolled chain reaction that results in a sudden release of energy and radiation. It can only occur when fissile material is present. A criticality accident can cause structural damage to the waste matrix and the immediate package. As a result, doses of radiation in the immediate vicinity can be harmful if no safety measures are provided to alert workers to the onset of an event or reduce the dose to safe levels. As the GDF will contain wastes with fissile material, the safety assessment must demonstrate that the magnitude and likelihood of a criticality accident is less than regulatory and RWM safety criteria.

1.3 Objective

The principal safety claim (SC) to be demonstrated for the criticality safety assessment is that:

OSC.SC4: All reasonably practicable steps will have been taken to implement design provisions whose function is to prevent or mitigate the consequences of nuclear accidents (i.e. unplanned criticality).

At this project phase, suitable hazard management strategies will be developed and implemented for those areas where there is scope for significant risk reduction. As a result, this provides confidence that the GDF can be operated safely and that all reasonably practicable steps will be taken to implement design provisions, engineered protection or process design and optimisation, whose function is to prevent or minimise the risk of criticality in the operational phase. As a result, risks to the workforce and members of the general public will be tolerable and as low as reasonably practicable (ALARP).

This volume presents the criticality safety assessment for the GDF in support of the 2016 generic Operational Safety Case (OSC) in order to:

- identify any potential feasibility issues associated with criticality safety in the GDF
- give confidence that the key criticality safety issues associated with the handling and emplacement of fissile materials within the GDF have been identified so that waste packages can be accepted and emplaced in compliance with RWM safety standards and regulatory expectations
- present the current position regarding the need for a criticality warning system (CWS); an overview of the relevant criteria and the arguments for a potential CWS omission will be presented. Any detailed assessment is impractical at this stage.

1.4 Scope

The scope of this report covers criticality safety issues associated with operation of the GDF.

The criticality safety considerations discussed in this report are generic across all waste types. The Disposability Assessment process develops the limits for package specific cases. For ILW packages this will be used in future to screen out those ILW packages for which criticality during operations is not a concern. This will enhance the generic safety arguments presented in this report, as the potential for a criticality accident will be further reduced.

Faults with potential to result in a criticality risk during decommissioning, backfilling and closure are not addressed. Recognising that the construction methods and needs related to decommissioning, backfilling and closure will vary significantly based upon the site and its geological environment, appropriate consideration of factors relevant to criticality has been undertaken. At this generic stage this has been limited to moderator addition scenarios due to either flooding during the backfilling process or groundwater re-entering the vaults and tunnels. However, there is not expected to be a significant criticality hazard associated with these activities because design optimisation will minimise the risk of flooding, and pumping systems will deal with any natural ingress.

This report provides a high level review of criticality safety requirements for the GDF. It presents the key aspects of criticality safety, arguments relating to fault conditions and the current position, based on these conclusions, on the need for a CWS.

Specific controls are not claimed for the criticality related hazard as the design detail does not yet support this. As a result there is no detailed substantiation to underpin any of the safety functions or claims. This is appropriate for the current stage. High level requirements to meet current best practice will be identified enabling the development of comprehensive hazard management strategies. When the GDF design is sufficiently developed a full assessment will be undertaken in accordance with RWM procedures which will reflect nuclear industry standards and relevant good practice.

This report considers the impact of key relevant developments since the 2010 version of the generic OSC, including:

- the introduction and use of the Nuclear Safety Operational Manual (NOSM) [4] which includes the operational criticality safety assessment process
- updated regulatory standards and guidance on criticality safety [5] and CWSs [6], which are reflected in the NOSM
- a revised Derived Inventory [7] based upon the 2013 UK radioactive waste inventory
- screening of ILW streams to identify those that could credibly exceed the safe fissile mass and therefore would require further analysis.
- the inclusion of a review of the importance of the role of the Disposability Assessment process, the potential impact of ‘out of specification’ material and the credible faults identified in the preliminary fault schedule

This report addresses only the criticality safety aspects of GDF operations. The assessment of radiological faults is contained in the generic OSC Volume 3 – Accident Safety Assessment [8]. Criticality safety aspects associated with transport and post-closure are addressed within the generic Transport Safety Case [9] and generic Environmental Safety Case [10] respectively.

1.5 Report structure

This report is structured as follows:

- Section 2 describes the risk factors which can impact on criticality safety and how the Disposability Assessment process interfaces with the operational phase criticality safety assessment
- Section 3 discusses the results of the qualitative criticality safety review and assessment process. This includes derivation of the faults identified in the preliminary fault schedule, together with a discussion on ‘out of specification’ waste packages and the radiological consequences of a criticality accident
- Section 4 provides a preliminary assessment of the need for a CWS

- Section 5 details the forward action plans (FAPs) which will help guide the future design development and ensure specific issues raised in this safety assessment are addressed
- Section 6 presents the conclusions of the criticality safety review and assessment

Common terms and acronyms used throughout the generic DSSC are defined in the glossary and acronym list in the Technical Background document.

2 Safety Assessment Approach

2.1 Introduction

This section presents an overview of the approach taken in the assessment of criticality risks (during the operation phase) in the generic DSSC.

The objective of the criticality safety assessment is to demonstrate that:

OSC.SC4: All reasonably practicable steps will have been taken to implement design provisions whose function is to prevent or mitigate the consequences of nuclear accidents (i.e. unplanned criticality).

This high level claim (OSC.SC4) is underpinned by application of the following approach:

For the waste itself, RWM has ensured that:

- it has a detailed knowledge of the radioactive waste inventory for disposal
    - for the majority of waste streams, criticality is not an issue; in ILW, the fissile material is mixed with a large excess of non-fissile material while for HLW, there is very little fissile material present as a result of reprocessing operations
- for high loadings of plutonium and HEU, such as may be found in some high heat generating waste streams, it is possible to design a stable sub-critical wasteform

For the waste packages:

- RWM specifies the content limits and the waste packager controls the content
- RWM undertakes qualitative assessment and review of fault credibility
- for the packaging of plutonium and HEU at higher loadings, criticality safety is assured by a stable sub-critical wasteform combined with a robust, long-lived container
- the robustness of waste containers is specified in a series of waste package specifications

2.2 Safety objectives

The criticality safety assessment provides the arguments and evidence to support the claim that:

- the proposed facility can be designed and operated within a well-defined, credible safe operating envelope
- the means of meeting the safety requirements through engineered or operational systems is both credible and feasible

2.3 Summary of risk factors impacting on criticality safety

The understanding of criticality safety within the illustrative disposal concepts in a range of potential geological environments has been established through a large quantity of research carried out over many decades in the UK and internationally [11].

The design of the wasteform and the packaging combined with the controls and conditions in the GDF that will be applied during emplacement will ensure ‘defence in depth’. This will include the provision of passive design features (such as the dimensions and shape of the waste package and the low fissile mass) and fault tolerance. For design basis events relevant to criticality safety, the double contingency principle is the preferred means of ensuring fault tolerance. This means that a criticality accident cannot occur unless at least two unlikely, independent and concurrent have occurred. The design basis faults related to criticality are derived from those in the preliminary fault schedule that are also of relevance in the accident safety assessment.

During emplacement operations, criticality safety is based on a combination of:

- deterministic controls:
    - setting limits based on:
        - quantity
        - waste form
        - fissile material content
        - moderator content
    - geometry control
    - neutron absorbers
- probabilistic controls:
    - reducing risk of credible accidents by robust design features to ensure that rearrangement to an unsafe configuration does not occur

This ensures that the risk of an unsafe configuration will be very low.

