Nuclear Decommissioning Authority

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Geological Disposal

Feasibility studies exploring options for storage, transport and disposal of spent fuel from potential new nuclear power stations

November 2010

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Executive summary

Background

In 2009, the Nuclear Decommissioning Authority's Radioactive Waste Management Directorate (RWMD) contributed to the Generic Design Assessment process for new nuclear reactor designs. RWMD undertook assessments under contract on behalf of Westinghouse and Electricité de France and Areva NP, to consider the disposability in a geological disposal facility of the higher activity wastes and spent nuclear fuel (SF) that would be expected to arise from operation and decommissioning of the AP 1000 and UK EPR reactor designs. RWMD concluded that given a disposal site with suitable characteristics, the wastes and SF from the new nuclear reactor designs are expected to be disposable.

The assessments noted that compared to legacy wastes and SF, no new issues arise that challenge the fundamental disposability of the waste and SF arising from new nuclear power stations. However, due to the higher burn-up proposed for SF in new nuclear power stations, a longer period of cooling had been calculated to be necessary to meet criteria for emplacement in a geological disposal facility. The assessments identified that various opportunities exist to reduce the required cooling period by, for example, considering options for the packaging arrangement and disposal configuration.

Subsequently, prospective new nuclear power station operators working together via the Nuclear Industry Association (NIA) have commissioned the NDA to conduct feasibility studies exploring issues associated with alternative options for storage, transport and disposal of SF from prospective new nuclear power stations.

The purpose of this work is not to make decisions regarding alternative options for SF management, but is intended to provide a better understanding of the issues and identify options for SF management where opportunities could potentially be realised.

Feasibility Study

The feasibility studies have addressed four SF management work strands which are of significance to operators of new nuclear power stations and a geological disposal facility, as follows:

a) Centralised storage facilities for SF. A centralised storage facility would enable SF to be removed from nuclear power station sites after an initial on-site cooling period;

b) Centralised packaging plant for SF. The current assumption is that a SF packaging plant would be provided on each new power station site;

c) Alternative SF cask types, i.e. dual-purpose and multi-purpose cask systems suitable for storage and/or transport and disposal. The current assumption is that SF would be loaded into a purpose designed disposal canister at some stage prior to disposal. Depending upon storage arrangements, this may involve transferring SF from a storage cask into a disposal canister. Such double handling of "aged" SF has risks which should be avoided or minimised if possible and dual-purpose or multi-purpose cask designs might offer benefits;

d) Alternative disposal concept options which are optimised for SF from new nuclear power stations. A range of conceptual designs for a geological disposal facility have been examined by RWMD based upon knowledge of legacy SF. It is recognised that whilst SF from new nuclear power stations can be accommodated within these designs, they may not present an optimal solution.

For each strand, (a) to (d), studies have been undertaken to explore the options and issues that arise. The studies are presented in this report.

Content

This report discusses the context, timings and assumptions that have been used in this work. This includes the implications identified by RWMD as a result of considering the drivers impacting potential new nuclear power station operators compared to the currently assumed disposal arrangements.

There is also a discussion of the issues and potential options for SF storage, packaging and transport. This illustrates some of the issues and uncertainties associated with the choices of both “at the site of arising” and “away from the site of arising” SF storage and packaging which need to be considered.

The issues associated with alternative cask types are explored and consideration is given to how the basis for planning for the implementation of new nuclear power stations may be developed to take account of alternative disposal canister sizes and options to mitigate temperature effects. The impact of adopting alternative disposal concepts for the disposal of SF from new nuclear power stations is also considered.

Conclusions

The work undertaken in these studies has identified that there are a number of feasible options for the management of SF from new nuclear power stations.

In the area of storage and packaging it has been established that there are a number of feasible potential centralised storage and packaging options and that both wet and dry technology is potentially suitable for the long term management of new nuclear power station SF.

In the area of alternative cask types it has been established that the use of Multi-Purpose Containers (MPC) could reduce the need for handling SF assemblies and avoid concerns about handling aged SF, but the implications of such a management approach for the SF may warrant further investigation.

In the area of alternative disposal concept options it has been established that there are a number of feasible opportunities to optimise the disposal concepts if SF arising from new nuclear power stations were to be included in the disposal inventory. One of these relates to the cooling period, where RWMD has previously identified that for high burn-up SF (65 GW/tU) a cooling period of the order of 100 years is required to comply with the current bentonite buffer temperature limit of 100^{o}C. This cooling period has been revisited and it has been identified, for example that with judicious mixing of long-cooled and short-cooled SF the duration of storage after the end of power station operation could be reduced to the order of 50 years before disposal.

It is envisaged that the information and understanding gained from these studies will inform future decision making.

Potential next steps

The studies have necessarily been pitched at a high level and further work is needed to develop the options further before they could be used with confidence to inform deliberations on a potential revised planning basis for the new nuclear power station programme.

List of Contents

Executive summary		**iii**
1	**Introduction**	**1**
1.1	Scope and objectives of project	1
1.2	Report structure	2
1.3	Background	2
2	**New nuclear power station programme overview**	**6**
2.1	Generic Design Assessment disposability assessment and Base Case implications	6
2.2	Prospective new nuclear power station operator timing assumptions	6
3	**Implications of currently assumed disposal arrangements**	**8**
4	**Spent fuel storage and packaging options and their role in the waste management lifecycle**	**10**
4.1	Potential options for spent fuel storage and packaging	10
4.2	Location options	11
4.3	Storage system	13
4.4	Packaging plant feasibility and costs	18
5	**Issues associated with alternative disposal canisters**	**20**
5.1	Option development methodology	20
5.2	Suitability of alternative disposal canisters to the reference conceptual design	20
5.3	Suitability of the reference conceptual design to alternative geological environments	24
5.4	Considering different packaging options to mitigate temperature constraints	25
6	**Suitability of alternative disposal concepts for the disposal of spent fuel from new nuclear power stations**	**31**
6.1	Concept key feature – In-tunnel (axial)	32
6.2	Concept key feature – Cavern	33
7	**Conclusions**	**36**
8	**The potential next steps**	**38**
9	**References**	**39**

1 Introduction

In 2009 the Nuclear Decommissioning Authority's Radioactive Waste Management Directorate (RWMD) contributed to the Generic Design Assessment (GDA) process for new nuclear reactor designs by the provision of assessments under contract on behalf of Westinghouse and Electricité de France and Areva NP, to consider the disposability of wastes and spent nuclear fuel (SF) that could be expected to arise from the operation and decommissioning of the AP 1000 and UK EPR reactor designs [1,2]. RWMD concluded that given a disposal site with suitable characteristics, the wastes and SF from the new nuclear reactor designs are expected to be disposable. Those assessments also identified that opportunities exist to improve the assessed disposal arrangements and that alternative options may be worthy of consideration.

Subsequently, prospective new nuclear power station operators working together via the Nuclear Industry Association (NIA) have commissioned the NDA to conduct feasibility studies exploring issues associated with alternative options for storage, transport and disposal of SF from prospective new nuclear power stations. It is envisaged that these feasibility studies will inform deliberations regarding the next steps.

The purpose of this work is not to make decisions regarding alternative options for SF management, but is intended to provide a better understanding of the issues and identify options for SF management where opportunities could potentially be realised. The work has been managed by the NDA's RWMD and this report represents the output of that commissioned work.

1.1 Scope and objectives of project

The work was commissioned by the NIA and was undertaken by NDA RWMD under a contract to provide advisory services relating to nuclear waste management. The work is fully funded by the NIA which is coordinating inputs and acting on behalf of potential new nuclear power station operators. The scope covers four key SF management work strands:

a) Centralised storage facilities for SF. A centralised storage facility would enable SF to be removed from power station sites after an initial on-site cooling period;

b) Centralised packaging plant for SF. The current assumption is that a SF packaging plant would be provided on each new nuclear power station site;

c) Alternative SF cask types i.e. dual-purpose and multi-purpose cask[1] systems. The current assumption is that SF would be loaded into a purpose designed disposal canister at some stage prior to disposal. Depending upon storage arrangements this may involve transferring fuel from a storage cask into a disposal canister. Such double handling of "aged" SF has risks which should be avoided or minimised if possible and dual-purpose or multi-purpose cask designs might offer benefits.

d) Alternative disposal concept options which are optimised for SF from new nuclear power stations. A range of conceptual designs for a Geological Disposal Facility (GDF) have been examined by RWMD based upon knowledge of legacy SF. It is recognised that whilst SF from new nuclear power stations can be accommodated within these designs, they may not present an optimal solution.

[1] In this report cask has been used as a generic term that could include a storage, transport or disposal canister.

For each strand, (a) to (d), studies have been undertaken to explore the options and determine the underlying issues. It is envisaged that the information and understanding will provide inputs to both the GDF programme and new nuclear power station development.

At the initial stage of the project, when an understanding of the drivers impacting potential new nuclear power station operators was developed, other specific matters were identified for consideration in the scope of the work. These are summarised as:

- Measures which could be adopted to reduce the SF storage timescales prior to disposal;
- Opportunities which may exist for reducing the cost of packaging SF, as well as the opportunity for a shared packaging plant facility;
- Consideration of how the waste management system for SF, including packaging, transport and disposal could be simplified with a view to reducing time to disposal and the cost;
- Opportunities which may exist for improving the logistics of SF handling, such as increasing the amount of SF in a disposal canister.

1.2 Report structure

This report has been structured as follows:

- Section 2 provides an overview of the programme that the Government has used to develop the Funded Decommissioning Programme and provides the key dates that have been assumed. It then compares these dates with the latest plans for developing new nuclear power stations by the two most advanced potential operators of new nuclear power stations – NNB Generation Company and Horizon Nuclear Power. This Section provides an overview of the timings so potential changes discussed in subsequent sections can be compared to the present timing assumptions;
- Section 3 considers the significant implications that have been identified by RWMD as a result of considering the drivers impacting potential new nuclear power station operators compared to the currently assumed disposal arrangements;
- Section 4 covers the first two work strands: centralised national storage facilities and a centralised packaging plant for SF and discusses issues and potential options for SF storage, packaging and transport;
- Section 5 covers the third work strand: issues associated with alternative cask types;
- Section 6 covers the last work strand: alternative disposal concept options;
- Section 7 draws together the conclusions of the feasibility studies and Section 8 identifies potential next steps resulting from the preliminary work undertaken.

1.3 Background

1.3.1 RWMD programme

UK Government policy is that geological disposal is the way higher activity radioactive waste will be managed in the long term: this will be preceded by safe and secure interim storage until a geological disposal facility can receive waste. The NDA has established the RWMD to manage the delivery of geological disposal for higher activity waste, as required under UK Government policy. RWMD's programme mission is: "To deliver a geological disposal facility and provide radioactive waste management solutions" [3], Supporting objectives include:

- Develop the specification, design, safety case and environmental and sustainability assessments for the disposal system and obtain regulatory support, and;
- In conjunction with waste producers, identify and deliver solutions to optimise the management of higher activity waste.

To implement this mission, RWMD is pursuing a programme of work in line with the framework set out in the Managing Radioactive Waste Safely (MRWS) White Paper [4]. The MRWS process is founded on the principles of voluntarism and partnership and RWMD is currently engaged in generic design and safety case studies to provide a basis for discussion with regulators and communities wishing to engage in the process.

Geological Disposal Concepts

Work carried out by RWMD in 2008 identified a range of possible geological disposal concepts for disposal of High Level Waste (HLW) and SF [5]. This work was based on previous UK work and that of disposal programmes in other countries, and identified disposal concepts suitable for various generic geological settings (host rock formations and associated geological and hydrogeological conditions). This effectively provides a catalogue of concepts for consideration. At the current stage of RWMD's programme, work is focussed on analysing and developing potentially suitable geological disposal concepts based on three stylised generic geological settings.

Generic design and safety case studies, together with underpinning research status reports together form the generic Disposal System Safety Case (DSSC) suite of documentation, which is planned to be published in 2011. The documentation is termed 'generic' because a GDF site has not yet been identified and hence site characteristics, including geological setting, are not known.

In addition to the uncertainty regarding geological setting, there are also uncertainties related to the nature and quantities of waste for disposal and the capacity of any host site (including volumetric and radiological capacity). These factors will all impact the finalised design solution. Furthermore, RWMD recognises that an important future step will be to demonstrate that the design and safety have been optimised.

Three illustrative concepts for SF disposal have been identified, one for each of the stylised generic geological settings. See Table 1. Each is supported by designs and safety assessments, thus giving confidence in their viability. The three concepts all propose the use of a robust disposal canister into which SF assemblies are loaded and sealed.

For the purposes of this study the starting point has been the illustrative disposal concept example for higher strength rocks. This is the reference conceptual design described in NDA report Steps towards implementation [3]. Whilst this is taken as the starting point, this study also uses the illustrative concept examples for lower strength sedimentary rock and evaporites to test whether findings are sensitive to the geological setting and associated disposal concept.

