Radioactive Waste
Management

NDA Report no. DSSC/458/01

Geological Disposal

Criticality Safety Status Report

December 2016

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Abstract

The Criticality Safety status report explains contributions to safety and technical studies that support our safety cases for demonstrating criticality safety. It is one of a suite of eight research status reports that form part of the generic Disposal System Safety Case. Each research status report draws on and summarises supporting technical and scientific references in order to provide an overview of the published scientific literature for each topic. The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

The objective of the Criticality Safety status report is to: define what we mean by criticality and criticality safety; summarise the contributions to safety; outline the wastes and their long-term management; show how package limits are set to avoid criticality in the short to medium term; discuss the processes that determine the likelihood of a criticality in the long-term; summarise our understanding of hypothetical post-closure criticalities and explain how one would impact on our safety case; and provide a technical summary and conclusions based on our current understanding. The key message emerging from the analysis presented in this status report is that waste packages are/will be produced to ensure that criticality is not a significant concern.

Executive Summary

The Criticality Safety status report is part of a suite of research status reports describing the science and technology underpinning geological disposal of UK higher activity radioactive wastes.

These wastes contain plutonium and uranium that are used, in pure and concentrated forms, as fuel to generate power in nuclear reactors. To do this, reactors are designed to reach and maintain a condition called criticality (a self-sustaining nuclear chain reaction). Criticality safety has been defined as protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention.

We use illustrative disposal concepts to discuss the safety provided by the geological disposal facility (GDF) in a range of potential geological environments. Our understanding of the safety provided by these concepts has been established through the large amount of research that has been conducted over several decades in the UK and by waste management organisations and research institutions overseas.

We assess criticality safety as part of safety cases that we are producing for waste transport, the construction and operational phase and following closure of the GDF. We also assess criticality safety as part of our advice to waste producers on packaging proposals.

The following high-level contributions to safety apply based on our understanding of how the waste packages and the GDF will evolve over time.

For the waste material:

- we have detailed knowledge of the inventory of radioactive wastes
- for the majority of the wastes criticality safety is not a concern; in intermediate level waste (ILW) the fissile material is normally mixed with a large excess of non-fissile material, while high level waste (HLW) contains little fissile material because it has been separated during reprocessing
- small amounts of ILW will contain separated plutonium and highly enriched uranium (HEU), but these are not present as pure materials – they are dispersed amongst other non-fissile materials
- for pure materials such as plutonium and HEU, we can design a stable wasteform that is sub-critical; depleted and natural uranium are not classed as fissile material
- most spent fuel (SF) is removed from nuclear reactors because a large proportion of the fissile content has been used up and actinides and fission products have been produced during irradiation, meaning it can no longer effectively contribute to producing power in the reactor

For the packages:

- we specify and ensures control of all waste package contents
- for the majority of SF the wasteform design is already fixed, so we will use a package design to ensure sub-critical conditions
- for packaging of HEU and plutonium at high loadings, safety will be provided by a stable, sub-critical wasteform and a long-lived container.

In all cases Radioactive Waste Management (RWM) aims to design packages that are robust to faults during transport and operations. We use well established methods with appropriate conservatisms. In the Disposability Assessment process we ensure that these packages are properly designed by assessing them against waste package specifications,

themselves derived from our generic disposal system safety case. We also ensure that the packages actually produced meet these specifications. In time, we will replace these specifications with Conditions for Acceptance.

We also assess criticality safety as part of the assessment of post-closure performance of the GDF and associated radiological risk. Depending on the type of waste, packages are designed to contain their fissile material for medium to long timescales. Over extended times, the packages will degrade as the containers corrode and a portion of the package contents may become mobilised. We consider a criticality post-closure to be unlikely; a low probability event. However, with large numbers of packages, and very long post-closure timescales requiring consideration, it is difficult to guarantee that a criticality cannot occur. Therefore we have also carried out research to understand how a criticality could begin, progress and end, including consideration of how such an event might affect the performance of the disposal system.

The likelihood of post-closure criticality is low because:

- waste containers will be emplaced in the GDF in a sub-critical configuration with multiple engineered barriers to minimise fissile material relocation
- many of the anticipated changes to the waste packages following closure are expected to reduce system reactivity
- for ILW, the fissile material is dispersed through waste packaging materials at concentrations well below critical values
- the majority of ILW is/will be encapsulated in cement, and ILW disposal concepts are based on cementitious backfill, the properties of which hinder the movement of fissile material
- for pure plutonium and uranium materials, RWM could design a wasteform that is stable and would only very slowly release fissile material
- for SF we will use a package and emplacement design capable of maintaining sub-critical conditions over long timescales and, in the majority of fuel types, the reactivity will tend to reduce with time as ^{239}Pu decays into the less reactive ^{235}U, both of which will be diluted by non-fissile ^{238}U. Furthermore, formation of critical configurations in SF containers is not possible provided the average irradiation of the fuel is above a certain amount (for example 35 GWd/tU for PWR SF).