Risk of criticality is waste category specific and is therefore assessed on this basis. The relationship between the waste categories is set out in Table 1.

Table 1 Waste Groups and Categories

Waste Group	Waste Category
HHGW	Spent fuel, HLW, Pu and HEU component of uranium
LHGW	ILW, LLW and DNLEU component of uranium

Further sub-division of the waste categories has been undertaken where there are specific factors relevant to a particular grouping. For example, for the HLW/spent fuel sub-division, the assessment considers the waste route rather than the specific waste. Consideration of the criticality fault sequence progression and consequences would require separation of HLW and spent fuel to reflect the very different criticality safety considerations and risks. This is illustrated by the different average fissile enrichment levels[2] in Table 2, which presents the 2013 Derived Inventory in terms of the masses of uranium and plutonium in tonnes (te). However, the fissile mass, concentration and enrichment vary considerably between waste streams in each waste group, and between packages in a waste stream, particularly for ILW. This variation in fissile content between waste packages in a waste stream must be accounted for in individual criticality safety assessments.

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[2] The average fissile enrichment across the entire waste category is calculated as (sum of Pu-239 and U-235)/(Total Pu+U).

Table 2 **2013 Derived Inventory in Terms of Masses of Uranium and Plutonium at 2200**

Waste Category	Waste Group	Packaged Volume (m^3)	Pu-239 (te)	Total Pu (te)	U-235 (te)	Total U (te)	Average fissile enrichment (wt %)
ILW/LLW	Robust Shielded Container	7,280	1.32E-03	2.15E-03	6.50E-03	3.17E+00	0.2
	Shielded ILW/LLW	93,000	2.77E-04	3.36E-04	2.39E-03	2.44E-01	1.1
	Unshielded ILW/LLW	327,000	6.08E+00	7.78E+00	7.39E+00	1.50E+03	0.9
	New build ILW (shielded)	18,900	2.42E-05	3.97E-05	1.99E-05	3.19E-03	1.4
	New build ILW (unshielded)	22,100	2.49E-05	5.58E-05	1.34E-04	1.46E-02	1.1
	Total ILW (inc. LLW)	**468,000**	6.08E+00	7.78E+00	7.40E+00	1.50E+03	**0.9**
HLW	HLW	9,290	1.06E-01	1.93E-01	1.23E-02	2.11E+00	5.1
Spent fuel (SF)	Legacy SF	14,800	2.10E+01	3.77E+01	4.07E+01	6.04E+03	1.0
	New build SF	39,400	9.06E+01	1.62E+02	7.80E+01	1.33E+04	1.3
	MOX	11,900	3.95E+01	7.33E+01	1.84E+00	1.29E+03	3.0
	Total spent fuel	**66,100**	1.51E+02	2.73E+02	1.21E+02	2.06E+04	**1.3**
Others	DNLEU	109,000	8.06E-06	1.21E-05	5.23E+02	1.84E+05	0.3
	HEU	2,470	0.00E+00	0.00E+00	2.18E+01	2.29E+01	95
	Pu	620	4.56E+00	5.52E+00	3.11E-02	5.88E-02	82

2.3.1 Facility

At this stage of GDF programme it is assumed that the GDF is serviced from a single site on the surface. All waste will be packaged at separate sites and no packaging will take place at the GDF.

The geological differences in potential sites may include factors relevant to criticality safety. However, the geological environment does not affect the high-level criticality considerations in this report.

One such factor is the use of either a shaft or a drift to transfer packages underground. The current illustrative concepts consider a drift in both hard and lower strength sedimentary host rock, and a shaft for an evaporite host rock. However, for the purposes of a bounding assessment, use of a shaft has been assumed for all host rocks. Illustrative risk reduction measures (see Volume 3) have been identified for consideration as the design develops and due account will be taken of international experience in similar GDF projects currently underway. The shaft systems will be based on prevailing relevant good practice and incorporate up-to-date control, monitoring and safety equipment. It is acknowledged that the use of shafts for waste package transfers will require detailed safety assessment and design substantiation in order to meet the UK nuclear regulatory requirements.

2.3.2 Inventory data

The quality and reliability of inventory data are a cornerstone of the conclusions drawn in any criticality safety assessment. Any variability needs to be considered when setting fissile limits. Inventory data, obtained from the Derived Inventory, will continue to be refined, to improve understanding and reduce pessimisms related to the quantity of fissile material which will be emplaced. The current safety arguments are independent of these quantities, since the criticality safety of the operational period is based on compliance with fissile limits calculated in generic criticality assessments or in package specific criticality assessments. The Disposability Assessment process (see section 2.3.4) provides a framework for demonstrating criticality safety, based on the most limiting assumptions regarding the inventory for disposal, moderation and other factors. The assessments consider criticality safety of a particular waste stream within the GDF operations and development of fissile limits through an approved methodology. This process is subject to rigorous quality assurance procedures. The waste packagers' quality assurance procedures ensure waste packagers demonstrate that they have met the requirements of the Disposability Assessment process.

2.3.3 Waste packaging

The waste package includes the container and the appropriately packaged and conditioned wastes. It is necessary to provide a passively safe waste package that can be safely handled and stored prior to transport and during disposal in the GDF. A number of generic waste package specifications have been established by RWM to enable the waste producers to achieve these requirements. At this stage, for the majority of LHGW, the final decisions on the form of conditioning and packaging have been made. However, for a proportion of the wastes, in particular HHGW, these decisions will be addressed in future criticality safety assessments.

2.3.4 Disposability Assessment process

The Disposability Assessment process, described in [12], has been developed to support the early conditioning and packaging of wastes and ensure they will be in a transportable and disposable form. Waste packagers assist in the development of the GDF by developing waste package designs to meet the requirements derived from the generic DSSC and supporting assessments, including the generic OSC. The Disposability Assessment process is applied, when appropriate, in a staged manner, starting at the conceptual stage when packaging concepts are identified by the packager, through plant and package design (interim stage), to a final stage before active operations. Criticality safety considerations form an integral part of the process.

There is a hierarchical structure for the definition of fissile limits with increasing levels of sophistication and knowledge required to justify the highest fissile limits:

- At the lowest level, a generic screening level is defined at 50 g equivalent of Pu-239. This provides a safe limit for the fissile content of any waste package, irrespective of the waste, based on pessimistic assumptions regarding the design of the waste package and the form of fissile material. This includes optimum geometries, masses and concentrations for the accumulation and interaction of fissile materials and the presence of reflectors and moderators.
- For the higher fissile limits two screening levels are derived for a range of generic wastes in the generic criticality safety assessments. These screening levels take credit for the specific nature of the fissile material in terms of its composition and characteristics, the operation of the packaging process and knowledge of the waste package. In this approach conservatisms are reduced through greater control of the package contents by providing:
    - A lower screening level that makes pessimistic assumptions about the wasteform and possible criticality scenarios.
    - An upper screening level, that relaxes some pessimisms if supported by enhanced information regarding the wasteform and other packaging arrangements. This permits the inclusion of larger quantities of fissile material in waste packages.
    - Where the packager believes that a case can be made for an even higher fissile loading, then the final option is to develop a package-specific case. This will take credit for the specific characteristics of the waste package. However, it does not have the benefit of previously generated generic cases. The application of a package-specific fissile limit normally requires specific information on geometry and isotopic concentration of fissile materials, together with the presence and persistence of neutron absorbers.