Table 1 Illustrative Geological Disposal Concept Examples

Host rock	Illustrative Geological Disposal Concept Examples[d]	
	ILW/LLW	**HLW/SF**
Higher strength rocks[a]	UK ILW/LLW Concept *(NDA, UK)*	KBS-3V Concept *(SKB, Sweden)*
Lower strength sedimentary rock[b]	Opalinus Clay Concept *(Nagra, Switzerland)*	Opalinus Clay Concept *(Nagra, Switzerland)*
Evaporites[c]	WIPP Bedded Salt Concept *(US-DOE, USA)*	Gorleben Salt Dome Concept *(DBE-Technology, Germany)*

Notes

a. Higher strength rocks – the UK ILW/LLW concept and KBS-3V concept for spent fuel were selected due to availability of information on these concepts for the UK context.

b. Lower strength sedimentary rocks – the Opalinus Clay concept for disposal of long-lived ILW, HLW and spent fuel was selected because a recent OECD Nuclear Energy Agency review regarded the Nagra (Switzerland) assessment of the concept as state of the art with respect to the level of knowledge available. However, it should be noted that there is similarly extensive information available for a concept that has been developed for implementation in Callovo-Oxfordian Clay by Andra (France), and which has also been accorded strong endorsement from international peer review. Although we will use the Opalinus Clay concept as the basis of the illustrative example, we will also draw on information from the Andra programme. In addition, we will draw on information from the Belgian super container concept, based on disposal of HLW and spent fuel in Boom Clay.

c. Evaporites – the concept for the disposal of transuranic wastes (TRU) (long-lived ILW) in a bedded salt host rock at the Waste Isolation Pilot Plant (WIPP) in New Mexico was selected because of the wealth of information available from this United States Environmental Protection Agency (EPA) certified, and operating facility. The concept for disposal of HLW and spent fuel in a salt dome host rock developed by DBE Technology (Germany) was selected due to the level of concept information available.

d. For planning purposes the illustrative concept for depleted, natural and low enriched uranium is assumed to be same as for ILW/LLW and for plutonium and highly enriched uranium is assumed to the same as for HLW/SF.

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1.3.2 Generic Design Assessment disposability assessments

The 2008 White Paper on Nuclear Power [6] established the GDA process, whereby industry-preferred designs of new nuclear power stations would be assessed by regulators in a pre-licensing process. As part of this process, RWMD was commissioned by Westinghouse and Electricité de France and Areva NP (UK) (EdF/Areva) to provide disposability assessments for the wastes and SF arising as a result of operation and decommissioning of the AP1000 and UK EPR reactor designs. The GDA disposability assessments [1,2] evaluated the implications of a single and a nominal fleet of AP1000 and UK EPR reactors.

In the assessments it was assumed that in line with the reference conceptual design, SF would be overpacked into robust disposal canisters prior to transport to the GDF. The assessments applied a temperature criterion to determine the acceptable heat output from a disposal canister and, hence, the cooling period required before the SF could be emplaced in a bentonite-lined deposition hole. Based on these packaging assumptions and the given SF characteristics, it was concluded that it would require of the order of 100 years for the activity and hence heat output of the SF to decay sufficiently to meet the temperature criterion required for disposal. This was based on initial, conservative assumptions about the fuel inventory and maximum fuel burn-up. The assessments flagged that further refinements to the packaging concept and consideration of alternative conceptual designs could have the potential to positively impact the time to meet the temperature criterion.

1.3.3 Funded decommissioning programme and Base Case

The Energy Act 2008 [7] created the framework by which operators of new nuclear power stations are required to have secure financing arrangements in place to meet their full share of waste management costs, including disposal. Those arrangements were the subject of a Government consultation in 2008 [8] and require a Funded Decommissioning Programme (FDP) to be approved by the Secretary of State which includes the estimate of the costs. The consultation document [8] contained a Base Case which allowed the Government to estimate the potential costs of waste management and to ensure that operators make adequate provision for their responsibilities (including waste management).

The consultation document assumptions for the Base Case can be summarised as:

- SF will be stored in cooling ponds for a period of time followed by storage in safe and secure interim stores on the site of the power station until disposal facilities are available;
- The SF stores must be technically capable of being maintained or replaced to last for 100 years from the time SF is first placed in them;
- SF will not be reprocessed;
- SF should be packaged in a form suitable for disposal and transported to a GDF;
- SF will be disposed of in a GDF (and it is desirable that it is the same GDF as legacy waste which will be explored through the MRWS programme).

2 New nuclear power station programme overview

Arrangements for the future management of SF following discharge from new nuclear power stations have been factored into Government planning for the FDP and into NDA considerations for the development of a GDF. The GDA disposability assessments of SF from AP1000 and UK EPR power stations have demonstrated that these arrangements are workable.

2.1 Generic Design Assessment disposability assessment and Base Case implications

The background presented in Section 1 summarised the Government position on estimating the potential costs of waste management through application of a Base Case, as set out in the Consultation on FDP Guidance [8]. A further consultation document has been published [9] setting out proposals for a methodology by which a fixed unit price could be determined for the disposal of waste and SF.

The Government has not set any fixed delivery timescale for a GDF but has adopted the planning assumptions developed by the NDA. The NDA planning assumption for a GDF is that it will be operational by about 2040 and that all legacy wastes will be emplaced by about 2130 (these dates are dependent on the disposal inventory). It is currently assumed that emplacement of waste from any new nuclear power station would begin once emplacement of legacy wastes and SF is complete.

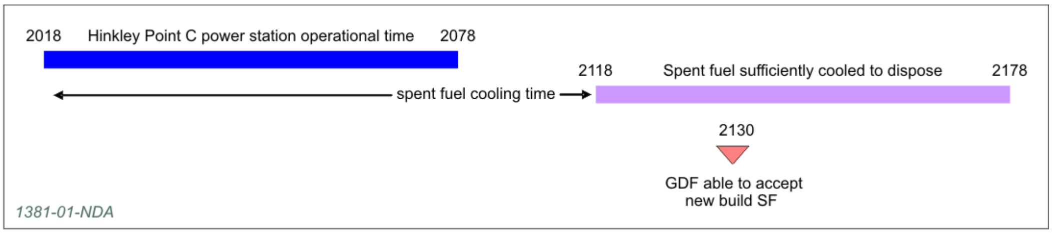
The Government considered that the first new nuclear power station could be operational by 2018 and the Base Case assumption is that the nuclear reactor operates for 40 years, to 2058. The summary GDA disposability assessments for the AP1000 and the UK EPR explain that if all the SF were to be subject to the maximum burn-up considered, which is 65 GWd/tU, then the SF might need of the order of 100 years of cooling in interim storage before it could be disposed of in a GDF. This uses the reference conceptual design assumptions that the SF is packaged in a KBS-3V type canister, is subject to the current assumed temperature constraint applied to the inner bentonite buffer surface and that a canister contains four SF assemblies.

The Base Case assumption is that the SF would have to be stored on the power station site until it can be dispatched in a suitable packaged form to a GDF. The cooling time consideration implies that SF could be disposed from 2118 to 2158, but the planning assumption is that the GDF would not be available to receive SF from new nuclear power stations until 2130.

2.2 Prospective new nuclear power station operator timing assumptions

The organisation that is most advanced with a prospective new nuclear power station programme is NNB Generation Company Limited (NNB Genco) which is wholly owned by Electricité de France (EdF) and Centrica [10]. NNB Genco is proposing the construction of four UK EPR reactors. The first proposed location for these is adjacent to the existing power station at Hinkley Point, to be called Hinkley Point C, where two EPR reactors are planned, with the first unit anticipated to be operational in 2018. The second location is adjacent to the existing power station at Sizewell, to be called Sizewell C where two EPR reactors are planned and which will follow the construction at Hinkley Point. It is expected that the construction period will be six to seven years with a 60 year operating life. NNB Genco is part way into the Infrastructure Planning Commission (IPC) process and is undertaking the pre-application consultation at the time of writing. The next stage, the application itself will include details of the waste management strategy. The first unit is therefore expected to operate from 2018 to 2078 These timings are illustrated in Figure 1 together with the disposal timings developed from the GDA disposability assessments.

Figure 1 Implications of GDA disposability assessment findings combined with timeframes assumed for operation of the first new nuclear power station



The other potential operator is Horizon Nuclear Power (Horizon) which is a joint venture between E.ON UK and RWE npower [11]. It is Horizon's intention to develop a new nuclear power station adjacent to the existing station at Wylfa and Horizon expects this new station to be operational by 2020 with an operational life of 60 years. Horizon is some 18 months behind NNB Genco in the planning process. The first unit is therefore expected to operate from 2020 to 2080.

The prospective new nuclear power station operators understand the assumptions and criteria that are expected to be used in any FDP but they have an aspiration to optimise the complete waste management system which includes storage, packaging and disposal. It is understood and accepted that the existing waste management arrangements and planning by RWMD has necessarily focussed on legacy [2] waste and materials since these arisings are certain and are explicitly defined within the MRWS White Paper. This project provides an opportunity to focus on the specific impacts of SF from new nuclear power stations and on the drivers impacting potential new nuclear power station operators.

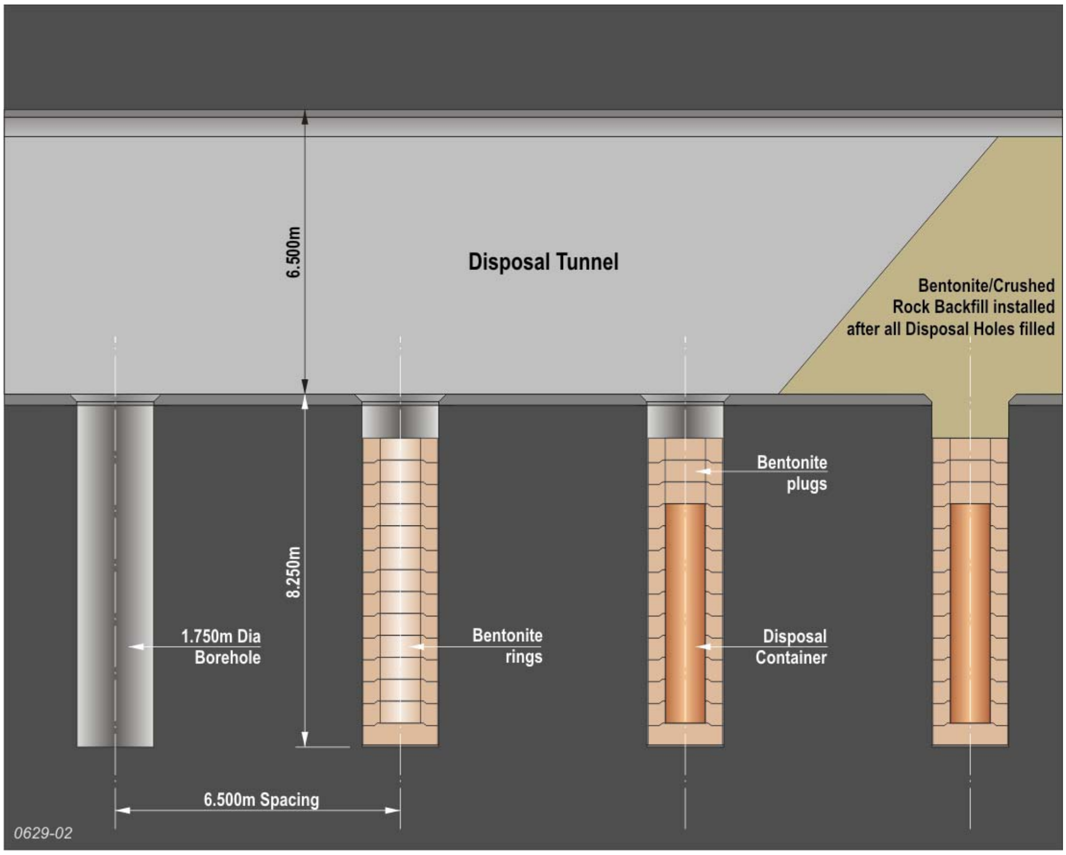
[2] Waste arising from previous and current UK nuclear facilities.

3 Implications of currently assumed disposal arrangements

The reference conceptual design used by RWMD as the basis for the GDA disposability assessments for the AP1000 and UK EPR assumes that SF assemblies will be loaded into a robust disposal canister prior to dispatch to the GDF. The disposal canister is assumed to be manufactured from a durable, corrosion-resistant material, which would provide long-term containment for the radionuclides within the SF consistent with the GDF safety case. The disposal canister itself would be loaded into a re-useable transport container for transport off-site. This is assumed to be accomplished by use of a Disposal Canister Transport Container (DCTC), which has been developed to a preliminary design stage by RWMD.

At this stage, the disposal canister material remains to be confirmed and the GDA disposability assessments considered the potential performance of both copper and steel in this role. In the copper canister case, it is assumed that a cast-iron inner vessel is used to hold and locate the SF assemblies, and also provide mechanical strength. Following receipt at the GDF, the disposal canister would be removed from the transport container and it is assumed it would be emplaced in deposition holes lined with a buffer made from compacted bentonite, which has the characteristic of swelling following contact with water. The reference conceptual design is based on the KBS-3V concept developed by SKB for SF disposal in Sweden [12]. The reference conceptual design is illustrated in Figure 2. More recent studies to explore other disposal concepts are described in Section 1.3.