The consequences of a post-closure criticality are low because:

- rapid transient criticality could only occur for a narrow range of hypothetical conditions, and such a criticality is not considered to be credible after about 100,000 years, due to decay of ^{239}Pu
- the consequences of a quasi-steady state (QSS) criticality are highly localised and would not affect the surrounding geosphere and therefore would not significantly impact overall risk
- direct radiation from a criticality event would be shielded by the surrounding rocks and there would be no direct risk posed to operators or members of the public
- for QSS criticality, the calculated temperature rise and power are very local and the maximum temperature would be less than a few hundred degrees Celsius, corresponding to a power output of a few kilowatts. Within a few metres the temperature rise would be of the order of degrees Celsius
- even if one were to occur, the effects of a criticality event are likely to affect only a limited part (of the order of tens of cubic metres) of the GDF

- criticality events involving very large amounts of fissile material might have a significant impact on a small fraction of the GDF, but these events are very unlikely and could only occur a long time after closure. Their effect on overall risk is small.
- the backfill/buffer and geological environment will still act to isolate the radioactive waste from the surface environment.

Based on modelling of the consequences of criticality events, and combining this with analysis of their likelihood, we consider that the risk from post-closure criticality is not a significant concern.

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List of key terminology specific to this report

$K_{effective}$: A useful way of quantifying how close a system is to being critical is by calculating a mathematical factor known as $K_{effective}$, the ratio of the rate of neutron production (by fission) to the rate of neutron losses (by absorption plus leakage).

Credible event: An event that is hypothetically possible and therefore has a likelihood associated with it, although (in terms of its use in this report) it is almost always considered to be of low likelihood.

Incredible event/not credible: Where the probability of an event occurring is expected (or has been demonstrated) to be vanishingly small or zero.

Package envelope: A generic “low-likelihood package envelope” (referred to as the “package envelope”) that establishes the packaging and disposal facility conditions under which post-closure criticality is considered unlikely to occur.

Deterministic calculations: Calculations in which all parameters take a single, fixed value.

Bounding calculations: Typically deterministic calculations where the single, fixed values selected are conservative or worst case.

Probabilistic calculations: Calculations in which many individual realisations are carried out – in each realisation some or all parameters take a randomly sampled value from a probability density function (PDF) representing the uncertainty in the parameter.

‘What-if’ criticality scenario: An assumed sequence of events whereby, within a localised volume of the geological disposal facility or the surrounding host rock, a critical configuration of fissile materials is reached.

Hypothetical criticality event: A specific example for a ‘what-if’ scenario whereby a critical configuration is selected for criticality consequence analysis.

Static criticality calculations: The use of criticality software to determine the neutron-multiplication factor $K_{effective}$.

Transient criticality models: The Quasi Steady State, Rapid Transient and Bounding Approach models.

Criticality consequence analysis: Use of the transient criticality models to understand the local consequences of hypothetical transient criticality events.

List of acronyms

AGR - Advanced gas-cooled reactor

ALARP - As low as reasonably practicable

AP1000 - Westinghouse Electric Company pressurised water reactor

BSO - Basic safety objective

BUC - Burn-up credit

CSA - Criticality safety assessment

CoRWM - Committee on radioactive waste management

DCTC - Disposal container transport container

DNLEU - Depleted, natural and low-enriched uranium

DSSC - Disposal system safety case

EC - European Commission

FEP - Features, events and processes

FETCH - Finite element transient criticality (the name of a computer code)

GCSA - General criticality safety assessment

gCSA - Generic criticality safety assessment

GDF - Geological disposal facility

GPA03 - 2003 Generic performance assessment

GRA - Guidance on requirements for authorisation

GSL - General screening level

GWd/tU - Gigawatt days per tonne of uranium

HEU - Highly enriched uranium

HHGW - High heat generating waste

HLW - High level waste

IAEA - International Atomic Energy Agency

ILW - Intermediate level waste

LoC - Letter of compliance

LEU - Low enriched uranium

LHGW - Low heat generating waste

LLW - Low level waste

LSL - Lower screening level

MOX - Mixed oxide

MRWS - Managing radioactive waste safely

NDA - Nuclear Decommissioning Authority

NEA - Nuclear Energy Agency within the Organisation for Economic Co-operation and Development (OECD)

NGO – Non-government organisation
NRVB - Nirex reference vault backfill
ONR - Office for Nuclear Regulation
PCCCA - Post-closure criticality consequence assessment
PCM - Plutonium contaminated material
PDF - Probability density function
PWR - Pressurised water reactor
RSC - Robust shielded containers
QSS - Quasi steady state
RT - Rapid transient
RTM - Rapid transient model
RWM - Radioactive Waste Management
SF - Spent fuel
SAP - Safety assessment principles
SWTC - Standard waste transport container
UCuRC - Understanding criticality under repository conditions
UK EPR - United Kingdom European pressurised reactor
UK RWI - United Kingdom radioactive waste inventory
USL - Upper screening level
WVP - Waste vitrification plant

1 Introduction

1.1 Background

In order to build confidence in the safety of the future geological disposal facility (GDF) for the UK[1], in the absence of potential disposal sites, RWM is developing a generic Disposal System Safety Case (DSSC), which shows how the waste inventory destined for geological disposal could be safely disposed of in a range of geological environments. Background information on geological disposal in the UK can be found in the Technical Background Document [1].

The documents comprising the generic DSSC are shown in Figure 1 and include a number of research status reports ('knowledge base'). The purpose of the research status reports is to describe the science and technology underpinning geological disposal of UK higher activity wastes by providing a structured review and summary of relevant published scientific literature and discussing its relevance in the UK context. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

Figure 1 shows how research status reports underpin different safety cases. They include:

- reports on waste package evolution [2], engineered barrier system (EBS) evolution [3], and geosphere [4], describing the understanding of the evolution of the specific barriers of the multi-barrier system
- reports on behaviour of radionuclides and non-radiological species in groundwater [5], and gas generation and migration [6], describing the release and movement of materials through the multi-barrier system, including the groundwater and any gas phase formed
- reports on criticality safety (this report) and on waste package accident performance [7], describing the behaviour of waste packages and the GDF during low probability events
- a report on the biosphere [8], describing how we think the biosphere may evolve in the future and how radionuclide uptake might be expected to take place.