Fissile limits are established for the generic wastes based on the assumption of stacking in uniform close-packed arrays [11]. It is recognised that mixed arrays of package types require further analysis in the operational safety assessment. Due to the nature of the waste, it is unlikely that mixed arrays would result in lower limits.

RWM provides advice on the disposability for all formal packaging proposals, either as generic or package-specific assessments. The waste packager must demonstrate how they intend to meet the limits and conditions derived in either the relevant generic criticality safety assessment or within the package-specific assessment. The criticality compliance assurance document (CCAD) records how the waste packager applies robust procedures and controls for manufacture of waste packages that will satisfy these limits and conditions. This process, and compliance with it, minimise the possibility of criticality incidents during all active stages of GDF operations.

The waste producer's quality management system (QMS) and the Waste Product Specification are also considered via the Disposability Assessment process. Quality management is an essential part of an effective waste management process and ensures that arrangements are in place covering all safety-related aspects throughout the lifetime of a waste package. The Disposability Assessment process requires and assesses the following:

- processes for the packaging of radioactive wastes, to ensure that packaged waste has the properties ascribed to it for the full lifetime of the packages

- the waste producer’s QMS, with the objective of assuring the quality of both the waste package and the data records in accordance with BS EN ISO9001 and providing a demonstration that the QMS has been applied through all stages of the package lifecycle
- the Waste Product Specification for the waste package, which fully defines for each waste package type, based on the most limiting fissile material limit between transport, operation and post closure:
    - the waste
    - waste container
    - conditioning materials
    - wasteform formulation
    - process conditions
    - storage conditions
    - all relevant supporting research and development
- confirmation that the waste is being packaged in compliance with the QMS and the Waste Product Specification including verification through independent audit or assessment and the ability for RWM to conduct assessments of activities that affect the quality of a waste package

These provisions complement and enhance the criticality safety margins, by providing assurance that the likelihood of ‘out of specification’ waste packages is minimised.

2.3.5 Package specific criticality review

ILW and LLW

The expected fissile concentration in the majority of the conditioned waste is very low, typically less than a few grams per package, and well below that at which criticality can occur. Typically, ILW will contain Pu-239 or U-235 as fuel residues, mixed with U-238, which acts as a diluent and neutron absorber. ILW will also contain plutonium contaminated materials comprising mainly plastics, paper and surface contaminated metals.

Any uncertainty and variability in the wasteform is accounted for when safety limits are set, through conservative assumptions in the derivation of the package limits within the Disposability Assessment process. The nature of the waste, with fissile nuclides generally distributed at a low concentration with other non-fissile materials, means that there will be very little neutron interaction between most packages and hence criticality is not a concern. Emplacement of the waste in large arrays within the GDF will not significantly increase reactivity as the safety limits and conditions are based on arrays of the same type of package.

Spent fuel

Spent fuel waste streams will include legacy fuel, new build fuel and the UK stockpile of separated plutonium as mixed oxide fuel. Very little of the legacy spent fuel has high residual enrichment due to the burn-up process within the reactor core, so it is less likely to sustain criticality and there is a reduced criticality concern. However, there may be certain waste streams with low burn-up fuel, mixed oxide fuel and certain commercial fuels that will have higher enrichments and may present an increased criticality concern. These need to be accounted for in the packaging design.

For most spent fuel waste streams, the expected fissile concentration in the wasteform will be significantly higher than that found in ILW. However, for these packages other features of the wasteform and package design will also contribute significantly to criticality safety:

- the spent fuel will normally contain significant amounts of neutron absorbers and diluents in the form of U-238 and fission products
- packaging, storage and transport of spent fuel is a mature technology supported by safety assessment methodologies based on many decades of industrial experience at reactor sites and reprocessing centres
- the wasteform is well defined, with less variability and uncertainty than ILW
- packaging arrangements could include the presence of fixed neutron absorbers in the container internal furniture to maintain sub-criticality during GDF operations
- robust wasteform and waste package to prevent rearrangement of fissile material into an unsafe arrangement

The criticality safety requirements associated with spent fuel for the operational phase of the GDF are currently under development through the RWM work programme [13].

Separated plutonium and uranium

For separated plutonium residues and HEU (and potentially DNLEU), the wasteform will be engineered to provide a well-defined and stable material. For plutonium and HEU, this may be a ceramic form and where necessary include neutron absorbing material. The processed waste will then be emplaced in a disposal container. It will be designed to be highly resistant to changes in factors that would increase the risk of credible accident conditions encountered during on-site storage, transport or emplacement at the GDF.

Development is at an early stage with RWM work programmes underway to provide a robust basis for the UK Government’s future decision process for disposal of these materials.

HLW

By its nature, HLW should contain insufficient fissile material to present a criticality risk. This is consistent with it being the product of a process designed to separate fission products from re-usable fissile material. Although the residual enrichment of the fissile material entrained in this waste is comparable with that of the other waste types considered, the fissile mass per package is much lower and the nature of the vitrified waste form is well mixed and passively safe.

Higher reactivity packages

The criticality safety assessment process includes the setting of fissile material limits for packages to which waste producers are required to adhere. However, the nature of some of the UK’s legacy waste and the conditioning and packaging processes may present situations where these limits could be exceeded and hence reduce the safety margin. Fissile limits have been established with large safety margins between the package limits and criticality safety limits. As a result, the majority of ‘out of specification’ waste packages would still be expected to remain well below fissile material levels that would present a criticality concern.

Requirements to demonstrate criticality safety during transport are expected to be more onerous than operational criticality safety requirements. As such, the treatment of higher reactivity packages can be addressed in future criticality safety assessments following development of the proposed design and operations.

There will also be some waste whose characteristics are such that the resultant waste packages are of higher reactivity. For such cases, special emplacement will be required to manage criticality risks.

3 Safety Assessment Results

At this stage of the GDF programme, the level of design definition and understanding of the package content limits the scope and detail of the criticality safety assessment. However, analysis can be undertaken to identify areas that would benefit from improved data or refinements of assumptions.

Waste packages will have been produced and stored on the waste producers' sites, often for many years, before shipment to the GDF, without a criticality event being realised. This provides a significant level of confidence that normal GDF operations will not result in criticality.

The criticality safety assessment presents an initial review of criticality safety during operations based on the following principal safety claim:

OSC.SC4: All reasonably practicable steps will have been taken to implement design provisions whose function is to prevent or mitigate the consequences of nuclear accidents (i.e. unplanned criticality).

This safety claim is underpinned by the following supporting safety claims:

- the key criticality safety issues associated with the handling and emplacement of fissile materials within the GDF have been identified, so that waste packages can be accepted and emplaced in compliance with RWM safety standards and regulatory expectations
- normal operations in the GDF will not be able to give rise to a criticality incident provided there is compliance with the conditions in the relevant Disposability Assessment such that the likelihood of criticality accidents under fault conditions is acceptably low
- there are no criticality safety issues which will challenge the feasibility of operating the GDF
- significant issues, such as rockfall, will be shown to be beyond design basis accidents through the implementation of hazard management strategies in the developing design

With regard to a CWS, the current position is that one will not be required.