Figure 2 Reference Conceptual Design for SF disposal



To accommodate the AP1000 and EPR fuel assemblies, it is assumed that the disposal canister would be 5.2 m in length and 0.9 m in diameter. This is a development of the canister envisaged for legacy SF from Sizewell B power station and is approximately 0.6 m longer. The reference assumption is for four SF assemblies to be packaged in each canister.

These arrangements have been adopted as the basis for disposability assessment and also for development of the fixed unit price methodology [9]. The following implications related to the assumed arrangements have been identified by RWMD:

- The requirement to package SF prior to dispatch to the GDF implies that loaded disposal canisters will need to be transported through the public domain. This will require the development of a purpose designed transport container;
- The potential use of separate canisters for storage, transport and disposal implies that SF will need to be recovered from on-site storage arrangements, inspected, loaded and sealed inside the disposal canister at the site of arising. Such arrangements would imply handling of SF assemblies which may have been in store for several decades;
- The disposal canisters are designed to accommodate four SF assemblies. Disposal concepts that could accommodate larger canisters, containing more assemblies, would result in fewer transport movements and potentially have the advantage of a smaller GDF footprint area. This would have to be balanced against thermal considerations which could see a higher heat density and accompanying higher temperatures;
- The use of bentonite as a buffer to protect the disposal canister currently leads to a temperature constraint of 100^{o}C applied to the inner bentonite buffer surface;
- Calculations conducted in support of the GDA assessment identified that SF packages would need to be cooled for of the order of 100 years based on the following fuel assumptions:
    - Four SF assemblies per canister;
    - All SF assemblies irradiated to maximum burn-up of 65 GWd/tU.

4 Spent fuel storage and packaging options and their role in the waste management lifecycle

The work described in this section focuses on work strands (a) and (b) (as described in Section 1) and examines potential options for centralised storage and packaging of new nuclear power station SF and the feasibility of packaging that SF in disposal canisters that are compatible with the reference conceptual design for disposal.

This section aims to illustrate some of the issues and uncertainties associated with the choices of both “at the site of arising” and “away from the site of arising” SF storage and packaging which need to be considered. Furthermore, it should be recognised that the drivers for storage system selection may change with time due to changes in Government policy and strategy, environmental and safety regulations, technological advances, and the capital and operational costs for the various storage systems.

4.1 Potential options for spent fuel storage and packaging

The management of SF discharged from a nuclear power reactor is a key part of the nuclear fuel cycle. It is currently assumed as described in Section 2 that the SF from new nuclear power stations in the UK might need of the order of 100 years of cooling in interim storage before it could be disposed of in a GDF. This once-through approach is commonly referred to as an ‘open fuel cycle’ and is practised in a number of countries in Europe. It can be contrasted with the closed fuel cycle that is operated by France, for example, where oxide SF is reprocessed and Uranium and Plutonium products are recycled as new fuel.

In an open fuel cycle, the typical lifecycle of a SF assembly freshly discharged from a power reactor can be broken down into a number of steps covering:

Storage – at the site of arising (reactor);

Packaging – of SF for transport or transport and disposal;

Transport – of SF to a central store, a packaging plant, or a GDF;

Disposal – of SF in a GDF.

There are many options within and permutations between these steps. Therefore, an analysis of the options for managing SF from new nuclear power stations has to consider a number of potential scenarios. For example, the location of each of these steps, i.e. whether at or away from the site of arising, will affect the type of storage, the period of storage and the type of transport utilised.

An examination of potential options can be simplified to the following key areas:

1. Location - covering the possible variants around where the “Store”, “Packaging Plant” and “GDF” are located;
2. Storage System – the type and period (short-term[3] and interim[4]) of storage system adopted including wet, dry vault and dry cask; the latter of which is sub-divided into dual purpose casks, and multi-purpose containers;

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[3] Short-term storage at the site of arising to facilitate cooling via the initial decay of short-lived radionuclides.

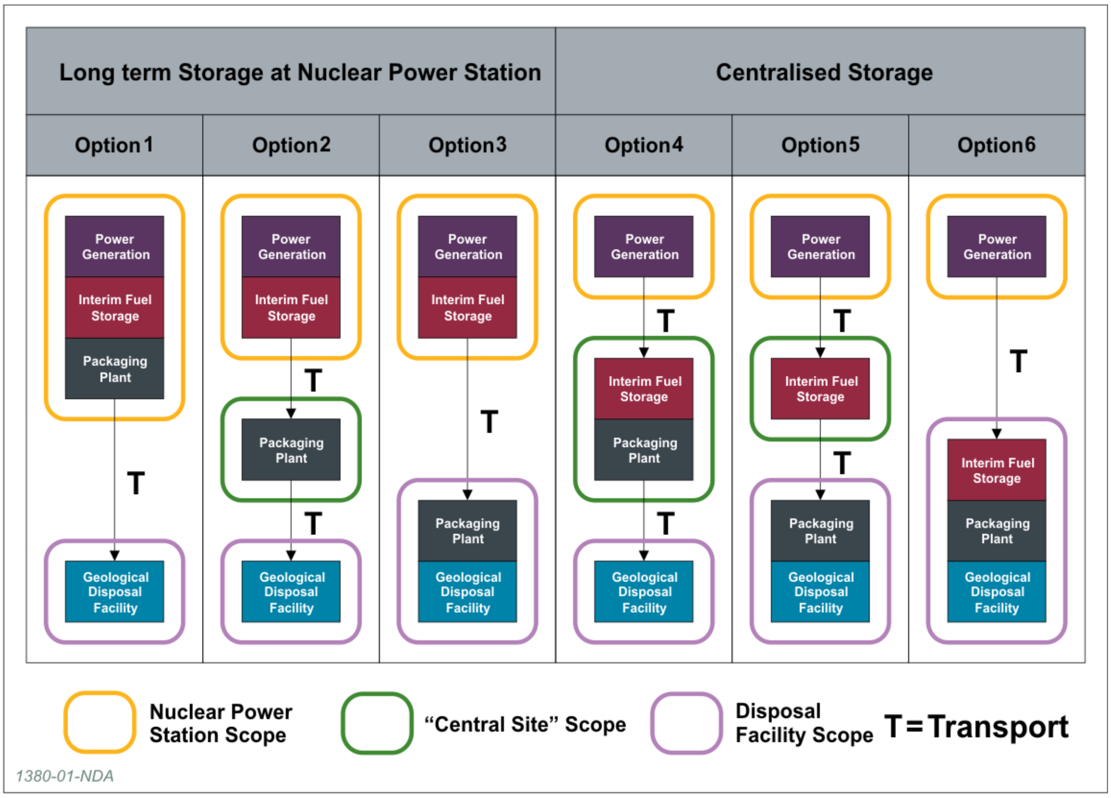
[4] Interim storage in this study includes both storage at the site of arising and at a site away from the site of arising.

A range of credible [5] options has been developed by considering the following areas: economics, security, technical, safety and environmental and the options include brief comment on commercially available storage systems.

4.2 Location options

There are six potential location combinations for the siting of the nuclear power stations, SF store, packaging plant and GDF. These are summarised in Figure 3.

Figure 3 The six possible location options for the siting of the power station, interim store, packaging plant and GDF



The current assumption for SF management is represented as Option 1 and is referred to as the base case, as described in Section 1.3. In this Option, following discharge from the reactor, fuel is interim stored at the power station site until it is sufficiently cool to be packaged and disposed of at the GDF. Given the currently assumed thermal constraints on disposal, the SF might be required to be stored for a period of the order of 100 years following discharge. As the new nuclear power stations are expected to operate for a period of 60 years this could mean SF is stored on site for a period of up to 160 years. This option would be expected to incur significant on-going annual costs due to the requirement to ensure secure and safe management of the SF over the storage period. In addition, it requires a packaging plant to be built at each site to prepare the SF for disposal. The packaging plants would not be expected to start operations until after the necessary cooling period (which currently requires packaging after cessation of power station operation). The duplication of construction, operation and decommissioning activities suggests this option is likely to be the most resource intensive and the least cost effective.

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[5] For the purposes of this study, the term 'credible' is taken to mean 'feasible based on existing proven technology'.

With respect to location, there are a number of options that could be potentially beneficial in terms of improving the management of SF compared to Option 1.

In Option 2, the SF is interim stored at the power station as Option 1 and then transported to a central site for packaging and onward transport to the GDF. The advantage of this option compared to Option 1 is the avoidance of building a packaging plant at each power station site and the opportunity of sharing a packaging plant with SF from other nuclear power stations and from legacy SF. However the disadvantage is that it would require two transportation steps: SF to the packaging plant and packaged SF to the GDF. There are three sub-options for Option 2:

- Packaging plants for SF from each reactor type (i.e. separate plants for AP 1000 and UK EPR fuel);
- A packaging plant for SF for all new nuclear power stations;
- A packaging plant for SF from new nuclear power stations and legacy plants.

In Option 3, SF is interim stored at the power station as Option 1 and then transported to the GDF site where it is packaged and disposed of. The advantage of this compared to Option 1 and 2 is that all the transport can be undertaken using existing types of transportation casks and when compared to Option 2 only one transport step is required. In addition, the packaging plant could be integrated with the disposal facility. It must be stressed that the MRWS framework for implementing geological disposal is founded on the principles of voluntarism and partnership with local communities and they will have an ongoing right of withdrawal until a late stage in this process. If this option was to be pursued further then discussions would need to take place with communities who are involved in the site selection process to determine their views on considering potential additional facilities at the site of a GDF.

A plant to package legacy SF and HLW has been investigated previously by UK Nirex Ltd. It is envisaged that SF from new nuclear power stations could be received on a campaign basis by modifying one of the three feed lines to accept slightly longer fuel assemblies, thereby sharing the facilities with the legacy waste and SF. No significant high-level feasibility issues were identified although further assessment of design modifications would be required to confirm viability of packaging both legacy SF and new nuclear power station SF through a common plant. This is discussed at Section 4.4.

Options 4 to 6 are all variants of centralised storage. The consolidation of SF at a single site may provide increased effectiveness and efficiency of arrangements for the security of SF given the storage periods envisaged. In Option 4, fuel is discharged from a reactor and stored for a period at the power station prior to transport to a central store for a period of interim storage. Following the period of interim storage at the central site, the SF is packaged and transported to the GDF for disposal. Option 4 has the advantage of removing the SF from the new nuclear power station site at an early date and the potential of building only one centrally-located packaging plant. Conversely, it has the disadvantage of requiring two transportation steps: SF to the store and packaged SF to the GDF.

In Option 5, SF is discharged from the reactor and stored for a period at the power station site prior to transport to a central store for a period of interim storage. Following the further period of interim storage, the SF is transported to a central packaging plant, co-located with the GDF, where it is packaged and disposed of. In this option the SF is removed from the new nuclear power station site at an early date and all transportations can be accommodated using existing types of transportation casks. The process for considering this scope change to the MRWS framework applies in the same way as discussed for option 3.

Finally, in Option 6, SF is discharged from the reactor and stored for a period at the power station prior to transport to a central store, which is co-located with both the packaging plant and the GDF. The process for considering this scope change to the MRWS framework applies in the same way as discussed for option 3. Following a further period of interim storage, the SF is packaged for disposal and emplaced underground. The advantage of this option is that SF is removed from the new nuclear power station site early, only a single packaging plant is potentially required, the transport of SF can use existing types of transportation casks and only one transport step is required.

4.3 Storage system

The framework established in Figure 3 for location options can also be used as the starting point for consideration of options for storage and subsequent transport. It is assumed that all SF is initially wet stored for a short-term period following discharge from the reactor, typically for at least 10 years, to facilitate cooling of the initial decay heat from short-lived radionuclides. Beyond this period, interim storage can be accomplished using either wet or dry storage technologies. With wet storage, SF is stored underwater in a cooling pond; with dry storage this may be achieved either by loading SF into a suitable design of cask or by loading into a purpose-designed vault store.

The various options for storage and subsequent transport are illustrated in Figure 4, which shows the short-term wet storage phase and four options for subsequent storage. These are: pond storage (W), dry vault storage (Dv) and two types of cask storage; dual-purpose storage and transport cask (Dc) and multi-purpose container (DMPC).

Dual-purpose storage and transport casks are an existing technology and various designs are available and licensed for this purpose including Castor, Excellox and Pollux. Multi-purpose containers (MPC) are also an existing technology and are designed around the philosophy of providing a seal-welded vessel for the SF which can then be protected by a specific overpack designed for a particular application. Thus different overpacks may be provided for storage and transport applications and in principle, for disposal. Dual-purpose and MPC illustrations, the number of fuel assemblies they hold, and the physical dimensions and weights are presented in Table 2.