Research status reports need to be read in conjunction with other documentation, including:

- the Data Report [9], which describes the values of specific parameters used in the safety assessments based on scientific information presented in the status reports
- the Science and Technology Plan [10], which describes planned future research and development activities.

1.2 Objectives and scope

The objective of the Criticality Safety status report is to explain the contributions to safety and technical studies that support our safety cases for demonstrating criticality safety of waste packages during transport, the operational phase of the facility and after disposal in the GDF.

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[1] Disposal of higher activity radioactive wastes in a GDF is current policy in England, Wales and Northern Ireland. Scottish Government policy is that the long-term management of higher activity radioactive waste should be in near-surface facilities. Facilities should be located as near to the sites where the waste is produced as possible.

The Criticality Safety Status Report shows how package fissile material limits are set to avoid criticality in the short to medium term. It discusses the processes that determine the likelihood of a criticality in the long term. It also summarises understanding of hypothetical post-closure criticalities. We assess criticality safety as part of our generic transport, operational and environmental safety cases and also in our advice to waste producers on conditioning and packaging proposals.

The scope covers all materials currently considered in the inventory for disposal, including intermediate and low level waste (ILW/LLW), high level waste (HLW), spent fuels, uranium (particularly depleted, natural and low-enriched uranium, DNLEU) and plutonium.

Figure 1 **Structure of the generic Disposal System Safety Case (DSSC). The suite of research status reports represents the knowledge base**

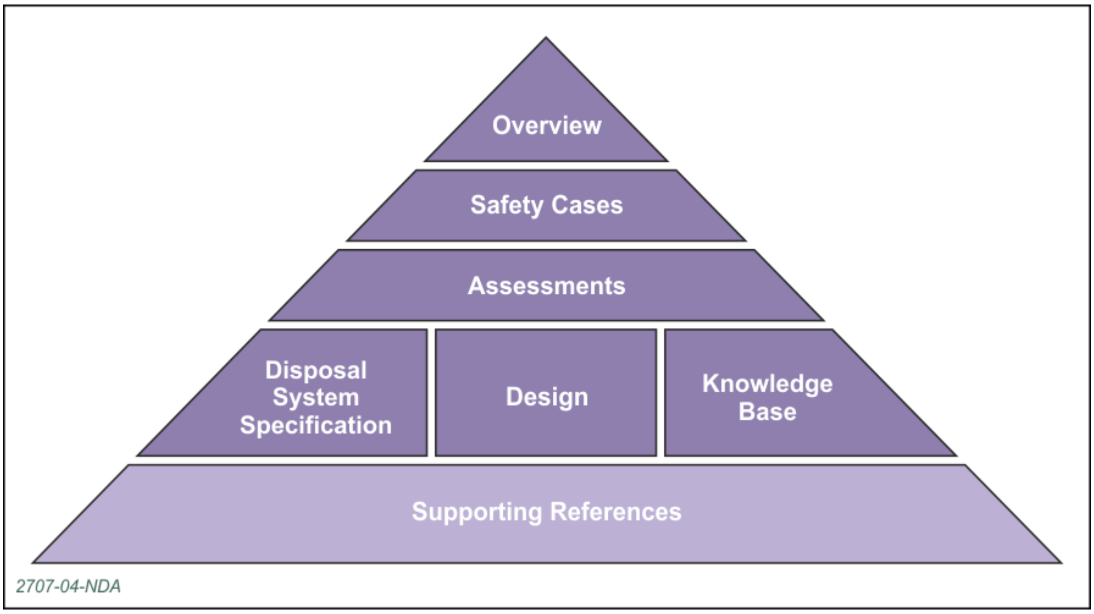
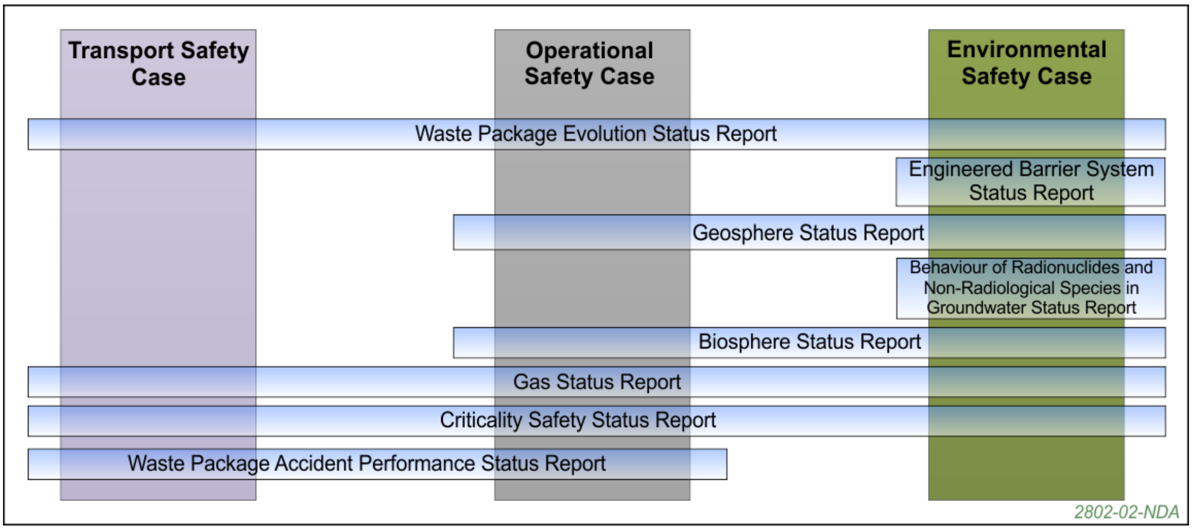


Figure 2 **Safety cases and status reports in which underpinning information can be found**



1.3 Audience and users

The primary external audience of the status reports is our regulators. The audience is also expected to include academics, learned societies and stakeholders such as the Committee on Radioactive Waste Management (CoRWM) and Non-Governmental Organisations (NGOs). The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The primary internal user of the information presented in the status reports is RWM's safety case team.