3.1 Identification of illustrative criticality faults

As discussed in more detail in Volume 3 [8] all faults identified in the preliminary fault schedule in the Basis of Operational Assessment report [14] have been derived from a systematic hazard identification exercise. Table 3 lists the faults of relevance to the assessment at this stage of the GDF programme. As discussed in Section 1.4 this includes consideration of topics that are dependent on the geological environment (ie risk of flooding).

For completeness, whilst not included in the preliminary fault schedule, an additional scenario is discussed. This relates to redistribution of spent enriched fuel following a severe impact. As discussed previously, whilst considered in the BDBA, a safety argument is also presented for faults of this type to demonstrate the robustness of the assessment and claims. In addition, two further fault categories are reviewed (section 3.5), as these are of relevance to the developing criticality safety assessments.

The assessment includes discussion of a major in-vault structural failure leading to package failure and potential redistribution of fissile material accompanied by flooding (Section 3.4.2). Structural failures and groundwater inrush due to construction errors are more likely to occur during the construction phase rather than the operational phase. Engineered measures such as physical separation and the use of a bulkhead between operational and construction areas to prevent interactions will be included as preventative safety measures. In addition, the conditioning of all vaults and tunnels and shafts prior to use for transfer and emplacement will be based on tried and tested engineered means, examples of which are contained in Appendix A. The design of all structural safety measures will be suitable for the anticipated operational period of 160 years. Waste package transfers and emplacement will only take place within systems that are in a stable structural configuration with water proofing.

Table 3 Illustrative Design Basis Criticality Faults Identified in the Fault Schedule

generic Fault Sequence Group ID	Fault Sequence Group ID	Fault Sequence Group Name
7.A	7.A.4.2.1	Criticality in UILW Transport Package (SWTC) containing fissile materials due to change of geometry following severe impact in transit to/from sub-surface
	7.A.4.3.1	Criticality in HLW/SF Transport Package (DCTC) containing fissile materials due to change of geometry following severe impact in transit to/from sub-surface
7.B	7.B.6.2.1	Criticality in UILW Transport Package (SWTC) containing fissile materials due to addition of moderator to Disposal Unit at sub-surface
	7.B.6.3.1	Criticality in HLW/SF Transport Package (DCTC) containing fissile materials due addition of moderator to HLW/Spent fuel Disposal Unit at sub-surface

3.2 Exclusions from criticality safety assessment

The following faults are excluded from the criticality safety assessment:

- HLW in the Disposal Canister Transport Container (DCTC) criticality fault in Table 3, as justified in section 2.3.5. This is underpinned by a large amount of research data to demonstrate that the likelihood of a criticality accident involving HLW is very low.
- Criticality accidents occurring at the surface, because the waste packages will be in their transport configuration and appropriate design controls will be in place. Accidents occurring at the surface are implicitly considered as part of the analysis of the ‘out of specification’ fault in section 3.4.2. This exclusion also covers faults at the surface that involve a change in configuration.
- Structural failures leading to collapses and inrush of water as justified in Section 3.1.
- The potential for post-event distribution and accumulation of spent fuel, for example on filters and sumps due to lack of design definition for these potential systems.

3.3 Criticality safety assessment focus

The focus of the safety assessment is on accidents during GDF operation that could result in:

- changes in geometry leading to the generation of a new configuration of fissile material
- re-distribution of fissile material as a result of impact damage to a waste package and transfer of the contents beyond the confines of the waste package

- addition of moderators and/or reflectors
- removal or loss of neutron shielding

The safety assessment is based on either demonstrating that these events cannot happen or that, if they are credible, the consequences are minor and acceptable. For each design basis fault and, for illustration, the beyond design basis event of structural collapse and flooding, the illustrative risk-reduction measures have been identified, based on the application of the risk reduction hierarchy:

- can the fault be eliminated by modification of the engineered design or the process itself?
- if the fault cannot be eliminated, what risk reduction measures could be incorporated into the developing design in order to:
    - provide a means of preventing the fault from challenging the safety function
    - provide a means of protecting against fault development by terminating the fault sequence prior to a radiological consequence being realised
    - provide a means of mitigating the radiological consequences of the realised fault

The illustrative safety measures provided may be engineered or procedural, and active or passive in their delivery of the safety function. The hierarchy to be applied is:

- engineered is preferred to procedural
- passive is preferred to active

This information is presented in Appendix A .

As stated earlier in section 2.3.4, packages are delivered to the GDF for emplacement and accepted based on compliance with limits which have been derived for those packages. Fissile limits have been established with large safety margins between the package limits and criticality safety limits due to the conservative assumptions made throughout the assessment process. As a result, the majority of ‘out of specification’ waste packages would still be expected to remain deterministically safe.

3.4 Fault assessments – fault categories from preliminary fault schedule

In this section, faults relevant to criticality are discussed in the context of the waste types to which they are applicable.

3.4.1 Change of geometry due to impact

Some waste packages will contain fissile material in excess of the minimum critical mass, justified by a package specific criticality assessment. The risk of criticality must be considered in the following scenarios:

1. fissile and moderating material is rearranged within the package from a sub-critical to a critical configuration; no fissile material is assumed to leave the confines of the package
2. fissile material escapes from one or more waste packages and is relocated and accumulates into a critical configuration

With respect to a criticality resulting from rearranged package contents with no loss of containment (scenario 1 above), the following considerations apply:

- Where the wasteform is either solid or very densely packed, any rearrangement of fissile or moderating material is severely impaired, while for encapsulated waste, any significant movement of the fissile material within the package following an impact event is highly unlikely.
- Where the maximum fissile loading is limited to below the generic minimum critical mass, no criticality is possible regardless of any material rearrangement. For packages with higher fissile masses, the package limits are generated based on conservative assumptions. It is therefore highly unlikely that such a configuration could result from an impact event.

For example, the minimum critical mass for U-235 is of the order of 275 to 300 g. This would be lower for Pu-239, but still significantly above the 50 g generic criticality safety assessments defined level discussed in section 2.3.4.

Scenario 2 above refers to a criticality resulting from fissile material leaving the package and is currently excluded from the preliminary fault schedule.

ILW packages

There are specific waste streams for which the geometry of the ILW within the package may be important and these will need to be assessed as special cases (FAP.2016.VOL4.02). In some cases, special emplacement strategies may be required in order to meet criticality safety constraints.

For ILW, destruction of the package and dispersion of the contents is expected to lead to a decrease in reactivity. Thus for a single ILW package subject to such an event, the arguments in scenario 1 apply, as the reactivity threshold or condition could not be reached.

For ILW, even if multiple breached packages are postulated, the low inventories of fissile material mean that many packages would have to release all fissile material before a critical mass could be assembled. The fissile material would then need to be concentrated into an optimised geometry with optimum moderation and reflection. The facility will be designed to ensure, if necessary, that no post-accident secondary events are possible, for example resulting from collection or accumulation in sumps or on filters.

The integrity of the waste package is also relevant in considering the likelihood of fissile material being released. Package accident performance is assessed through the Disposability Assessment process, including tolerance to impact faults. The design and performance of the waste package combined with the immobility of the contents ensures that the potential for release is minimised.

Even when taking into account the immobility of the waste outlined above, criticality as a result of fissile material rearrangement outside the package is not credible without the simultaneous fault of addition of water, or a simultaneous fault of ‘out of specification’ material being inside the package. The further development of criticality safety arguments will confirm that a criticality involving ILW is highly unlikely.