Table 2 Dual-purpose storage and transport cask and Multi-purpose Container

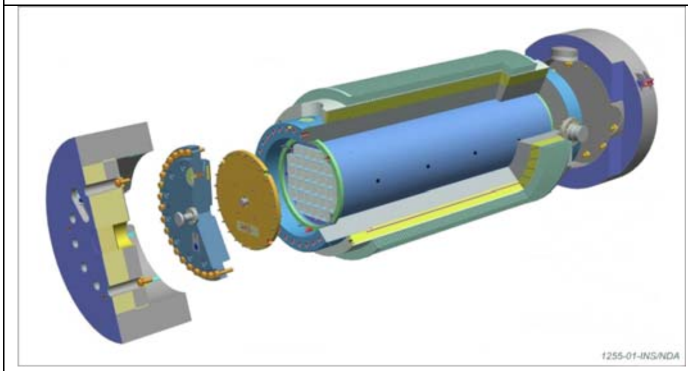
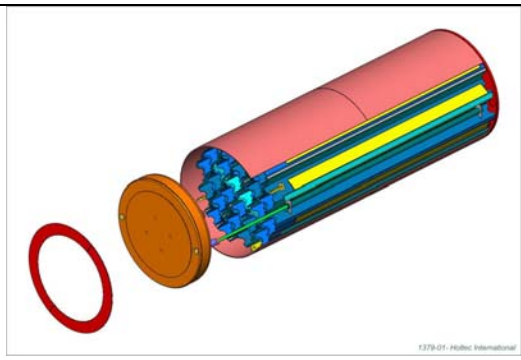
Dual-purpose storage and transport cask		Multi-Purpose Container (MPC)
		
Excellox Flask: Image Courtesy of INS Ltd.		MPC: Image courtesy of Holtec International
Number of Fuel Assemblies, Physical Dimensions and Weight	**Medium: 65t – 130t** **Castor V/19**: 19 PWR fuel assemblies, Diameter of 2.4 m x 5.9 m long, 125.6 t **Excellox 8**: 12 PWR fuel assemblies, diameter of 1.9-2.5 m x 5.7-6.3 m long, 115 t **Pollux cask**: 10 PWR fuel assemblies, Diameter of 1.55 m x 5.5 m long, 65t	**Large: >130 t** **Holtec**: 24 PWR Fuel Assemblies, diameter of 3.4m x 5.8 m long, 163 t **NAC-UMS**: 24 PWR Fuel Assemblies, diameter of 3.4 m x 5.8 m long, 146 t

Figure 4 also shows the various options for subsequent transport to a “Central Site” for the remainder of the storage period. The transportation of the fuel from wet or dry vault storage can readily be achieved by a dual-purpose cask, a technology already demonstrated to be transportable, although there may be constraints regarding accessibility across all of the UK rail network. The transportation of proprietary designs of MPC in their transport configuration however is not possible on the UK rail network, due to their size and weight, this is discussed further in Section 5.2.2. It is believed that road and sea transport would be available albeit with constraints. In principle the MPC concept could be developed on a smaller scale, working within UK rail transport constraints.

Following the period of interim storage at the central site the fuel is transferred or transported to the packaging plant. Figure 4 shows that the fuel from wet or dry vault storage is packaged in disposal canisters. There are two options for SF from dual-purpose or MPC containers; these may be unloaded with the fuel transferred to robust disposal canisters or the fuel left in-situ and disposed of in the cask without unloading. Further work would be required to confirm the suitability of casks or containers for this role.

4.3.1 Credible options for spent fuel storage

As outlined above there are a number of credible options for the storage of new nuclear power station SF. Selection of a preferred option, including location and storage system, by an operator will depend on the interplay of a number of factors.

This high-level work has not attempted to evaluate and compare the merits of each of the many potential options. At this stage both wet and dry storage options are considered credible and equally feasible.

However, a high-level consideration of the types of storage systems, implications of transport, the relative periods of interim SF storage at the power station site and central site does allow a number of general observations to be made.

Interim wet storage of SF whether at or away from the site of arising is a well-established technology. Interim wet storage of SF at the site of arising for a relatively short period, where fuel is then removed and consolidated at a central site, is similar to the AGR fuel cycle already operating in the UK. Short interim storage periods at the reactor site avoid the potential for the duplication of storage capacity at both the new nuclear power stations and the centralised storage site. The choice of storage technology and facility at the central site following interim wet storage at the reactor site would depend on the remaining period of interim storage and the packaging and disposal concept, but all storage concepts are likely to be suitable, depending on the drivers. Wet storage whether at new nuclear power station sites or a central site is potentially very flexible allowing inspection, monitoring and retrieval of SF to underpin its long term storage, transport and disposal. The potential flexibility of this option may facilitate co-packaging of long and short-cooled, or higher and lower burnup SF if this strategy was adopted to facilitate earlier disposal.

Dry vault storage of SF is aligned towards longer periods of interim storage whether at the site of arising or at a central site. Like wet storage, dry vault storage is potentially flexible allowing inspection, monitoring and retrieval of SF to underpin interim storage, transport and disposal. Consequently dry vaults may offer flexibility where there are uncertainties over the location and requirements for the packaging and disposal of SF. This option is likely to facilitate co-packaging of fuels if this strategy was adopted to facilitate earlier disposal of SF from new nuclear power stations. Due to the projected economies of scale with vault-type structures this system may favour larger electricity generating programmes, however, there is limited cost data to compare and evaluate this.

There are many commercially available dry cask storage systems. Storage and transport casks are likely to be suited to all types of interim storage at the site of arising. Although further work may be required to underpin transport of the SF and casks following an extended period of storage, either at the site of arising or a central site, due to the need to demonstrate compliance of the SF and cask with the transport safety case. Early transport of the casks to a central site for storage or packaging for disposal could be considered. Storage and transport casks may offer the advantage of avoiding duplicate build of storage infrastructure if a simple structure for storing the casks at a central site is sufficient.

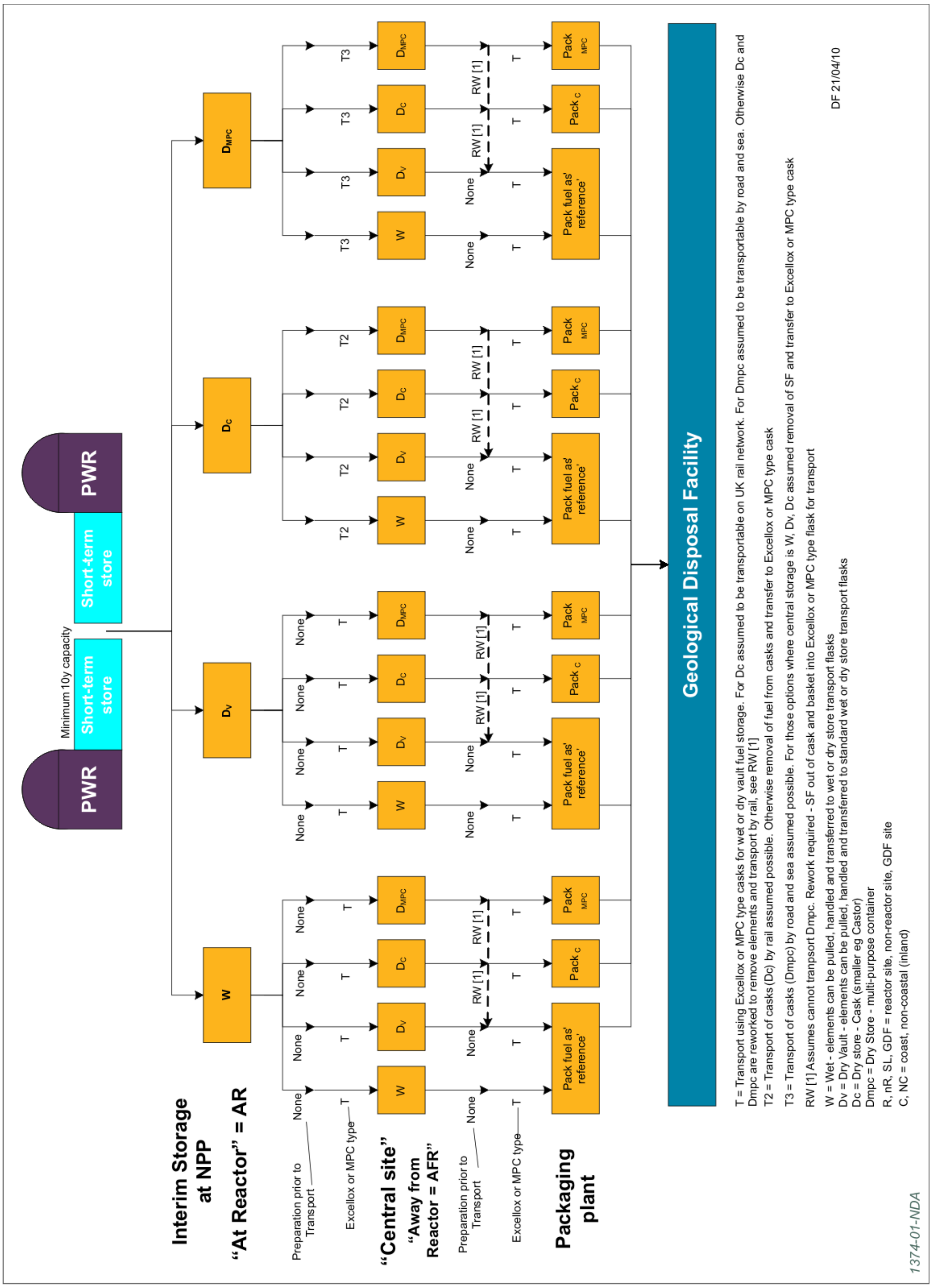
Whilst there are uncertainties over future transport or retrieval of SF from these casks, there would be considerable time to develop technologies and infrastructure to handle them. Commercially available storage and disposal casks systems are available that may be suited for transport by removal of the central metal canister containing fuel assemblies from the storage overpack and transfer to a transport overpack. The potential of such hybrid systems could be examined in more detail. Storage and disposal casks are also likely to be particularly suited to centralised site storage once the location and concepts for the GDF and packaging plant have further matured. This option could potentially reduce the handling and repackaging of SF for disposal.

Given the timescales before SF requires discharge from the short term cooling ponds of new nuclear power stations, considerable work could be done to optimise the design of both storage and transport or storage and disposal casks to align these systems to the UK-specific constraints for storage, transport and disposal of SF.

Both wet and dry storage systems have advantages and disadvantages when considering storage of SF at a central site. Given the 100 year period of interim storage currently required before SF from any new nuclear power stations can be disposed of, the passive nature of some sealed dry cask storage systems may offer an advantage. However, given the uncertainties over future SF management, the possibility and siting of both a central SF storage site and the GDF, the option of wet storage provides good flexibility and extensive operating experience, especially for higher burn-up SF.

Figure 4 illustrates the many credible options covering storage of SF at the power station, its subsequent transport to and storage at a centralised facility and ultimately the packaging and disposal of the SF. This study has not attempted to discriminate between the storage systems and their suitability for centralised storage. The figure illustrates the many varied aspects of the SF management route that would need to be considered to arrive at a preferred option for the SF storage system.

Figure 4 Schematic of potential options for the short and interim storage of spent fuel at reactor and at a "central site", including transport options



4.4 Packaging plant feasibility and costs

Work to explore the feasibility of a centralised packaging plant for disposal canister production has only considered a plant that is compatible with the GDF reference conceptual design described in Section 1.

A detailed description and cost estimate of a packaging plant design for legacy HLW/SF was prepared in 2007-08 to support studies at that time. That work was based on SKB's encapsulation plant process [13].

The packaging plant design and associated cost estimate assumed that:

- Location is at the GDF surface site;
- The receipt and processing is for three types of dry feed:
  - PWR fuel assemblies provided from Sizewell B power station;
  - consolidated AGR fuel elements in slotted cans or sealed canisters from Sellafield; and
  - HLW from Sellafield.
- Each feed would be received at an individual receipt line;
- Disposal canister components would be manufactured at an off-site facility;
- The plant capacity would be 200 disposal canisters per annum (this figure was adopted to maintain compatibility with the SKB design);
- The canister lid incorporates the canister lifting feature so lid-welding is necessary before a sealed canister can be moved.

The plant capacity and underground emplacement rate is matched at 200 disposal canisters per annum. If the underground emplacement rate was to be increased it is considered feasible that the packaging plant capacity could be increased.

A review of the design studies undertaken in 2007-08 indicates that it is feasible to adapt the receipt and processing of the PWR feed to accept SF from new nuclear power stations. Further consideration would need to be given to the impact of increased burn-up leading to increased gamma and neutron dose rate, increased thermal load, the increased length of SF assemblies and the potential desire to include associated non-fuel core components within the disposal canister.

Using the historical information prepared in 2007-08 and supplemented by more recent studies undertaken for RWMD by SKB [14] it is possible to develop a packaging plant cost that would be required for a new nuclear power station. The cost estimate of the packaging plant design [15] undertaken in 2007-08 with a throughput rate of 200 disposal packages per annum identified that the cost to construct a packaging plant was circa £410 million (the most likely estimate in a range of circa £350 million to £575 million). The most likely estimate was broken down in to its component parts and included mechanical plant and equipment of £84.2 million. That mechanical plant and equipment was broken down to the three types of feed – AGR SF, PWR SF and HLW. In order to estimate the cost of a packaging plant for SF from a new nuclear power plant it has been assumed that the SF is not significantly physically different to the legacy PWR and so if the mechanical plant and equipment for AGR SF and HLW costs are not allocated then the revised cost is £390 million.

In order to consider the total costs of packaging SF the following specific additional costs to the packaging plant construction cost itself need to be included:

- the production costs of the disposal canisters;

- the operation and maintenance costs of the packaging plant; and
- the packaging plant decommissioning costs.