1.4 Relationship with other status reports

There are important interfaces between this and other research status reports. Information providing underpinning to the Criticality Safety status report includes:

- the expected evolution of various wasteform and waste container materials, which is discussed in the Waste Package Evolution status report [2]. This is a key input to our post-closure criticality considerations, as it influences the timeframe on which fissile material could be released from waste packages and mobilised within the near field of the GDF.
- The Engineered Barrier System status report [3], as post-closure criticality considerations depend strongly on our understanding of the expected evolution of conditions in the near field of the GDF and the migration of fissile radionuclides over long time periods.

1.5 Changes from the previous issue

This document updates and replaces the 2010 Criticality Safety status report [11], published as part of the 2010 generic DSSC suite. This issue includes the following developments:

- an explanation of the revised position for setting post-closure derived package fissile limits/levels
- recent work on package fissile limits for robust shielded containers (RSC)
- recent work on the disposal container transport container (DCTC)
- a new section detailing scenarios for post-closure safety assessment
- a rewritten and expanded section presenting recent results on the likelihood of criticality
- a rewritten and expanded section presenting recent results on the consequences of hypothetical criticality
- an update of the generic post-closure criticality consequences assessment (PCCCA).

1.6 Knowledge base reference period

The knowledge base described in this document contains scientific information available to RWM up to March 2016. Where, within RWM's research programme, progress relative to important topics was made after such date, efforts have been made to reflect such progress up to the publication date of this document.

1.7 Document structure

The remainder of this report is structured according to the following format:

- Section 2 introduces the nature of the criticality hazard, defines criticality safety, and summarises the contributions to safety during transport, pre-closure operations and the post-closure phase of GDF
- Section 3 shows how limits are set to specify, and enable control of, waste package contents
- Section 4 discusses the processes that are relevant in determining scenarios that could give rise to a post-closure criticality, noting the importance of the barriers provided by the waste package, the backfill, and the surrounding geology; we outline the scenarios for post-closure criticality that we have used in assessments of the likelihood and consequences of criticality
- Section 5 provides a summary of our work to estimate the likelihood of criticality for various scenarios, describes the methodology and models used for the analysis, including their limitations, and presents arguments about the likelihood of criticality for different types of waste
- Section 6 summarises our understanding of the consequences of post-closure criticality, outlines the models that have been developed to predict the consequences of a postulated criticality and indicates the role of these models in the overall assessment of post-closure risk
- Section 7 links the research on likelihood and consequences of criticality to the implications for post-closure safety
- Section 8 provides a technical summary and conclusions based on our current understanding.

We have used coloured boxes at the beginning of each section to provide a short summary of the key messages and help the reader in following the ‘golden thread’.

2 Criticality Safety in Waste Management and Disposal

In this section we:

- define what we mean by criticality and criticality safety
- list the means by which criticality may be prevented
- briefly outline the consequences to the GDF if a criticality should occur post-closure
- identify the relevant contributions to safety that underpin the arguments made in the criticality safety cases
- discuss our broad approach used to demonstrate criticality safety for waste management operations.

2.1 Nature of criticality hazards

If enough fissile material were to be brought together in the GDF by some mechanism an uncontrolled nuclear chain reaction (criticality) might occur. Two broad types of criticality event are hypothetically possible, each characterised by significantly different durations and consequences.

When some heavy radionuclides absorb a neutron they may split into two smaller radionuclides, releasing energy and several neutrons in the process. This is called nuclear fission. In a system containing fissile[2] material, the neutrons released may go on to produce more neutrons by further fission or be lost through absorption in non-fissile radionuclides, or may leave the fissile part of the system to be absorbed in surrounding materials (a process referred to as leakage). In certain very specific configurations a self-sustaining neutron chain reaction of fission can be established. When controlled, this is the process by which heat/energy is produced in a nuclear power plant.

If enough fissile material (both in quantity and concentration) were to be brought together outside the carefully engineered environment of a nuclear reactor core an uncontrolled chain reaction might occur, releasing dangerous amounts of radiation to anyone in close proximity, and in certain circumstances, producing significant amounts of energy. This type of uncontrolled event is known as a criticality accident. Criticality safety can be defined [12] as protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention of the chain reaction.

At the point where the chain reaction becomes self-sustaining the system is said to be critical and there is a balance between the number of neutrons being produced by fission and the numbers being lost by absorption and leakage. In this condition the fission rate is steady. If the number of neutrons produced by fission exceeds the numbers being lost, the neutron population and fission rate will increase and the system is said to be super-critical. In a sub-critical system neutron losses exceed neutron production so that a chain reaction cannot be sustained.