For specific packages with a higher fissile limit, fewer would need to fail in order to give a critical mass of material. However, because of the solid nature of the wasteform, only a small fraction of the fissile material would actually be expected to be released. This low release fraction substantially increases the number of failed packages necessary before a critical mass could be assembled. In addition, any material released is likely to be non-fissile waste materials present in the container or the encapsulant material. This will make the fissile material much less mobile and also act to increase the mass required for criticality.

Spent fuel waste packages

The integrity of the transport container and the disposal container and the nature of the fuel are relevant when considering the likelihood of a criticality accident for spent fuel. Package accident performance is assessed through the Disposability Assessment process. The nature of the spent fuel disposal container, the solid and passive nature of the spent fuel and the internal geometry within the disposal container, will provide substantial protection against impacts.

The transport criticality assessments for spent fuel assume that the fissile material is in its most reactive condition (ie at maximum enrichment with no benefit of irradiation) leading to fission product and actinide formation and a reduction in reactivity ('burn-up credit'). This is an area of future research for RWM through the forward programme of work that aims to reduce levels of over-conservatism assumed in the assessments.

The fault schedule development exercise identified in-package rearrangement of spent fuel as a significant event that requires consideration.

If a disposal container containing spent fuel suffers major damage, the criticality safety argument regarding the dispersion of the fuel is the same as for ILW, in that the dispersion leads to a less reactive state. There is an interim condition that represents the limiting case for criticality where the disposal container remains intact but there is significant redistribution of the fissile material within voids in the container. If there is sufficient material accumulated in the voids, then a potential critical geometry could be formed with the presence of water as a moderator. There are currently two disposal container designs: V1 (copper) and V2 (carbon steel). The copper disposal container has a solid cast iron insert, whilst the carbon steel V2 design has a basket and more void space. In most disposal containers, there is insufficient void space for this to be possible, but for the carbon steel V2 design, there may be sufficient void space.

Fresh or low burn-up fuels could, if flooded, go critical without a geometry change. However, the double contingency argument will still apply in that there needs to be major disposal container failure involving fresh or low burn-up fuel coupled with ingress of water.

For spent fuel waste streams, including the specific case of pressurised water reactor (PWR) fuel, criticality as a result of fissile material rearrangement inside the disposal container is not credible without the simultaneous fault of addition of water through a crack or defect in the container as a result of the impact. A minor level of water ingress into the tunnels and vaults is anticipated and will be monitored and managed through dedicated channelling and pumping systems to remove water. Hence water ingress can only occur if there is a failure of the pumping system, failure to detect the ingress, and if these failures go undetected for a sufficiently long time for the ingress to lead to corrosion damage of the package or structural collapse.

The internal furniture of the disposal container could prevent significant rearrangement of the contents. The option of boronated steel for the internal furniture and other neutron absorbers may be considered to increase the safety margin for the fissile material mass. The possibility of these being separated in an impact could result in an increase in reactivity and this scenario will then require assessment in any design including such features.

The packaging design for spent fuel has not yet been finalised, but it is expected that it will not be practicable to ensure sub-criticality by limiting the quantities of fissile material in the package. The package and the wasteform will be designed such that it remains sub-critical with significant safety margins. This will include consideration of:

- multiple water barriers to exclude water ingress prior to removal of the disposal container from its transport container
- taking account of burn-up credit
- inclusion of neutron absorbers

The further development of criticality safety arguments will confirm that a criticality involving spent fuel is highly unlikely based on the above considerations

3.4.2 Additional moderation/reflection in ILW packages

Additional moderation and reflection by water could be envisaged, with water presence due to fire-fighting, flooding or during the vault backfilling process. There is a possibility that a vault could be flooded due to failure of the sub-surface supply or collection system or inrush from the rock or a significant event at the surface. The vaults will be below the water table so water ingress during the operational period may occur. The extent and timescale for water ingress to the vaults through the vault walls is dependent on the surrounding geological environment. Water ingress into the tunnel and vaults over time is envisaged, and provisions will be included in the design for pumping systems to remove any water. This will control conditions for waste packages and underground structures.

In addition, these scenarios could result in leakage via the package seals and vents or a loss of package containment and damage due to corrosion allowing water ingress to the package. The presence of water may have a direct effect on the reactivity of packages or of an array of packages, by providing reflection and moderation. Depending on the contents of the packages and the distribution of fissile material, flooding may increase or decrease the reactivity of the package or array. The only materials that are potentially better moderators than water are hydrocarbons, but insufficient quantities are envisaged to be present to warrant individual consideration.

The Disposability Assessment process applies initial, highly conservative package limits assuming the worst configuration, water-filled packages in an infinite lateral array with rock above and below and air between the packages. Hence ILW packages will be already compliant with the most stringent moderation/reflection conditions.

Given the large safety margins between the package fissile limits and criticality safety limits, a criticality event would require both a gross loss of control remaining undetected and the addition of moderation. This is considered to be a double failure of contingencies and highly unlikely. Options are available to further reduce the risk of a criticality from these faults, such as reduced payload or addition of neutron poisons. The requirement for these additional measures will be assessed in future documentation following the further development of the proposed design and operations.

3.5 Fault assessments – additional faults

3.5.1 Accumulation of fissile material originating from ILW packages

A criticality hazard could result from fissile material accumulating from fugitive releases from ILW packages via vents and seals (for example, material escaping from a package following a fire). Material released from packages may settle on the vault walls or the floor and, if mixed with water, may accumulate in the drain system or in the effluent treatment system.

For a criticality to result from this scenario, both the following must occur:

- sufficient fissile material must be released from the packages such that it could form a critical geometry if it accumulated
- the material must travel to the point of accumulation and must accumulate in a reactive geometry

The conditions of moderation, geometry and neutron reflection will be sub-optimal in a ventilation or drainage system, when compared with bounding assumptions.

The fissile material would be released along with other materials (grout, other waste stream components, container wall corrosion products). If accumulation took place, then these other materials would act as poisons and diluents. This will mean that more fissile material would be required to produce a critical system.

An alternative fault scenario is the accumulation of fissile material by chemical means, for example, dissolution of fissile material then precipitation in an area with different chemical characteristics such as pH. The low solubility of fissile materials makes this scenario highly unlikely and hence it is not considered further at this stage, although this will be kept under review.

3.5.2 Out of specification ILW packages

This section considers packages being received which are ‘out of specification’. Waste packagers manufacture packages in accordance with procedures that ensure that agreed fissile limits are not exceeded. Occurrences of ‘out of specification’ packages, which originate at the waste producing site, are not controlled by the GDF design but by the Disposability Assessment process.

Ensuring that waste packages are within specification limits is dependent on the quality and integrity of waste packager’s operations. It depends on:

- the quality and quantity of available information on the waste stream
- the method and procedures used to package the waste
- meeting required package specifications, for example on conditioning (such as density, composition and uniformity), container and poison requirements (for example, the amount of hydrogenous material, ceramic density, uniformity of pucks) and enrichment levels
- the extent and quality of assay, including the detection limits of any assay equipment, and the extent and quality of assay of completed packages

For an ‘out of specification’ package to cause a criticality during GDF operations, it would need to be initially sub-critical so that it did not result in criticality in the waste packagers’ facility, and yet have the potential for sufficient increase to become critical due to GDF operations. As stated earlier, given the large safety margins in the calculation of package fissile limits, this is considered to be highly unlikely.