The most robust information concerning these costs is considered to be that published by SKB in their latest cost information – Plan 2008 [16] supplemented with more recent studies by SKB for RWMD [14].

The unit production cost of the disposal canister has been derived as £82k (outlined at table 4.13 [14]) but as this does not include any contribution to the initial investment costs a 15% uplift is considered appropriate. The unit procurement cost is therefore £94k.

The total operation and maintenance costs of the SKB packaging plant are £870 million[6] (outlined at table 2.5 [16]). However this value is for the reference SKB inventory of six thousand canisters and includes the canister production costs. After removing the production costs (outlined at table 4.11, [14]) it is possible to derive a unit cost of operation and maintenance costs of £53k.

The decommissioning costs of the SKB packaging plant are £16 million[6] (outlined at table 2.5 [16]).

In order to develop the cost of a packaging plant for a single power station then an estimate has to be made of the number of disposal canisters produced. The GDA disposability assessments [1,2] indicated that a 60 year operating scenario would give rise to 640 for an AP1000 and 900 for an EPR.

Based on the above information and assumptions the estimated total costs of a packaging plant for a single power station (assuming one reactor) are presented in Table 3.

Table 3 Estimated costs of a SF Packaging Plant for a new nuclear power station

Packaging Plant costs - £m (2008 money values)	Packaging Plant for an AP 1000 reactor (assumes 640 disposal units)	Packaging Plant for an UK-EPR reactor (assumes 900 disposal units)
Construction costs	390	390
Decommissioning costs	16	16
Disposal canister procurement costs	60	84
Operations and maintenance costs	34	47
Total	**500***	**537***

* based on most likely construction cost and contains no contingency

It is recommended that if some form of centralised packaging plant is to be considered further then the previous packaging plant design for legacy HLW/SF be reviewed in detail to consider the specific new nuclear power station SF characteristics and requirements. A detailed design and construction cost estimate would be required and throughput studies could be undertaken as part of an overall optimisation process.

[6] Exchange rate 12 SEK to £1

5 Issues associated with alternative disposal canisters

The work in this section focuses on work strand (c) and takes account of the Project scope, the drivers of the prospective new nuclear power station operators outlined in Section 1 and issues raised by the GDA disposability assessments set out in Section 3.

The issues associated with alternative disposal canister types are explored and consideration is given to how the basis for planning for the implementation of new nuclear power stations may be developed to take account of alternative disposal canister sizes and options to mitigate temperature effects.

5.1 Option development methodology

To determine feasible canister options for the GDF reference conceptual design, constraints which impact the design of a GDF were identified. This allowed potential relaxations from the criteria applied in the GDA disposability reports to be identified. A series of “bounding parameters” were established through a process of joint working between RWMD and representatives from the prospective new nuclear power station operators. Bounding parameters were identified in the following areas:

- Physical constraints in respect to the size and weight of disposal canisters;
- Operational constraints in respect of the estimated throughput rates of different disposal canister types, estimated dates of facility availability to allow disposal to commence and scheduling of disposal canisters;
- Disposal constraints with respect to ability to dispose, influenced by buffer material, the configuration and orientation of disposal canisters and the reference conceptual design.

The disposal canister options are aligned to the storage options discussed in Section 4.

Potential changes and modifications to the existing reference conceptual design are outlined below and are broken down into the following categories:

- Suitability of alternative disposal canisters to the reference conceptual design (Section 5.2);
- Suitability of the reference conceptual design to alternative geological environments (Section 5.3); and,
- Considering different packaging options to mitigate temperature constraints (Section 5.4).

5.2 Suitability of alternative disposal canisters to the reference conceptual design

The disposal canister options, aligned to the interim storage options discussed in Section 4.3 have been categorised into three broad disposal canister types:

- Small (up to 65 tonnes) requiring remote handling. These designs would typically be derivatives of the designs for the three host rocks as shown in Table 1 (and could be applied to storage option D_v in Figure 4);
- Medium (65 to 130 tonnes). This would cover canister types such as Pollux and Excellox flasks which are established designs but at this stage only certified for storage and transport of intact fuel assemblies (and could be applied to storage option D_c in Figure 4);

- Large (above 130 tonnes). This would cover Multi-Purpose Containers (MPC's) such as the Holtec and NAC systems developed for the storage and transport of SF (and could be applied to storage option D_{MPC} in Figure 4).

The current reference conceptual design can handle and transport packages weighing up to 80 tonnes and would require modification to accommodate the physically larger and heavier disposal canisters.

5.2.1 Handling alternative disposal canisters at the GDF

For handling and interchange at the surface facilities of the GDF, the principal consequence of using alternative disposal canisters would be different crane lifting attachments or a separate, dedicated crane and transfer line within the waste receipt and transfer building and the raising of the existing building height to permit vertical transfer of the larger casks type packages and MPC's. No insurmountable technical issues have been identified for any of the disposal canister options considered as the technology for handling, storage and interchange is well proven in current surface store applications.

Drift transfer to the underground facilities is currently constrained to an 80 tonne limit at a gradient of 1:6. It is judged that the heavier 'medium' disposal canister designs could be transported via the drift rack and pinion system, although this is likely to necessitate a shallower drift gradient which would result in an increased excavation and overall slower transfer rates, the impacts of which have not been quantified in this study.

The drift excavation profile has been sized to accommodate the W6A rail gauge profile and both the 'small' and 'medium' disposal canister options would be accommodated within the current excavation profile of the underground openings.

If shaft access was adopted the limits on cable winding technology and effects of cable stretch would be more problematical to overcome as the package weight increases. The limits of this technology have not been explored in this study but are likely to preclude shaft transport of the 'large' category MPC type packages.

The proprietary MPC systems are not designed for transport in a horizontal configuration. In their vertical orientation they are too large and heavy to be feasibly transported underground using either rack and pinion drift or shaft system. To mitigate these issues, the MPC system would need to be developed with a smaller design that could be rotated to a horizontal orientation and would be expected to then fall into the 'medium' category and be transferred using the existing drift system.

The disposal canisters would arrive underground at the SF transfer hall. The weight of the 'medium' and 'large' waste packages would require modification of the lifting and handling arrangements to provide substantially increased capacity, although no insurmountable technical issues are envisaged. It is also recognised that the excavation profile may require increasing to accommodate the up-rated systems and larger package dimensions.

For the 'medium' and 'large' disposal canisters the physical diameter and length of the deposition holes would require increasing. No insurmountable technical issues are envisaged for any of the canister types as the required size would remain feasible to construct.

Manufacturing of prefabricated bentonite buffer rings in increasingly larger diameters would require increased compaction force. The limits of the current technology in this respect have not been explored, although work undertaken under the EC 6th Framework ESDRED project demonstrated manufacture of buffer rings suitable for the 'small' disposal package size in a single piece [17]. Increasingly larger sizes of buffer rings would exceed the compaction force capacity to manufacture in a single piece, in which case the buffer rings would need to be produced in segments.

The pre-placement of bentonite blocks and rings could be accomplished but the emplacement of existing designs of casks with trunnions and irregular external features would be difficult and require the orientation of the disposal canister to be controlled with respect to that of the pre-installed buffer. To overcome this issue the preference is for disposal canister to have a regular (smooth) external profile. Alternatively arrangements for introducing the buffer after package emplacement, such as a pelletised system would be required, as used for example, in Nagra's concept.

The deposition machine is capable of handling and emplacing disposal canisters measuring 0.9 m in diameter and 5.2 m overall length and weighing up to 25 tonnes. The larger variants of the small disposal packages and the 'medium' and MPC's would all necessitate significant modification to the current deposition machine design. A benefit however of the larger package types may be the provision of greater self-shielding, which if sufficient to allow manned operations, would result in a simpler system.

The reference conceptual design assumes vertical deposition holes. The need to rotate the package within the deposition tunnel complicates the deposition process, and for the larger heavier canisters would necessitate larger equipment and corresponding larger overall excavations. With increased excavation sizes, the spacing between deposition tunnels for a design assuming vertical (or horizontal deposition) holes could also need to be increased for geotechnical considerations. These have programme, cost and potentially footprint implications, although these may be off-set by the smaller number of disposal canisters required as they contain a larger number of fuel assemblies.

In summary, the handling of disposal canisters including any transport overpack weighing up to 80 tonnes is compatible with the reference conceptual design and it is expected to be possible to handle the heavier, medium sized disposal packages of up to about 130 tonnes with up-rating and re-design of the infrastructure and handling system.

5.2.2 Options for transporting medium and large disposal canisters to the GDF

UK transport infrastructure and regulations impose constraints on the size and shape of package that can be transported to a centralised store or to the GDF. The transport system planned by RWMD is based around the use of disposal canisters and shielded transport containers that work within these constraints and provide maximum flexibility. If it were desired to transport disposal canisters of the 'medium' or 'large' size, then it would be necessary to have a correspondingly larger transport overpack.

The MPC systems, when fully assembled with shielded overpack can weigh well over 130 tonnes. In assessing the transportability of all these systems, within the UK, there are a number of key issues and system design criteria that need to be considered.

The ability to transport packages on the rail network within the UK is limited by allowable wagon axle loadings and physical size of the wagon and load. These vary throughout the rail network, but maximum access to the system is assured if the weight of the load can be restricted to suit the limitations of a four-axle wagon and the size limitations imposed by the W6A rail gauge. This effectively limits the weight to be transported to 65 t and the diameter of a cylindrical load to 2.5 m. Therefore disposal canisters within the 'small' category effectively have unrestricted access to generation or disposal sites anywhere on the UK rail network.

In the case of disposal canisters within the 65 t to 130 t range, an eight-axle rail wagon is required to give generally acceptable axle loadings over the widest extent of the rail network. However, due to its larger physical size, access to the rail network for an eight-axle wagon is much more limited than for a four-axle wagon. Hence, further work would be required to assess the routes to be used to determine acceptability for use with disposal canisters of this size. Potentially, there could be a need for new track laying and track-side reconstruction if disposal canisters of this size were to be used.

For the 'large' disposal canisters, an eight-axle wagon would most likely still be suitable for rail transport in terms of axle loading, but with typical diameters of around 3.4 m the complete packages would be too large to fit through the majority of the rail gauges which control access to the rail network. At this stage, therefore, it seems likely that the 'large' disposal canisters could not be transported on the majority of the UK rail network.

All three disposal canister sizes (small, medium and large) could be transported by road using Category 3 Special Type General Order (STGO) vehicles. The vehicle speed would be limited to 30, 25 and 20 mph on motorways, dual carriageways and other roads respectively, and appropriate bridge authorities and the police would need to be notified in advance. In the case of MPC type loads, the operation would constitute a wide load and would not be able to be transported vertically as they are likely be too tall for many routes. Clearly, large numbers of movements over long distances by road would present challenging logistical and public acceptance issues.

For sea transport, the use of the Atlantic Osprey, owned by International Nuclear Services Ltd (INS) has been considered. This ship would allow the carriage of around twelve casks of the medium type and could be loaded either by dockside crane, or could be used in roll-on/roll-off configuration. In terms of port handling it is considered that the smaller the cask the less demanding the loading operation in terms of what crane capacity is likely to be present at most ports. However, providing safe and suitable cranes would be practical for all disposal canister types. Also, all disposal canister types can be loaded on by road vehicle if required.

In terms of receipt and handling facilities there would appear to be little to differentiate between the disposal canister sizes. Compared to the reference conceptual design there would be a requirement for uprated systems to handle greater sizes and weights, but there would be no additional technical challenges arising because of that. Only dry transport has been assumed to-date. If wet transport was required, for example because of a greater number of assemblies being carried then this would require the addition of facilities to drain the casks and dry the contents at the receiving site.

All SF transport casks to be used in the UK need to be approved for use by the transport regulator, the Department for Transport (DfT), the UK Competent Authority. If the transport cask to be used already has a Type B(U) approval from another country this process would be considerably facilitated. This process ensures that the design of the transport cask complies with the requirements of IAEA transport regulations [18]. The safety of the transport operation is inherent in the design of the cask itself.

The disposal canisters which fall in to the 'medium' and 'large' categories are essentially existing designs which have been approved for transport by Competent Authorities in the USA and Europe. This gives a high degree of confidence that all necessary technical information and test results are available and that these designs can be approved for use in the UK. Since all fissile packages need to be approved by the country they are to be operated in (i.e. multilateral approval is required) it is likely that new package design safety reports will be required, particularly covering those changes resulting from the inclusion of new contents.

The headline areas pertinent to the safety cases will be criticality, heat generation, shielding, accident performance, and radionuclide containment issues. These issues will be common to all safety cases and the majority of challenges should have already been addressed.

All disposal canisters and concepts described are designed to use proven technology in their design and operation. Sufficient detailed design, testing and the production of a safety case, to show compliance with the transport regulations [18], will be required, but the work done so far gives confidence that designs would be approvable (by DfT) for use in the UK.

5.2.3 Disposal canister throughput rates at the GDF

The planning assumptions for the duration of each phase of the implementation programme, lead to a GDF operational date of 2040 for first receipt of Intermediate Level Waste (ILW) and 2075 for the first receipt of HLW/SF (in disposal canisters) [3]. Disposal of legacy waste and materials in the reference case programme is estimated to be completed by about 2130 and it is currently assumed that disposal of any new nuclear power station SF would begin once disposal of legacy SF is completed.