A useful way of quantifying how close a system is to being critical is by calculating a mathematical factor known as $K_{effective}$, the ratio of the rate of neutron production (by fission) to the rate of neutron losses (by absorption and leakage). At the point of criticality $K_{effective}$ is

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[2] This report focuses on wastes that contain substantial amounts of ^{239}Pu and ^{235}U, which are the key fissile radionuclides present (fissionable radionuclides that can undergo fission with low energy neutrons). Radionuclides that fission predominantly as a result of interaction with fast neutrons are not considered to present a criticality concern in the GDF because disposal systems are expected to be moderating (and potentially over-moderating) in the presence of waste materials and water.

equal to unity (1.0). For super-critical systems $K_{effective}$ is greater than 1.0, and it is less than 1.0 for sub-critical systems. The 'reactivity' of a fissile system is a measure of the departure of $K_{effective}$ from unity.

The balance between neutron production and neutron absorption/loss, which is the key to ensuring criticality safety, is influenced by many factors. The factors generally found to be most useful in imposing criticality safety control include:

- mass, density, volume, geometry
- concentration, enrichment
- moderation, absorption, reflection and
- interaction[3].

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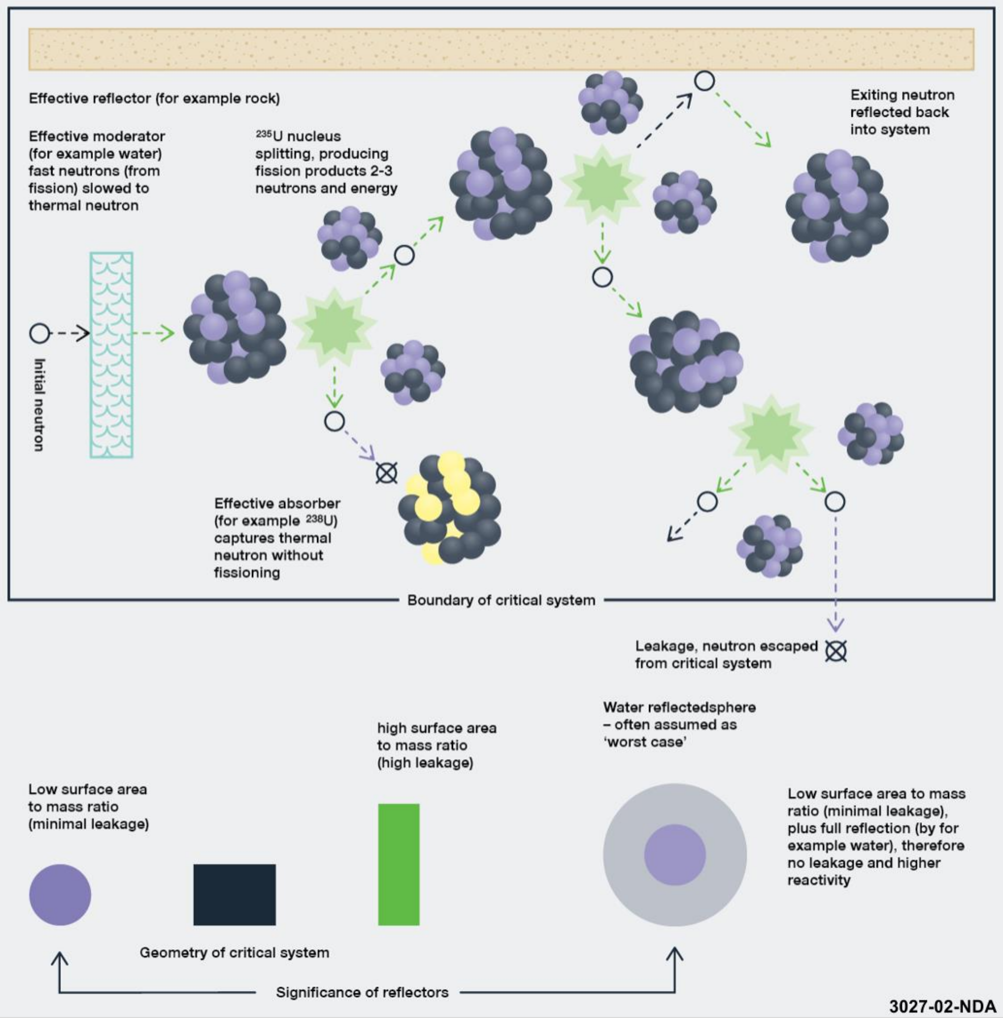
[3] Neutron interaction concerns multiple fissile units (or waste packages), each of which is subcritical in isolation. However, the combined system may be critical due to the interaction between the units, that is, the transfer of neutrons between units. In cases where interaction effects may be important, safety measures are put in place to ensure criticality safety.

Box 1 Introduction to critical systems

The interplay between nuclear fission and system moderation, absorption, reflection, geometry and leakage is illustrated below:



A neutron **moderator** is a medium (such as water, graphite or polythene) that reduces the speed of fast neutrons, turning them into thermal neutrons. This process dramatically increases the probability of neutron capture leading to fission.

A neutron **absorber** is a medium (such as boron or ^{238}U) with a large neutron absorption cross-section[4] that allows it to capture neutrons. The presence of efficient neutron absorbers therefore decreases the $K_{effective}$ of a system.

A neutron **reflector** is a medium (such as rock) that possesses a high scattering cross-section and a low absorption cross-section. Such media are capable of changing neutron direction. Reflectors on systems reduce leakage and therefore increase $K_{effective}$.