The robustness of the processes and controls adopted by the waste packagers, combined with the rigour of the Disposability Assessment process and the controls that will be adopted at the GDF, means that a criticality in the GDF is highly unlikely. Due to the limitations of waste stream inventory data, despite the waste packager’s responsibility to comply with the Disposability Assessment requirements, consideration is being given to implementing a waste acceptance check at the GDF.

A full analysis and justification will be required in future safety cases in order to screen this event out on the basis of low frequency (FAP.2016.VOL4.01). In addition, the combination of ‘out of specification’ packages with other faults (for example, impact) would be double contingencies, and criticality risks from such combinations will be highly unlikely.

3.5.3 Other ‘what if’ considerations

The Dounreay Prototype Fast Reactor fuel has higher enrichment levels and the dispersion of the fuel within or beyond the disposal container has the potential to create a criticality without the addition of moderator. At the current stage, this potential criticality hazard has been identified based on the details in the 2013 Derived Inventory without availability of a disposal or transport package design. This fuel will require specific consideration as the waste package design is developed. It should be noted that the amount of fuel in a package will be limited to meet other requirements, for example to limit heat output and ensure post-closure safety.

4 Criticality Warning System Assessment

4.1 Criticality consequence analysis

The purpose of assessing the radiological consequences of potential criticality accidents is to provide input for the accident management plan, specifically to identify potential evacuation zones. The potential for making a CWS or criticality incident detection and alarm (CIDAS) omission case is considered below.

The restriction of criticality doses should not be a part of any criticality safety justification; the likelihood of criticality is the relevant issue and should be demonstrated to be highly unlikely and meet the frequency targets in the NOSM. Criticality safety arguments are to ensure the incredibility of a criticality incident, irrespective of the dose to personnel. However, for criticality emergency planning purposes, the potential dose is relevant, as stated in the Office for Nuclear Regulation (ONR) CWS guidance [6].

When considering doses, the 'absorbed dose' (in units of Gray, Gy) is generally relevant for non-stochastic effects and 'equivalent dose' (in units of Sievert, Sv) is relevant for long-term stochastic health effects. However, the radiation weighting factor for neutrons will significantly increase the equivalent dose and high dose equivalents may cause deterministic effects to specific organs.

Criticality incidents are often characterised by a high energy spike followed by decay in the energy levels of emitted radiation, although in some incidents, the system has remained critical or there have been further secondary spikes until the system shuts down.

In a review of all known criticality incidents world-wide over the 90 year life of the nuclear industry [15], records of 60 nuclear criticality accidents were found. Considering process facilities alone, 22 accidents have been recorded. The majority of these events have been related either to the processing of liquids containing fissile materials or the manufacture or handling of nuclear fuel. Of these accidents, 9 fatalities have occured as a result of absorbed doses in excess of 3.5 to 4.5 Gy. This is the threshold for deterministic radiation health effects. The yields ranged between 1E15 and 4E19 fissions and so a yield of 2.0E19 fissions is used as a reference accident for a bounding assessment. This is the maximum credible size of criticality incident in the UK, used when determining whether a CWS is required (see section 4), and using a *"maximum acceptable equivalent dose of 20 mSv"* [4].

The radiological consequences of a criticality comprise two distinct contributors:

- The direct dose received from neutrons and gamma radiation which will depend on the magnitude of the event, an individual's distance from the event and the quantity of shielding between the event and the affected individual. This is the dominant contributor for workers.
- The indirect dose due to the release of fission product gases or of radioactive material dispersed by the energy of the event, which depends on the degree of pressure containment of the initial event and whether the incident occurs within a secondary containment.

The dominant component of radiation equivalent dose from a criticality accident is from neutrons, substantial gamma shielding is relatively ineffective against criticality accidents. However, dense shields with significant hydrogen content including concrete and rock structures, can be effective in shielding both gamma and neutrons.

The calculation of consequences to members of the public is dependent on the location and design of the site. If a criticality occurred underground, any direct dose will be substantially reduced due to the shielding effect of the overbearing rock. The dispersion coefficients depend on many parameters such as the height of the release, distance from the release point and weather conditions.

Off-site doses will be reviewed as part of the future criticality safety assessments associated with the developing design. Criticality emergency plans and potential monitoring and control measures will be considered at the appropriate stage of the GDF programme. The intent will be to demonstrate that the risk to a member of the public will be diminishingly small.

In the highly unlikely event that a criticality accident were to occur underground, it would result in significant doses to workers although detailed assessment is not possible until the design is further developed.

4.2 Criticality warning systems

The provision of CWSs in nuclear facilities is intended to protect workers from the effects of a criticality event by limiting their exposures through prompt warning and evacuation. For example, some general considerations related to a satisfactory safety argument are that:

- to argue CIDAS omission on the basis of dose limitation will require very substantial shielding for example, several metres of concrete or equivalent
- to avoid deterministic effects from the maximum probable criticality yield will require tens of metres separation from the incident and around a metre of concrete shielding or equivalent
- to restrict the dose from a maximum probable yield to 100 mSv (for evacuation zone definition) will require hundreds of metres distance if no shielding or substantial concrete shielding for close distances

There are two possible approaches in making a CWS or CIDAS omission case:

- based on the radiological consequences of a criticality incident, or
- based on the potential for a criticality incident occurring

The approach is set out in the relevant sections of the NOSM based on ONR guidance [6] and the criterion developed by Aspinall and Daniels in the 1960s [16].

For the safety case, the aim is to demonstrate that the likelihood or frequency of a criticality accident is acceptably low. In contrast, the CWS/CIDAS criterion specifically ignores the controls on which the safety case may be dependent and looks at ‘reasonable expectation’ of criticality, rather than a specific low frequency target.

In the UK, CIDAS omission cases for facilities handling fissile material are based on one of the following two criteria:

1. a CIDAS system is not required where an assessment shows that the maximum dose to the most exposed individual from a maximum credible criticality incident (outside a nuclear reactor) will not exceed the maximum acceptable emergency dose
2. a CIDAS system must be provided at all places where fissile material may be used or stored, unless it is confidently judged that in the event of the failure of any or all of those criticality controls which rely on human agency or on mechanical or electrical devices, criticality would not reasonably be expected, having regard to the nature of the particular operations and facility concerned

The omission argument is based on the second criterion due to the potential for high doses to a limited group of on-site workers from a criticality in the GDF. If all operational controls failed, it is assumed that conditions are what will be reasonably expected, as detailed in the NOSM. This requires the application of qualitative ‘confident judgement’ and ‘reasonable expectation’ and does not involve any quantitative estimate of frequencies.

Consideration is also given to what has been done in similar facilities in the past. For example, if a CIDAS system has been installed in a particular type of facility in the past, then it will be reasonable to expect that this practice should be continued in the future unless a robust omission case can be made. This review will be included in the CWS/CIDAS omission justification in future safety cases as the design is developed. This may include the requirement to consider whether a limited CIDAS in certain specific areas carrying an enhanced criticality risk would be appropriate.

The CIDAS omission justification focuses on the failure of criticality controls. For the GDF, the key criticality control is the achievement of the waste acceptance criteria by the waste packager.