All waste is proposed to be transported via the drift which has an estimated maximum capacity of 3,900 package transports per annum. The ILW is proposed to be disposed of in either shielded or unshielded packages. The unshielded packages are remotely handled through an inlet cell which has an estimated maximum capacity of 2,500 packages per annum. The SF disposal canisters after being transported via the drift are transferred to a deposition machine and placed into deposition holes at a rate of 200 per annum, which is the rate limiting step for disposal canister emplacement within the GDF reference concept.

The inventory used in the reference case programme equates to circa 125,000 unshielded ILW packages disposed over a period of circa 90 years. The scheduling of receipt and emplacement of legacy and potential new nuclear power station wastes and SF has not been considered in detail. However, the currently assumed disposal capacities of the GDF would allow ILW from new nuclear power stations to be emplaced before the legacy SF disposal has been completed in 2130. The potential exists to commence emplacement of SF from new nuclear power stations earlier if the currently assumed disposal rate can be increased. However optimisation studies would need to be undertaken to confirm how it could be changed.

5.3 Suitability of the reference conceptual design to alternative geological environments

The reference conceptual design is based on the “in tunnel vertical borehole” concept as described in the previously referenced options report [5] and is suited to implementation in a wide range of geological environments, where in principle the properties of the engineered barrier could be tailored to suit geological conditions. For example in geological environments with higher hydraulic conductivities (such as fractured crystalline rock), highly corrosion resistant SF disposal canister materials and low permeability buffers could be employed to provide very long term containment of radionuclides, reducing the emphasis on the host rock and geosphere retardation properties. In contrast, in sedimentary geological environments with a lower hydraulic conductivity (such as in clays and mudstones) the emphasis on the engineered barrier could potentially be reduced and less corrosion resistant SF disposal canister materials, such as carbon steel, employed. Work recently undertaken by RWMD has identified that opportunities exist for the consideration of other SF disposal canister materials [19].

Other options may also be available depending upon the host rock type. For example, in an evaporite (salt) geology where, based on international precedent, the temperature limit in the backfilled state would be significantly increased beyond the 100°C restriction applicable to a bentonite environment. The temperature limit for the evaporite case could be in the region of 200°C [20]. For SF this would be a significant advantage in reducing the cooling period prior to emplacement.

Other concepts (discussed in Section 6) could realise similar advantages with respect to allowing use of buffer material other than bentonite. Studies have been undertaken using cement based buffers by ONDRAF/NIRAS in the Belgium concept in plastic clay which would merit further investigation.

5.4 Considering different packaging options to mitigate temperature constraints

The previous GDA disposability assessments assumed emplacement of SF in vertical disposal holes and protection by a bentonite buffer material in high strength rock. The assessments identified that the SF would be required to be cooled for a period of the order of 100 years to meet the temperature limit of 100°C applied to the inner bentonite buffer surface in high strength rock.

A key driver for considering different packaging options is managing the heat output from SF. The thermal model developed by SKB has been used. The SKB model [21] was developed as a scoping tool to assist in establishing key design parameters and is considered to be appropriate for this application. However, once more detailed and site specific parameters are available there will be a need to switch to a more sophisticated model.

The illustrative disposal concept for SF assumes a copper canister with a cast iron insert containing four SF assemblies. The disposal canister is placed in a vertical hole lined with a series of compressed bentonite rings, which completely surround the canister. The thermal model can be used to explore thermal behaviour of the system when various parameters are changed.

The model has been used to examine the inner bentonite buffer surface temperatures that would arise for new nuclear power station SF at burn-ups of 65 GWd/tU (the expected assembly-average burnup of the peak-rated assembly at discharge) and 50 GWd/tU (the whole-reactor average) for the following permutations:

- Varying the number of assemblies per canister (as described in Section 5.4.1);
- Varying the disposal canister diameter and the thickness of the bentonite buffer (as described in Section 5.4.2);
- Mixing assemblies with different cooling times in a single canister (as described in Section 5.4.3); and
- Considering medium and large disposal canisters (as described in Section 5.4.4).

5.4.1 Varying the number of assemblies per canister

The SKB thermal model was used to explore how the inner bentonite buffer surface temperature varied according to increasing heat load. In order to maintain a constant emplacement tunnel length, the distance between canister emplacement positions was increased in proportion to the number of SF assemblies per canister.

Table 4 shows the cooling times required to meet the temperature limit of 100°C and for two higher temperature limits (to demonstrate how the cooling times vary if it was possible to increase that limit) for different numbers of fuel assemblies per canister. In this modelling the canister length was retained as 5.2 m but the canister diameter was varied to suit the number of SF assemblies.

For the peak-burnup (65 GWd/tU) and four SF assemblies, a cooling time of 110 years was required to reach a peak bentonite buffer inner surface temperature of 100°C. This compares to, of order of 100 years calculated previously [1, 2]. The difference between the two calculations is due to the more sophisticated and realistic modelling of the evolution of the waste packages' heat output following deposition. This now includes use of a greater number of heat contributing radionuclides in the modelling, more representative proportions at the time of deposition and representation of the in-growth of Am-241 from Pu-241 in the first few decades following deposition.

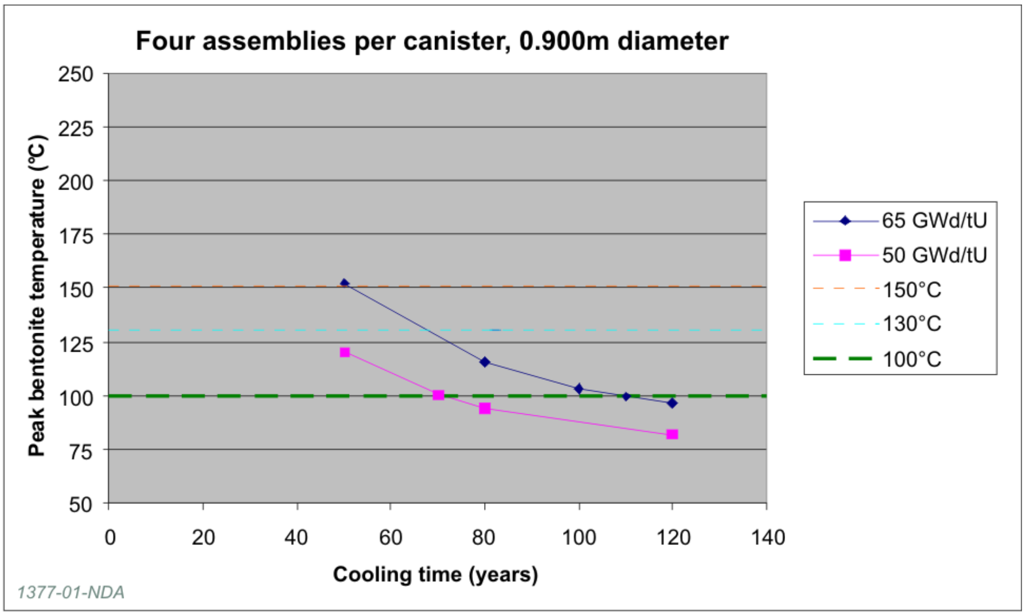
Table 4 Estimated cooling times, to nearest whole year

		Burnup 50 GWd/tU			Burnup 65 GWd/tU		
		Estimated cooling time (years) to reach peak bentonite temperatures					
Assemblies per canister	Canister diameter/ m	100°C	130°C	150°C	100°C	130°C	150°C
1	0.52	42	—	—	70	< 50	—
3	0.83	62	< 50	—	97	~60	—
4	0.90	70	< 50	—	110	~68	~52
9	1.28	104	~70	~55	163	~99	~78
12	1.34	132	~86	~71	—	~118	~99

— represent times that are outside the range considered in the calculations.

Figure 5 shows the peak inner bentonite buffer temperatures against pre-emplacement cooling time for a disposal canister with four fuel assemblies and illustrates the rate of cooling over time.

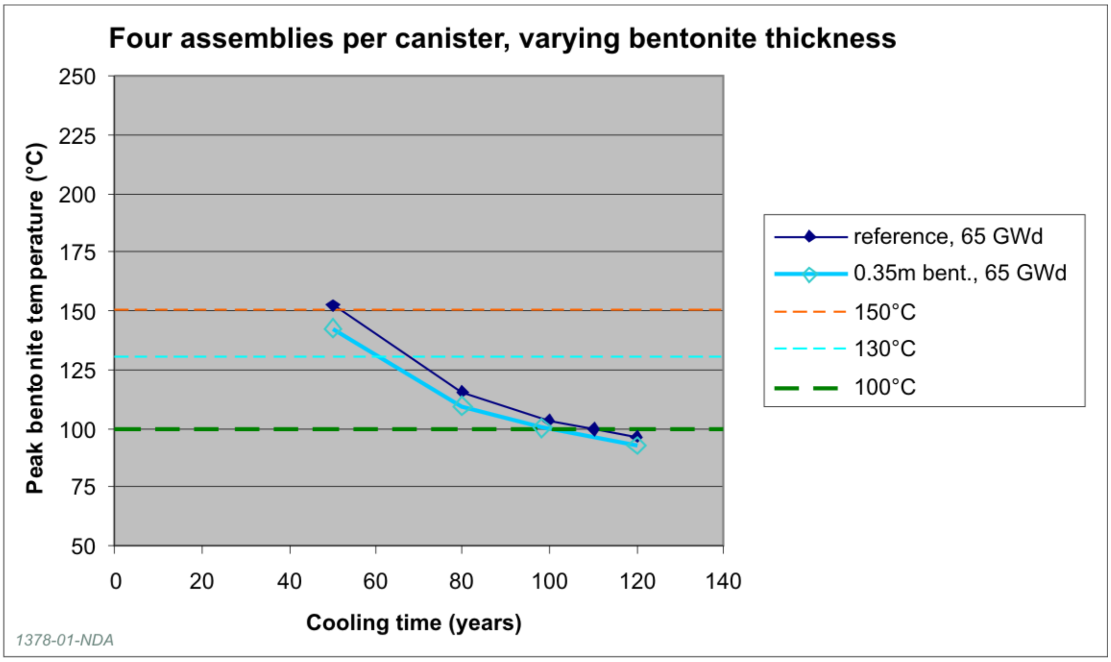
Figure 5 Peak inner bentonite buffer temperature against pre-emplacement cooling time, four assemblies per canister



5.4.2 Varying the diameter of the disposal canister and the thickness of the bentonite buffer

SKB's application of the KBS-3V concept includes disposal canisters of 1.05 m diameter which when emplaced in a 1.75 m diameter emplacement hole results in a bentonite buffer layer of thickness 350 mm. The reference conceptual design applied by RWMD has used a 0.9 m diameter canister, which with the same diameter emplacement hole results in a bentonite buffer thickness of 425 mm. Modelling the SKB concept application using a disposal canister diameter of 1.05 m, reduces the cooling period by 8 years for the same peak burn-up assemblies due to the combined effects of reduction of bentonite buffer thickness and reducing heat flux resulting from the increase in the surface area of the disposal canister. The rate of cooling over time is illustrated in Figure 6.

Figure 6 Effect of increasing canister diameter and decreasing bentonite buffer thickness for a canister containing four peak burn-up assemblies



5.4.3 Mixing fuel assemblies with different cooling times in a single canister

The work conducted in support of the GDA disposability assessments was known to be pessimistic due to the assumption that all SF assemblies would be irradiated to the maximum peak burn-up of 65 GWd/tU. For this study a wider view has been taken and it considered options for mixing SF assemblies with characteristics appropriate to the operating life of a reactor.

The schemes presented in this section should be regarded as scoping calculations as neither the time taken for each assembly to be irradiated nor the actual distribution of burnups in the various SF assemblies is taken into account. However, they do serve to illustrate how sensible and proactive management of SF could offer reductions in cooling time before disposal.

Figure 7 illustrates a mixing scheme for packaging peak-burn-up fuel assemblies, three per disposal canister. At 45 years after reactor[7] shut-down, a disposal canister containing one SF assembly from the start of operation (which by then will have cooled for 105 years) is emplaced along with two assemblies discharged at 40 years after reactor start (which each have 65 years' cooling), in the reference configuration of a 0.9 m diameter canister in a 1.75 m diameter hole, this results in an estimated peak bentonite buffer surface

[7] A reactor is used in this example as one power station is expected to have more than one reactor.

temperature of 96.0°C. It is assumed that over the next five years, i.e. up to a total cooling time of 50 years after discharge from the reactor, disposal canisters are progressively emplaced. The assemblies from the final third of operation (represented by red rectangles in Figure 7) are selected in order of discharge, as are those from the first third of operation (represented by green rectangles), while those from the middle third (represented by orange rectangles) are taken in reverse order. The peak inner surface bentonite buffer temperatures in the proposed scheme are all less than 100°C which demonstrates that by mixing fuel assemblies in this way it may be possible that all the disposal canisters can be emplaced at 50 years after reactor shutdown.