Leakage is the escape of neutrons from a fissile system. Leakage is reduced and neutron **interaction** increased if an efficient reflector is present.

In criticality safety assessment, **optimally moderated and fully water-reflected spheres** are often conservatively assumed to occur, as they tend to bound any likely accumulation of fissile material (or are broadly the highest reactivity system), since a sphere is generally the most reactive (lowest surface area to volume) **geometry.**

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[4] The concept of a neutron cross-section is used to express the likelihood of interaction between an incident neutron and a target nucleus.

By limiting one or more of these factors, operations involving fissile material can be maintained in a sub-critical condition. Failure to maintain sub-critical conditions, mainly as a result of human error, has been the cause of about 60 criticality accidents worldwide, resulting in 21 known fatalities [13]. Of these 60 criticality accidents 22 occurred in fissile material processing facilities, and thus occurred in facilities not designed to manage critical conditions, whilst 38 occurred during criticality experiments or operations with research reactors. Importantly, with regards to waste management and geological disposal of solid wastes, 21 of the 22 known process accidents occurred when fissile material was contained within solutions or slurries, meaning that the geometrical arrangement was not necessarily fixed, so geometry could not necessarily be relied upon to ensure sub-critical conditions. Nearly all of these accidents occurred during the early years of the nuclear industry, particularly during the ‘Cold War’ years. In all cases significant radiological effects were limited to operators working within a few metres of the event.

During transport to, and the operational phase of, the GDF, workers (and members of the public in the case of transport) need to be protected against exposure to radiation from a criticality accident. This is generally achieved through the production of waste packages that will remain sub-critical. Following closure of the GDF, deterioration of the physical containment provided by the waste packages, movement of fissile material out of the waste packages and subsequent accumulation into new configurations could in principle lead to a criticality. At this stage there will be no operators present and any radiation produced during the criticality would be safely shielded by the surrounding rock. The issue therefore then becomes the potential effects of a criticality event on the post-closure performance of the repository system.

In the unlikely event that enough fissile material is brought together during the post-closure phase of the GDF by some mechanism, broadly two types of criticality event are hypothetically possible, each possessing significantly different timescales and consequences.

Briefly, in the first type of criticality event, referred to as a quasi-steady state (QSS) criticality, an increase in temperature causes a decrease in the reactivity of the fissile material (a negative temperature feedback). Assuming that further fissile material is still accumulating (for example, from in-flowing groundwater) this allows a steady state to be reached, often with only a modest rise in temperature, in which a ‘just-critical’ configuration is maintained. This just-critical configuration could last for many millennia, but would only yield physical consequences (temperature rise and power) that are typically limited to a few kilowatts of power, and a maximum temperature rise of a few hundred degrees Celsius. Therefore consequences from a QSS criticality are not expected to significantly impact the surrounding geosphere (rock properties). Furthermore, it would only impact a highly localised region.

In the second type of criticality, known as rapid transient (RT) criticality, an initial increase in temperature causes an increase in the reactivity (a positive temperature feedback). In these circumstances it is not possible to maintain a ‘just-critical’ configuration, so the neutron flux and power rise, leading to a rapidly escalating temperature. At some point the pressure will become sufficient to drive expansion of the critical region, leading to possible damage to the surroundings (such as possible void formation in the near field and cracking of the surrounding geosphere). This expansion may be sufficient to terminate the criticality. The timescale for a rapid transient event, from start to finish, is typically less than one second.

Importantly, the majority of hypothetical criticality events from fissile accumulation would only evolve as a QSS criticality. Post-closure RT criticality is only thought to be credible over a narrow range of ^{239}Pu concentrations (and not from predominantly uranic systems) [14]. Therefore, the passage of time lowers the possibility of rapid transient criticality occurring (as ^{239}Pu decays to ^{235}U), and after 100,000 years have passed (or about four half-lives of ^{239}Pu) RT criticality is no longer thought to be credible.

A more detailed discussion of these two types of criticality event is given in Section 6.

It is therefore hypothetically conceivable that a post-closure criticality could adversely affect the performance of a GDF because the heat and energy released might be sufficient to affect engineered barriers designed to contain the radionuclides in the waste. This is considered as part of the post-closure safety assessment [15] and is discussed further in Section 7.

2.2 What do we mean by criticality safety?

Criticality safety can be defined as protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention of the chain reaction.

We describe something as being 'safe' if we can demonstrate that there is little risk associated with it, or that we can manage the situation to keep the risk to an acceptable level. Criticality safety has been defined as protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention of the chain reaction [12]. To do this we impose limits on the contents of waste packages containing fissile material such that they will remain sub-critical in all normal and credible accident conditions.

The design of the wasteform and packages, and the conditions during transport and emplacement, provide a series of layers of defence, ideally to prevent a criticality occurring at all, or by limiting its consequences if such an event cannot be ruled out entirely. This concept of 'defence-in-depth' is central to our approach to criticality safety.

Evidence from criticality accidents shows us that most have been caused, to a greater or lesser extent, by failure of safety measures relying on operator actions [13]. Where practicable this type of protection should be avoided, and the aim is to provide layers of defence based on passive features of the design (for example, the dimensions and shape of containers, or some inherent property of the fissile material like low fissile concentration) to prevent a critical system being formed.

If it is not practicable to establish this type of deterministic demonstration of safety, criticality safety must be demonstrated through a probabilistic approach. Probabilistic assessments are based on estimating the risk associated with certain processes, given the uncertainties. Here risk is defined as the product of the frequency of an event multiplied by its consequences.