There are therefore two issues to consider for CIDAS omission in the GDF when applying criterion 2:

1. would the failure of the controls on waste package specification in the packagers' facility be 'reasonably expected' to subsequently result in criticality 'having regard to the nature of the particular operations and facilities concerned'?
2. if 'yes', would the criticality be 'reasonably expected' to occur during GDF operations, rather than in the packagers' facility or transportation prior to arrival at the GDF, or in subsequent disposal following GDF operations?

If the answer to either of these questions is 'no', then a CIDAS omission argument can be made for GDF operations according to Criterion 2.

The initial CIDAS omission assessment has concluded that the nature of the waste material is inherently unfavourable to criticality. The control failures on waste packages would not result in a critical configuration. The likelihood of a high content package arising in the short time interval before the control failure was revealed, is also highly unlikely. Further, if a package with potential to cause criticality was produced, the likelihood is that the criticality would occur at the time of production in the packagers' facilities. Normal operations in the GDF would not expect to result in a change of configuration from sub-critical to critical.

Taking the above into account, it is judged that, at this stage of the GDF programme, it is considered feasible that a CWS/CIDAS can be omitted from all activities associated with the operational period of the GDF. However, the justification will continue to be re-assessed as the design develops. A full justification will be presented when relevant operational details in the packager's facility and the GDF have been defined.

5 Implementation

This safety assessment has identified at a generic level the issues that relate to risk of criticality during the operational phase of the GDF. A hazard management strategy will be developed and implemented as the GDF design is developed.

Further work will be required in terms of optioneering and design development in order to develop solutions which will ensure that RWM safety criteria are met.

This will include confirmation that:

- procedures, processes and controls are sufficiently comprehensive and robust
- base assumptions related to package criticality limits can be verified from measurements or records

The FAPs are listed in Table 4.

Table 4 FAP Listing

FAP ID	FAP Description
FAP.2016.VOL4.01	Undertake a study to determine the likelihood of receipt of ‘out of specification’ packages and the safety margins to prevent the potential for a criticality accident.
FAP.2016.VOL4.02	Undertake a study to determine thresholds at which criticality needs to be considered within a UILW disposal unit to minimise the risk of a criticality accident.

6 Conclusions

The extent to which the principal safety claim (OSC.SC4) has been demonstrated is summarised below.

This illustrative criticality safety assessment presents evidence regarding the nature of hazards and hazard management strategies to prevent or mitigate the consequences of nuclear accidents (ie unplanned criticality).

The GDF will be designed and operated safely with regard to criticality hazards and plans for resolution of identified issues are in place. The nature of the waste material is inherently unfavourable to criticality and the failure of controls on waste packages would not result in a critical configuration, either in individual packages or in combination. Normal operations in the GDF would not result in a change of configuration from sub-critical to critical.

In conjunction with waste packagers, safe fissile masses are defined to cover the operational phase for all waste packages destined for the GDF. These safe fissile masses are based on pessimistic assumptions regarding waste characteristics, waste package design and emplacement arrangements. The Disposability Assessment process provides the mechanism for checking that criticality controls are proposed and applied in a quality assured manner. As such, there is a large safety margin between the fissile limits set for waste packages and the criticality safety limits.

This illustrative assessment has concluded that normal operations in the GDF cannot give rise to a criticality incident provided the safety margin is maintained so that there are no cliff edge effects. Design basis fault scenarios within the GDF have been reviewed and only double failure of contingencies could result in criticality. The likelihood of such scenarios is very low. Following the detailed definition of the procedures and processes at the waste packagers' plants and at the GDF, the criticality safety arguments will be fully developed and a safety case produced.

Dounreay Prototype Fast Reactor fuel is an exception where there is the potential to create a criticality without the addition of moderator due to the higher enrichment levels. This fuel will require specific consideration as the waste package design is developed. It should be noted that the amount of fuel in a package will be limited to meet other requirements, for example to limit heat output and ensure post-closure safety. This will be further assessed as the waste package design is developed.

The illustrative assessment also indicates that a CWS is unlikely to be required in the GDF.

Design development will be required to optimise criticality safety provisions. This will be considered through the integrated design and safety process, as detailed in the NOSM and the RWM design process and in accordance with current nuclear industry standards and relevant good practice. This will include the requirement to ensure that optioneering, design optimisation and risk reduction have been applied throughout the design development process.

Overall, this illustrative assessment concludes that the likelihood of criticality in the GDF is very low. Claims of future compliance against targets and tolerability of risks can be made subject to design development and the resolution of the FAPs. RWM recognises its responsibility to reduce the likelihood of criticality accidents at the GDF to meet relevant criteria and standards and to reduce risk to levels that will be both tolerable and ALARP.

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Glossary

A glossary of terms specific to the generic DSSC can be found in the Technical Background document.

Appendix A – Summary of Safety Analysis and Identification of Illustrative Risk Reduction Measures

Fault Description	Criticality in UILW transport package (SWTC) or HLW/spent fuel transport package (DCTC) containing fissile materials due to change of geometry following severe impact in transit to/from sub-surface
Initial Fault Class	N/A
Indicative Risk Reduction Target	N/A
Conceptual Safety Function	Prevent criticality as a result of waste package integrity failure leading to dispersion of fissile material and accumulation into a critical geometry

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Eliminate the potential for an uncontrolled transit of a waste package to the sub-surface.	Eliminate	Use of an alternative means of transporting the waste package from the surface to the sub-surface.	No	Not currently feasible as RWM wishes to retain shaft option.
Provide a means of preventing loss of load path integrity leading to comprised waste package internal geometry or integrity.	Prevent	High reliability lifting arrangement and equipment preventing drop of a waste package.	Single system unlikely (taking account of all diverse and redundant measures within it) to meet all safety requirements - to be confirmed through FAP (See Note)	Note, a high integrity nuclear lifting arrangement with specific safety measures to prevent a drop is likely provide a maximum probability of failure on demand of 1E-06.

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Provide a means of preventing loss of waste package internal geometry or integrity in the event of a drop or impact.	Prevent	Independent segregated operable load path capable of supporting the load such as an independent load follower or similar device. Minimise impact to less than the withstand capability of the waste package and transport unit such as staggered shaft (passive). Means of minimising impact damage to waste package and transport such as over-pack which prevents damage and/or contains the radiological inventory of the waste package. Means of dissipating energy to prevent structural failure of waste package – local measures such as cage with crush zones or shaft measures with crush zones or controlled means of deceleration.	To be confirmed through FAP	Means of minimising acceleration need to be explored such as air brakes or systems which maximise air resistance. Guided platforms provide an alternative means of arresting movement to braking systems via the wire rope load path. It is recognised that some waste packages will be transported to the sub-surface in transport containers made from high integrity materials that provide containment of radioactive materials and shielding even under surface transport accident conditions (severe impact and fire). However, the depth of the GDF shaft is at least 600m which is significantly greater that the IAEA regulatory requirements for the type B packages impact test which is a free drop of 9m.
Provide a means of preventing loss of waste package internal geometry or integrity in the event of a drop or impact.	Prevent	Waste package and transport unit capable of withstanding accident worst case impact force without damage to internal geometry or a release of radioactive material.	To be confirmed through FAP	Does not prevent the initiating event from occurring and is likely to result in significant damage to the shaft in the event that it does occur; note that there could be significant energy potential, for impact accident involving a waste package (65 tonnes gross).