Figure 7 Proposed mixing scheme for three assemblies at burn-up of 65 GWd/tU, canister diameter 900 mm

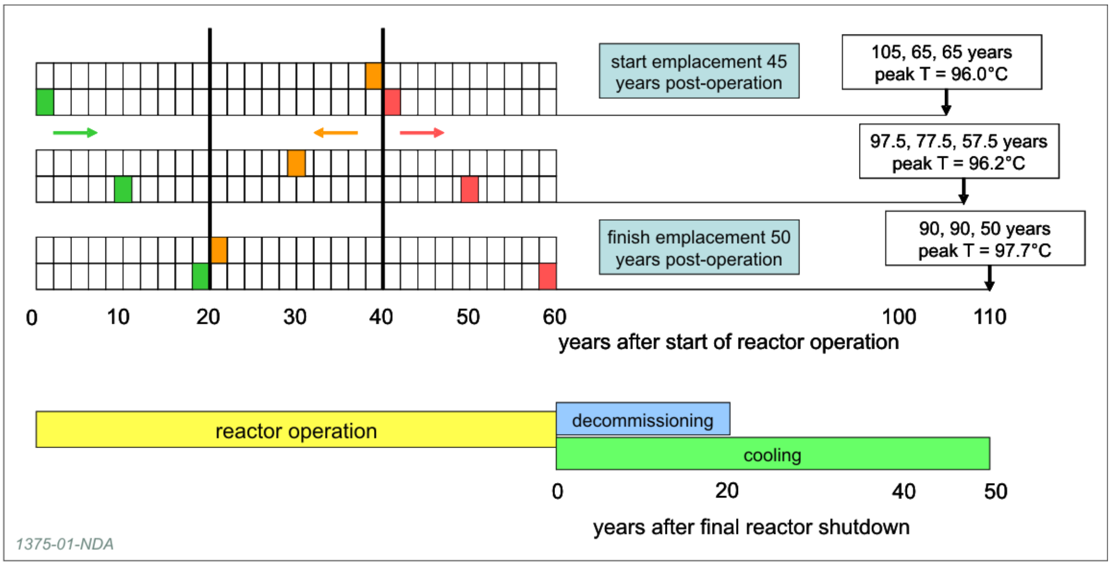


Figure 8 illustrates a mixing scheme for average burn-up SF assemblies, at four per disposal canister. At 45 years after reactor shut-down, a canister containing four SF assemblies from 30 years after the start of operation (which by then will have cooled for 75 years) gives a peak inner bentonite buffer surface temperature of 97.0°C. Over the following five years, fuel assemblies are mixed in the proportion of two from the first half of operation, moving backwards (as represented by green rectangles in Figure 8) and two from the second half, moving forwards (as represented by red rectangles), ending with two that have been cooled for 50 years and two that have been cooled for 110 years. Peak inner bentonite buffer surface temperatures are estimated to be 96.8°C for the disposal canisters at half-way through this process (i.e. cooling times of 92.5, 92.5, 62.5, and 62.5 years) and 99.3°C at the end of the process (110, 110, 50, 50 years).

Figure 8 Proposed mixing scheme for four assemblies at burn-up of 50 GWd/tU, canister diameter 900 mm

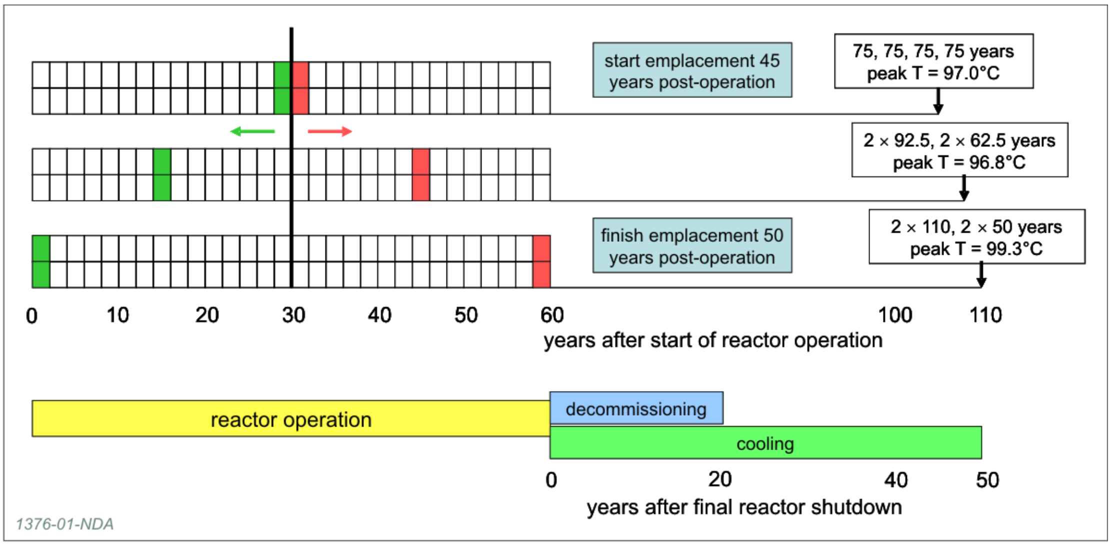


Table 5 summarises the peak temperatures and the power at emplacement for the six cases considered here. If emplacement were assumed to be instantaneous at 50 years after the end of operation, rather than being spread over the range from 45 to 50 years, the peak temperatures would be lower. The approach models the emplacement of disposal canisters with appropriate power output. The model assumes that all disposal canisters in the GDF have the same characteristics and are emplaced at the same time. This approach is judged to give satisfactory results at this stage for scoping studies. It does not model the transient and time-dependent factors. More sophisticated modelling would be needed to produce temperature estimates that took into account the following factors:

- Emplacement over an extended period;
- Disposal canisters that have varying power outputs at emplacement;
- Disposal canisters that have different thermal decay characteristics.

Table 5 Emplacement power and peak temperatures for selected mixed-age canisters

Unit	Cooling times to emplacement years	Power output at emplacement W / Cu canister	Peak bentonite temperature °C
Burnup 65 GWd/tU			
	105, 65, 65	1,265	96.0
	97.5, 77.5, 57.5	1,270	96.2
	90, 50, 50	1,308	97.7
Burnup 50 GWd/tU			
	75, 75, 75, 75	1,257	97.0
	2 × 92.5, 2 × 62.5	1,255	96.8
	2 × 110, 2 × 50	1,326	99.3

5.4.4 Considering medium and large disposal canisters

In addition to modelling the temperature effects and identifying the required cooling time for a disposal canister length of 5.2 m as outlined in Section 5.4.1, modelling has also been undertaken for ’medium’ and ’large’ categories respectively, as described in Section 5.2.

The physical characteristics used for the thermal modelling is:

- ‘Medium’ canisters such as the cast iron Castor cask, are assumed to contain 19 fuel assemblies, to be 5.9 m high and have an external diameter of 2.4 m;
- ‘Large’ canisters (such as a MPC) consist of an inner vessel of cast-iron surrounded by a concrete overpack, and are assumed to hold 24 fuel assemblies, to be 5.8 m high and have an external diameter 3.4 m.

Table 6 Estimated cooling times, to nearest whole year, for medium and large canisters.

		Burnup 50 GWd/tU			Burnup 65 GWd/tU		
		Estimated cooling time (years) to reach peak bentonite temperature					
Assemblies per canister	Canister diameter/ m	100°C	130°C	150°C	100°C	130°C	150°C
19	2.40	~122	~80	~70	~142	~114	~97
24	3.40	~124	~80	~70	~145	~116	~98

Accepting the indicative status of the results it can be seen from Table 6 that with an average-burnup fuel, a cooling period of 120 years plus is required meet the 100°C temperature criterion assuming backfilling with bentonite for both the medium and large disposal canister.

6 Suitability of alternative disposal concepts for the disposal of spent fuel from new nuclear power stations

This section focuses on work strand (d) and considers the impact of adopting alternative disposal concepts for the disposal of SF from new nuclear power stations. This has been undertaken by considering the disposal canister options against the catalogue of potential geological disposal concept options reported in Geological Disposal Options for HLW and SF [5], and summarised in Table 7. The study identified and described twelve disposal concepts, based on international precedents, which were grouped by key features and variants. The twelve concepts were considered to represent a comprehensive range of concepts that could be considered applicable for implementation in the UK. For this study two of the key features from the twelve concept options presented in the study [5] were considered in order to:

- Provide a manageable number of concepts to consider within the timeframe of the study;
- Extend the illustrative disposal concepts addressed by RWMD in the DSSC, to consider the implications of larger disposal canisters;
- Introduce a cavern type concept which is significantly different to the illustrative disposal concepts considered to date, and which could be better suited to large disposal canisters.

The two key feature concepts selected are the In-tunnel axial, which covers concept numbers three to seven as shown in Table 7 and the implications of this option are outlined in Section 6.1; and the Cavern which includes concept options eight and nine as shown in Table 7 and the implications of this option are described in Section 6.2.

It should be noted that the other disposal concepts described in the study [5] are not excluded from potential consideration in the future.

Table 7 Key features and variants of concepts applicable to the UK based on a report to RWMD

Key Feature	Variants	Concept No.
In-tunnel (borehole)	Vertical borehole	1
	Horizontal borehole	2
In-tunnel (axial)	Short-lived canister	3
	Long-lived canister	4
In-tunnel (axial) with supercontainer	Small working annulus	5
	Small annulus + concrete buffer	6
	Large working annulus	7
Caverns with cooling, delayed backfilling	Steel MPC + bentonite backfill	8
	Steel or concrete/DUCRETE container + cement backfill	9
Mined deep borehole matrix		10
Hydraulic cage	Around a cavern repository	11
Very deep boreholes		12

6.1 Concept key feature – In-tunnel (axial)

In-tunnel axial concepts have been studied in several national programmes including those of Switzerland (NAGRA), Japan (NUMO), Spain (Enresa), Belgium (Ondraf/Niras) and Germany (DBE Technology) and includes concepts three to seven in Table 7.

The concepts are technically mature with over 30 years of underpinning research and development in both crystalline and sedimentary rocks (including evaporite). The concepts are suited to implementation in a wide range of geologies, where in principle the properties of the engineered barrier could be tailored to suit geological conditions.

In these concepts disposal canisters are emplaced axially along disposal tunnels, typically up to 800 m in length, and up to several metres in diameter. The canisters are surrounded by a thick buffer layer typically of bentonite, or salt in an evaporite geological environment, to completely fill the tunnel. In some of these concepts the canister and the buffer are pre-assembled at a surface facility into an enclosed steel handling shell in the form of a "supercontainer". The disposal tunnels are closed immediately after completion of waste emplacement with substantial seals to resist the bentonite swelling pressure. An example of this concept is illustrated in Figure 9.

In considering the issues of accommodating larger disposal canisters (as described in Section 5.2) into in-tunnel axial concepts, commonalty is recognised with many aspects of GDF operations considered in the reference conceptual design, in-tunnel vertical concept. The issues for surface handing and drift transfer are the same as discussed in Section 5.2, which explained that although different handling arrangements would be required, there were no insurmountable issues identified for medium sized disposal canisters.

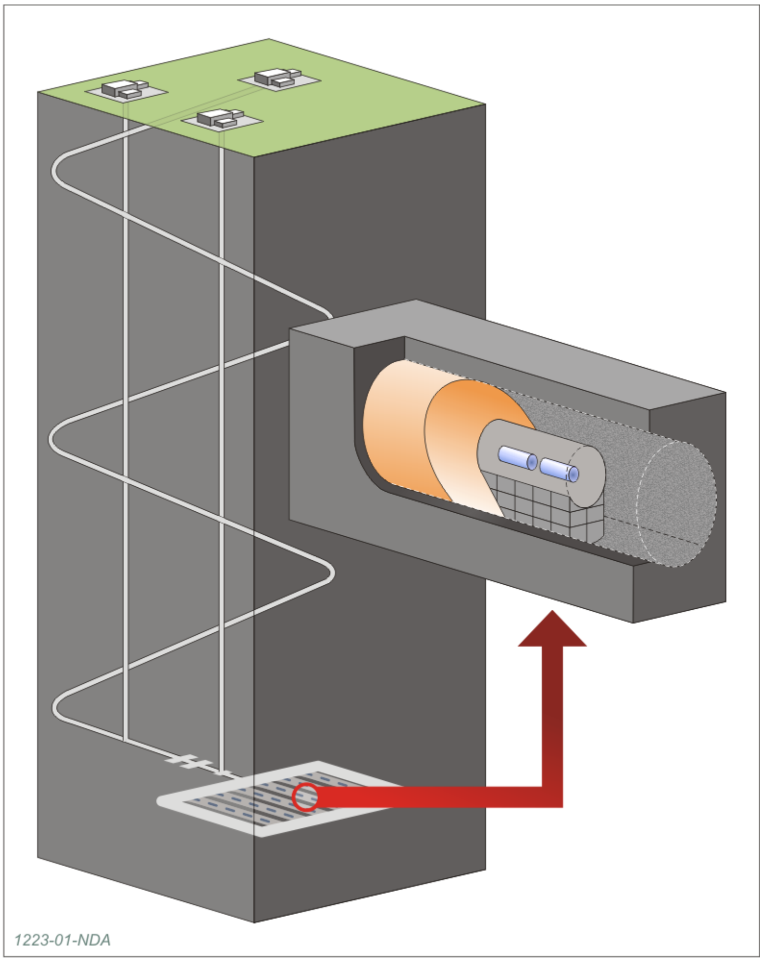
The axial configuration of the disposal tunnel considerably simplifies the emplacement operations and emplacement machine design as there is no requirement to rotate the disposal canisters.