The requirements for criticality safety assessment of various phases of the disposal route are specified by the relevant regulatory bodies. Safe transport of fissile materials to the GDF will be addressed by our transport safety case [16] and regulated by the Office for Nuclear Regulation (ONR) following international regulations established by the International Atomic Energy Agency (IAEA) [17]. During transport there is potentially a hazard to members of the public and there is strong emphasis on deterministically demonstrating that a criticality cannot occur in normal, or any credible, accident conditions.

The safety of operations on licensed nuclear sites (including at a future GDF) is also regulated by the ONR. A fundamental requirement of the ONR is that the risks associated with proposed operations must have been demonstrated to be 'As Low As Reasonably Practicable' (ALARP) [18]. In the context of criticality safety this may be by showing that there is sufficient defence in depth, or through a probabilistic argument showing that risks comply with numerical targets. Our operational safety case [19] must also show that any further risk reduction could only be made at a cost considered to be grossly disproportionate to the benefit achieved.

Once the GDF has been closed regulatory responsibility falls under the relevant environment agency. At this stage the risk of direct radiation exposure to operators or the public is removed due to the location of the material deep underground in an engineered facility. However, criticality might conceivably affect the ability of the GDF to contain the radionuclide inventory and the environmental safety case must therefore demonstrate that:

> ‘*The possibility of a local accumulation of fissile material such as to produce a neutron chain reaction is not a significant concern.’*

Furthermore, RWM as the implementer is also required to investigate as a ‘what-if’ scenario:

> *‘The* impact *of a postulated criticality event on the performance of the disposal system.’*

These requirements are expressed in the environment agencies’[5] ‘Guidance on Requirements for Authorisation’ (GRA) [20].

2.3 Contributions to safety

We need to demonstrate criticality safety both prior to closure of the GDF (during transport and operations) and following GDF closure.

This section identifies the relevant contributions to safety that underpin the arguments made in the criticality safety cases.

Criticality is a key FEP (features, events and processes) in the NEA FEP list [21]. The work presented in this report summarises our full understanding of this important FEP. A detailed and structured approach is used in our studies of the likelihood of criticality post-closure (see Section 5). Also, it is implicit in the approach to criticality safety in earlier phases of waste management. The outputs of these approaches are presented here as the main contributions to safety during pre-closure operations, which are discussed in subsection 2.3.1, and those following closure, which are discussed in subsection 2.3.2.

2.3.1 Pre-closure operations

Prior to GDF closure, in most cases, criticality control is based on limiting the fissile content of packages (for example for ILW) and/or controlling the geometry of the fissile distribution (for example for SF). The robust nature of the packages ensures that rearrangement of the fissile component into an unsafe configuration cannot occur during transport or operations.

Operations involving processing, storage and transport of fissile material in the form of nuclear fuel have been subject to criticality assessment over many years using well established methodologies. The general principles of those methodologies are also applicable to the assessment of similar operations on fissile waste. Responsibility for the production of safety cases for conditioning, packaging and interim surface storage of these materials lies with the site operators of those facilities.

We assess criticality safety as part of the safety cases for transport to and operation of the GDF. We also assess criticality safety, as part of our advice to site operators on conditioning and packaging proposals through the Letter of Compliance Disposability

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[5] The Environment Agency, the Scottish Environment Protection Agency (SEPA) and the Northern Ireland Environment Agency (NIEA) are responsible for regulating the disposal of radioactive waste in England and Wales, in Scotland, and in Northern Ireland respectively. The GRA referred to was issued by the Environment Agency and the NIEA. For simplicity this report uses the term environment agencies’, but in reality it only refers to these two organisations.

Assessment process, to ensure that every waste package will comply with the requirements of the Disposal System Specification [22] and the Waste Package Specifications [23, 24]. The contributions to safety listed in Box 2 apply in some or all of these safety cases.

Box 2 Pre-closure contributions to safety

For the waste material:

- RWM has a detailed knowledge of the inventory of radioactive wastes and materials.
- for the majority of the wastes criticality safety is not a concern. In ILW the fissile material is nearly always mixed with a large excess of non-fissile material. HLW contains little fissile material because this has been separated during the reprocessing of SF.
- small amounts of ILW will contain separated plutonium and HEU, but these are not present as pure materials – they are dispersed amongst other non-fissile waste materials.
- for pure materials such as plutonium and HEU, RWM can design a stable wasteform that is sub-critical.
- most spent fuel (SF) is removed from nuclear reactors because a large proportion of the fissile content has been used up and actinides and fission products have been produced during irradiation, meaning it can no longer effectively contribute to producing power in the reactor.

For the packages:

- RWM specifies and ensures control of all waste package contents.
- for the majority of SF, the wasteform design is already fixed by the nature of the waste, that is, it comprises a metallic or ceramic fissile material surrounded by cladding, so we will use a package design to ensure safe sub-critical conditions (for example, this might include using materials that absorb neutrons to prevent criticality).
- for packaging of HEU and plutonium at high loadings, (for example, in the current packaging assumption of a ceramic wasteform emplaced in the HLW disposal area), contributions to safety will be provided by the stable, sub-critical wasteform and a long-lived container.
- in all cases, we aim to design packages that are robust to faults during transport and operations.

In most cases, criticality control is based on limiting the fissile content of packages (for example for ILW) and/or applying geometric control of the fissile distribution (for example for SF). Once the waste containers are loaded, the robust nature of the packages ensures that rearrangement of the fissile component into an unsafe configuration cannot occur during transport or emplacement. The process applied to derive safe package fissile material limits is discussed in Section 3.