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Provide a means of excluding moderator materials from the surface to sub-surface transit areas.	Prevent	Tunnel/shaft liners. Pumping systems.	Yes	-
Provide a means to protect operators from radiation exposure from criticality following a drop or impact.	Protect	Shield (gamma/neutron) and containment door(s) located at the base and top of the shaft to protect operators or members of the public in the event of a drop leading to a criticality accident.	To be confirmed through FAP	Combined with operational requirement below (exclusion of personnel).
Provide a means to mitigate radiation exposure from failure of waste package internal geometry or integrity following a drop or impact.	Mitigate	Means of minimising impact damage to waste package and transport container. Examples include 'soft target' such as shaft bottom arrestors. Exclusion of personnel from operational areas, for example, lowering of waste packages remotely. Emergency ventilation system. Radiation monitoring equipment and alarm and CWS to alert operators to increased radiation levels in the event of a fault condition and aid evacuation. Criticality warning system.	To be confirmed through FAP	-

Fault Description	Criticality in UILW transport package (SWTC) containing fissile materials due to addition of moderator to disposal unit at sub-surface
Initial Fault Class	N/A
Indicative Risk Reduction Target	N/A
Conceptual Safety Function	Prevent criticality as a result of addition of moderation or reflection to emplaced waste packages

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Eliminate potential for moderating material to be present in emplacement vaults.	Eliminate	Ensuring that no moderating materials can enter emplacement vaults.	No	Can be partially achieved through exclusion of any moderator storage and transfer systems within vaults but cannot eliminate potential for groundwater ingress from vault structures. This means that systems designed to manage this potential will be preventative.
Prevent potential for in-leakage of moderating materials into waste packages.	Prevent	Provide an external concrete structure or cover around the package for transfer and emplacement.	Yes	Provides waste package with a robust external barrier which permits emplacement directly, provides additional protection against damage to package, as well as possibly partial backfill component with high quality control. This prevents loss of the waste package integrity and prevents the possibility of dispersion of the contents beyond the container or ingress of water into the waste package.
Prevent potential for in-leakage of moderating materials into waste packages.	Prevent	Removal of all penetrations and entry points to waste packages (for example filters and vents)	Partial	Certain waste packages will require filters and vents to prevent pressurisation.

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Prevent potential for in-leakage of moderating materials into waste packages.	Prevent	All waste packages to be constructed from materials consistent with ensuring containment and corrosion resistance for at least 200 years.	No	-
Prevent potential for waste package content redistribution in event of in-leakage of moderator.	Prevent	Immobilisation of waste package contents. Minimise potential for moderator ingress and distribution within package.	Yes	-
Provide a means of protecting operators from direct and indirect radiation from criticality accident in vault.	Protect	Shield (gamma/neutron) and containment door(s) located at vault entry to protect operators or members of the public.	Yes	Combined with operational requirement below (exclusion of personnel).
Provide a means to mitigate radiation exposure from in-vault criticality accident.	Mitigate	Exclusion of personnel from operational areas, for example, lowering of waste packages remotely. Radiation monitoring equipment and alarm to alert operators to increased radiation levels in the event of a fault condition and aid evacuation. Criticality warning system.	To be confirmed through FAP	-

Fault Description	Criticality as a result of accumulation of fissile material originating from ILW/spent fuel packages
Initial Fault Class	N/A
Indicative Risk Reduction Target	N/A
Conceptual Safety Function	Prevent criticality in the event of waste package integrity failure leading to dispersion of fissile material and accumulation into a critical geometry

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Prevent potential for dispersion of fissile material outside waste packages.	Eliminate	All waste packages to be constructed from materials consistent with ensuring containment and corrosion resistance for at least 200 years.	No	-
Provide a means of preventing fissile materials being mobilised outside the package.	Eliminate	Immobilisation of waste within packages.	Yes	Prevents possibility of friable fuel fragments or dispersible waste being transferred and mobilised within vault.
Provide a means of preventing the contents of a waste package being dispersed into areas where accumulation is possible.	Prevent	Provide an external concrete structure or cover around the package for transfer and emplacement.	Yes	Provides waste package with a robust external barrier which permits emplacement directly, provides additional protection against damage to package, as well as possibly partial backfill component with high quality control. This prevents loss of the waste package integrity and prevents the possibility of dispersion of the contents beyond the container or ingress of water into the waste package.

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Provide a means of preventing release or build-up of moderator with a vault	Prevent	Ensure no moderator storage or pipework systems in emplacement vaults. In-vault pump extraction systems.	Yes	-
Provide a means of protecting operators from direct and indirect radiation from criticality accident in vault.	Protect	Shield (gamma/neutron) and containment door(s) located at the vault entrance.	Yes	-
Provide a means to mitigate radiation exposure from in-vault criticality accident.	Mitigate	Radiation monitoring and alarms assuming collection area is radiation controlled. Criticality warning system and evacuation.	Yes	-

BDBA Event 1	
Fault Description	Criticality as a result of major structural collapse and/or rockfalls in ILW or spent fuel vaults
Initial Fault Class	N/A
Indicative Risk Reduction Target	N/A
Conceptual Safety Function	Conceptual Safety Function (CSF): Prevent in-vault criticality as a result of structural collapse

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Provide a means of preventing the integrity of the disposal unit from being compromised in the event of a structural collapse.	Prevent	Provide an external concrete structure or cover around the package for transfer and emplacement.	Yes	Provides waste package with a robust external barrier which permits emplacement directly, provides additional protection against damage to package, as well as possibly partial backfill component with high quality control. This prevents loss of the waste package integrity and prevents the possibility of dispersion of the contents beyond the container or ingress of water into the waste package.
Prevent potential for concurrent construction activities to impact on waste emplacement activities.	Prevent	Change strategy so that no construction activities are taking place while GDF is in operational phase.	Partial	Requires complete change of construction and operational strategy and leads to long extension of pre-emplacement construction phase. However, it is feasible to undertake construction and emplacement operations in geographically separated areas with engineered barrier such as bulkheads and independent services so as to isolate construction and operational areas from each other.

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Provide a means of preventing structural failures within an underground vault.	Prevent	Use of most appropriate excavation techniques, such as drill and blast and the use of mechanical excavation techniques including tunnel boring machines or roadheaders. Installation of structural support systems such as concrete liner, mesh or rockbolts. Pre-construction investigation of the ground conditions.	Yes	Included within current GDF assumptions.
Provide a means of preventing the integrity of the disposal unit from being compromised in the event of a structural collapse.	Prevent	Amend emplacement strategy, for example, grouting material or by filling vault a level at a time, etc.	To be confirmed through FAP	Lateral emplacement followed by backfilling by layer could provide protection of emplaced disposal units from effects of rockfalls, etc.
Provide a means of early detection of structural defects to prevent the potential for structural collapse.	Protect	Ensuring the walls and roof are properly maintained and inspected at suitable intervals.	Yes	Limited once emplacement begins unless system for remote inspection and intervention can be designed.
Provide a means of protecting operators from direct and indirect radiation from criticality accident in vault.	Protect	Shield (gamma/neutron) and containment door(s) located at the vault entrance.	Yes	-

Conceptual Safety Functional Requirement (CSFR)	Risk Reduction Hierarchy	Example Risk Reduction Measures (RRM)	Is the RRM Feasible?	Notes
Provide a means to mitigate radiation exposure from in-vault criticality accident.	Mitigate	Radiation monitoring and alarms assuming collection area is radiation controlled. Criticality warning system and evacuation.	Yes	-

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