For emplacement, the disposal canisters are emplaced horizontally on pre-compacted bentonite plinths. Once the disposal package is emplaced the peripheral buffer is introduced in a highly compacted pelletised form. This method overcomes many of the issues associated with the compacted pre-fabricated bentonite blocks used in the vertical disposal hole concepts in higher strength rock and is flexible to a wide range of disposal canister sizes. The use of the pelletised buffer also overcomes the issues associated with high compaction forces required to produce the large single piece prefabricated buffer rings.

At this stage it is reasonable to assume that a pelletised bentonite buffer could be used in a range of host geologies as performance of the engineered barrier system would need to be evaluated when the actual geological conditions are known.

Overall, the horizontal in-tunnel axial concepts are well suited to medium and large MPC type packages if the latter were suitably modified, and emplacement operations are expected to be relatively simple but a temperature constraint resulting from using a bentonite buffer, if used would still apply.

Figure 9 Schematic illustration of an in-tunnel concept with a supercontainer



6.2 Concept key feature – Cavern

Cavern concepts have been considered internationally as potential options for heat generating wastes including HLW and SF. Studies to date on cavern concepts have been limited, with the most recent work undertaken in Japan where the concept is referred to as the CAvern REtrievable (CARE) concept.

In the cavern concepts the disposal canisters are emplaced in an upright orientation and in close proximity in large ventilated caverns which are cooled by a combination of natural and forced ventilation. Once the packages are sufficiently cooled the buffer can be introduced and the GDF sealed and closed.

This concept would be flexible to small, medium and suitably modified large disposal canister sizes and could be designed to be either remote handled or shielded. The cavern concept provides maximum flexibility with regard to long term monitoring and ease of retrieval during the operational period. The cavern concepts are flexible to a range of canister types and due to the close proximity of emplaced canisters and caverns would result in a relatively small GDF footprint. This concept could be implemented in theory in a range of rock types if suitable structural support was installed. These benefits are however at the detriment of requiring a long operational period before closure requiring continued institutional control due to the high packaging density requiring long cooling times before backfilling. An illustration of this concept is provided in Figure 10.

In considering the issues of accommodating larger disposal canisters (as described in Section 5.2) into cavern concepts, commonalty is recognised with many aspects of GDF operations considered of the reference conceptual design, in tunnel vertical concept. The issues for surface handing and drift transfer are the same as discussed in Section 5.2, which explained that although different handling arrangements would be required, there were no insurmountable issues identified for medium sized disposal canisters.

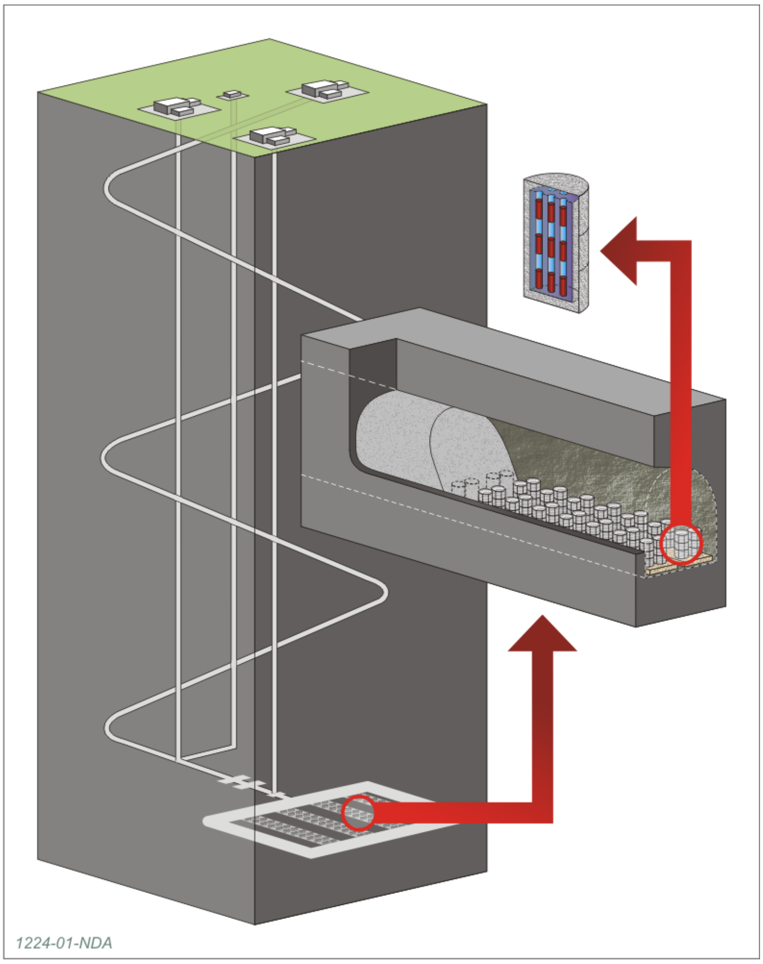
Emplacement within the caverns would essentially use existing crane technology employed in surface storage facilities. For the smaller disposal packages types this would require remote handling whereas the larger disposal canister and MPC systems which if self shielded could allow manned operations. Ventilation would be a combination of forced and natural ventilation during the operational period to maintain temperatures at a suitable level for the cavern crane operation and man-access.

The physical operation of deploying a granular buffer around the disposal canisters could be achieved using a backfill gallery system in which smaller tunnels would be constructed above the main caverns allowing delivery of the backfill to the main caverns. However, studies to date have indicated advantages in multiple layers of buffer / backfill which have complementary roles. One such buffer design includes a layer of silica sand around the disposal canister, which is then enclosed in a thick layer of a compacted mixture of sand and bentonite. This type of buffer system would potentially necessitate the installation of prefabricated buffer modules around the canisters or emplacement horizontally, which would allow the required engineered barrier system layers to be built up around the canisters.

A key attribute of the cavern concept is the ability to turn the storage caverns into a passive repository system when it is appropriate to do so. The timing at which that decision could be undertaken is largely dependent upon the design of the system, principally the heat output of the waste and its spatial arrangement. The high thermal loading would potentially foreclose options of early closure and studies undertaken for HLW disposal by NUMO have indicated for HLW an institutional control period of circa 300 years. If early closure was required then this would require modification to the engineered barrier system and the significance of the thermal transient on post-closure performance would need more careful consideration.

Overall the cavern concepts are well suited to the medium and the large MPC type packages, if the latter were suitably modified and could result in a small overall GDF footprint. The high thermal loading is problematic in the case of requiring early closure and to date only limited studies have been undertaken on the performance assessment of caverns concepts.

Figure 10 Schematic illustration of a cavern concept with steel MPC's or concrete disposal casks



7 Conclusions

This work has identified that there are a number of feasible opportunities for the management of SF from new nuclear power stations.

Centralised storage and packaging of spent fuel

The study has examined the feasibility of options for centralised storage and packaging of SF compared to the option of storage and packaging at the nuclear power station sites.

It has been established that there are a number of feasible potential centralised storage and packaging options.

Advantages identified for centralised storage and packaging include:

- Increased effectiveness and efficiency of arrangements for the security of SF, with the greatest benefit at a single national site;
- Potential reductions in the long term, ongoing costs associated with storing fuel for such extended periods;
- Reduction of packaging costs as only one packaging facility is required;
- Option to align with the current transportation infrastructure for SF management;
- Exploitation of economies of scale for some storage options.

And if a centralised storage and packaging plant were located at the GDF site, additional advantages include:

- Early transport of the fuel and avoidance of uncertainties over moving long term stored fuel or casks; and,
- Reduced handling of the fuel and number of package transports.

A disadvantage of centralised storage and packaging is:

- Duplication of storage capacity if the type of storage system and the relative period of interim storage at the reactor and central site are not optimised.

It is concluded that both wet and dry technology centralised storage options are feasible for the long term management of new nuclear power station SF. The choice of SF management system chosen by operators for implementation will depend on many factors including national policy and strategy, the size of any new generating programme, safety and environmental factors, cost, economics and security. In deciding which option would be optimal it would be very important to consider the views of stakeholders who may be affected by the development of storage, transport and packaging facilities associated with managing SF from any new nuclear power stations.

Optimisation of the current illustrative disposal concept examples

The study has identified a number of feasible opportunities to optimise the disposal concepts if SF arising from new nuclear power stations were to be included in the disposal inventory.

RWMD previously identified that the disposal concepts that included bentonite, were the most limiting in terms of achieving post-emplacement temperature criteria and estimated that SF of 65 GWd/tU burn-up would require a cooling period of the order of 100 years to comply with the current bentonite buffer temperature limit of 100°C. This present study has revisited this issue and identified that with judicious mixing of long-cooled and short-cooled

SF the duration of storage after the end of power station operation could be reduced to the order of 50 years before disposal.

Other feasible options with minimal impact on the illustrative disposal concepts and which would permit earlier emplacement of SF would be to utilise a smaller diameter disposal canister of reduced payload.

In the event that the MRWS process provides a volunteer community with an evaporite host rock then this would be advantageous from heat transfer considerations as the limiting temperature applicable to the evaporite backfill option is in the region of 200°C and therefore SF from any new nuclear power stations would require a shorter cooling period before emplacement. RWMD cannot plan on the basis of such an outcome at this stage.

Alternative packaging and disposal options

This study also considered the issues associated with handling larger disposal packages. There exist several designs of storage and transport casks, and MPC's which could be used as part of the solution for management of new nuclear power station SF. It is concluded that disposal packages (including any transport over-pack) weighing up to 80 tonnes would be compatible with illustrative disposal concepts currently being examined by RWMD, but would require individual components to be up-rated. The ability to handle disposal packages exceeding these mass limits up to about 130 tonnes is expected to be possible but would require significant up-rating and re-design of GDF infrastructure and handling systems from those in current plans.

Some existing MPC designs, including an overpack, can weigh in excess of 130 tonnes and could not be handled within any geological disposal concepts potentially available to RWMD. Such proprietary designs will also place constraints on their ability to be transported on the UK rail infrastructure. However, the MPC concept in which SF is loaded and sealed into a canister at the power station site, encased in a variety of overpacks during subsequent storage and transport phases is worthy of further consideration. Two broad potential packaging options are identified:

- Development of a purpose designed MPC destined for emplacement in a cavern concept and of a size and mass that can be handled with a GDF. This design would, like the existing designs, enable SF to be packaged and sealed into the inner container and protected during storage, transport and disposal by an appropriate shielded overpack. The emplacement concept would be similar to the CARE concept developed by the Japanese waste management organisation, NUMO. Within this option, the MPC would be stored underground initially in an un-backfilled vault, with backfilling following at a later date when the SF was sufficient cooled and when it was decided to move to a disposal phase. Further consideration would need to be given to issues arising in the event of a requirement for early backfilling.
- Development of a small MPC which is sized to be compatible with disposal options where bentonite buffer is emplaced around the package at the time of emplacement. The MPC could be deployed to be suitable for direct disposal or form part of a "supercontainer" assembled at the GDF. Such an option would still require consideration of heat transfer and temperature limits within the bentonite, but could take advantage of the benefits identified for mixing long and short-cooled fuel.

The use of the MPC solutions would reduce the need for handling of SF assemblies and avoid concerns about handling aged SF but the implications of such a management approach for the SF may warrant further attention.

8 The potential next steps

The following activities have been identified as worthy of further investigation and/or development. Some of these could be implemented quickly whilst others would require discussion with decision-makers, regulators and stakeholders.

If development was to be pursued in relation to temperature constraints:

- Undertake research and development to reduce the cooling period between removal from reactor to disposal, this would include improved understanding of bentonite behaviour at temperatures in excess of 100^{o}C (with a view to defining an increase in the acceptable temperature limit), considering alternative materials to bentonite and concept development that could delay the emplacement of buffer material;
- Develop a better understanding of the sensitivity of the temperature model parameters and the impact of the uncertainties associated with the input parameters;
- Undertake further heat transfer modelling to understand the behaviour of backfilled and un-backfilled canisters, in either vertical or horizontal disposal configurations and in a cavern concept.
- Undertake sensitivity studies to identify the impact of burn-up distribution recognising that SF assemblies will not all be irradiated to the assumed maximum.

If development was to be pursued in relation to centralised storage and packaging:

- Develop a holistic view of centralised storage and packaging plants informed by macro-economic analysis. This would lead towards developing an approach to inform decision-making on a storage strategy and on the choice of storage technology systems. A key part of this would be to understand how other countries have evaluated the benefits and approached decision-making on these matters.

If development was to be pursued in relation to concept development:

- Focussed studies on MPC options and the development of complementary disposal concepts such as the cavern or “supercontainer” options for geological disposal. This may require development of smaller MPC designs better suited for the UK rail infrastructure and proposed GDF handling systems. This would need to involve development of the safety case for transport and disposal and would require dialogue with regulators.

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