2.3.2 Post-closure

After GDF closure, package fissile material limits will help to prevent a criticality for a considerable time. Once packages have degraded, we aim to demonstrate that the likelihood and consequences of post-closure criticality (following a reconfiguration and/or accumulation of fissile material) are both low.

Packaging, and package limits, will help prevent a criticality for such time as the waste packaging affords a high level of containment. However, once the GDF is sealed these engineered measures will start to degrade as the containers corrode; a portion of the package contents may eventually become mobilised by groundwater.

In contrast to preceding phases of the disposal route, criticality safety for the entire duration of the post-closure phase of the GDF (perhaps a million years) cannot readily be demonstrated in a deterministic assessment of the protection offered by engineered measures and fixed package limits. In the post-closure assessment there is necessarily more reliance on probabilistic arguments in order to demonstrate that the likelihood and consequences of post-closure criticality are both low.

The contributions to safety listed in Box 3 apply in the post-closure criticality safety case.

Box 3 Post-closure contributions to safety

The likelihood of post-closure criticality is low because:

- waste containers will be emplaced in the GDF in a sub-critical configuration, with multiple engineered barriers in place to retard the effects of processes that might lead to significant relocation of fissile material.
- many of the anticipated changes in the evolution of waste packages in this environment following closure are expected to reduce system reactivity.
- for ILW, the fissile material is well spread out; the total fissile content of 13.5 tonnes being dispersed through ~470,000 m^3 of waste packaging materials, at concentrations well below critical values.
- the majority of ILW is/will be encapsulated in cement, and ILW disposal concepts are based on cementitious backfill, the chemical and physical properties of which hinder movement of fissile material.
- for pure plutonium and uranium materials, which are not yet categorised as wastes, RWM could design a wasteform that is stable for long times and would only very slowly release fissile material, as in the current packaging assumption.
- for SF we will use package and emplacement designs capable of maintaining sub-critical conditions over very long timescales and, in the majority of fuel types, the reactivity will broadly reduce with time as ^{239}Pu decays into less reactive ^{235}U, both of which will be diluted by non-fissile ^{238}U. Furthermore, formation of critical configurations in SF containers is not possible provided the average irradiation of the fuel is above a certain amount (for example 35 GWd/tU for PWR SF).

The consequences of post-closure criticality are low because:

- rapid transient criticality could only occur for a narrow range of hypothetical conditions, and such a criticality is not considered to be credible after about 100,000 years post-closure, due to decay of ^{239}Pu to ^{235}U.
- for a QSS criticality, the physical consequences are highly localised and would not be expected to affect the surrounding geosphere, and therefore would not significantly impact on overall risk.
- direct radiation from a criticality event would be shielded by the surrounding rocks and materials. Unlike during the transport or operational phases of the GDF there will be no direct risk posed to operators or members of the public.
- for QSS criticality, the calculated temperature rise and power are less than 300 °C locally and a few kilowatts, irrespective of whether the underlying scenario is accumulation, stack slumping or in-package flooding.
- even if such were to occur, criticality events are likely to affect only a limited part (of the order of tens of cubic metres) of the GDF.
- criticality events involving very large amounts of fissile material might have a significant impact on a small fraction of the GDF and the engineered barrier system, but these events are very unlikely and could only occur a long time (hundreds of thousands of years) after closure, when the radioactive inventory will have decayed to much lower levels. Therefore their effect on the overall risk will be small.
- the backfill/buffer and geological environment will still act to isolate the radioactive waste from the surface environment.

We have carried out a detailed research programme to provide technical underpinning for these arguments. In particular we aim to demonstrate that both the likelihood and consequences of a post-closure criticality event are low and therefore are not of significant concern. The evidence provided by these studies is summarised in Sections 5, 6 and 7.

2.4 Approach to demonstrating criticality safety

Our overall understanding of the processes affecting criticality safety involves complementary types of investigation, comprising analysis of existing knowledge, modelling using both widely used and specially created software, and analysis of a natural analogue.

Almost all of our studies are modelling, supported by existing knowledge. Criticality experiments have been conducted and documented, mostly in facilities that are no longer operational. Analysis and re-analysis continues to this day, for example in the International Criticality Safety Benchmark Evaluation Project [25]. This supports the validation of neutron transport codes that are used in our criticality safety assessments, for example to demonstrate the criticality safety of SF in transport containers [26] and of waste in robust shielded containers [27]. Unplanned criticalities have been analysed internationally, mainly to learn lessons to avoid further events [13], but also to confirm limits on key parameters and to support predictions of consequences.

Super-critical experiments are represented in historical underground testing, the consequences of which were documented [28,29] and have been analysed as part of our research programme [30].

Modelling is used in a number of ways to build understanding of criticality safety. For example, modelling of SF assemblies, in specified geometries during normal and accident conditions of transport, formed a major part of the DCTC analysis [26]. The models used the internationally recognised and validated neutron transport code MONK [31].

The evolution of waste packages and migration of fissile material post-closure has been modelled using GoldSim [32,33] to assess the likelihood of criticality post-closure [34]. It is not always possible to validate such post-closure computer models, due to, for example the long post-closure timescales of interest meaning that you cannot make use of real time experiments. You can, however, use natural analogues and other studies to build confidence in the model. The Oklo natural reactors [35,36] (see subsection 4.9) present just such a natural analogue, the analysis of which [37] has been used to build confidence in an approach that models the post-closure consequences of hypothetical accumulations of fissile material [38].