Nuclear
Decommissioning
Authority

Higher Activity Waste

The Long-term Management of Reactor Core Graphite Waste Credible Options (Gate A)

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Executive Summary

This paper establishes the credible options for the long term management of graphite wastes arising from the final decommissioning of reactors. The scope of the paper includes core and reflector graphite wastes arising from the final decommissioning of the Magnox and AGR reactors, and from the Sellafield Ltd., RSRL and DSRL research reactors. There is an established strategy for managing reactor core graphite that is embedded in site lifetime plans and is broadly similar across them, with the vast majority of the inventory from the final decommissioning of the Magnox and AGR reactors not planned to be generated for several decades. As such, there will be frequent opportunities to review the credible options set out in this paper as time progresses. The strategic tolerances to alternative site restoration strategies and GDF availability scenarios are explored in this paper. A high level plan for progressing the topic strategy and options for supporting R&D that there may be merit in undertaking is also described.

This paper identifies a number of potential options for the management of reactor graphite including both direct disposal and pre-disposal treatment options. These options are screened against four criteria for each of the Site Licence Companies (SLCs) within scope. The conclusion of this screening exercise is that it is not currently considered credible to directly dispose of reactor graphite to either the Low Level Waste Repository (LLWR) or to other radioactive waste permitted landfill sites. Opportunities are highlighted for the use of near-term waste arisings (for example RSRL and DSRL research reactor graphite) as pathfinder material for core dismantling or treatment trials to inform decisions on the management of larger volume, later arising Magnox, Sellafield and EDF Energy reactor graphite.

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1 The Strategic Case (Gate A)

1.1 Purpose

The purpose of this paper is to establish the credible options for the long term management of graphite waste arising from the final decommissioning of graphite moderated reactors.

It will also describe the relationship between site restoration strategy and the management of the graphite waste arisings and as a sensitivity set out the strategic tolerances that influence the choice of a preferred waste management option for different scenarios. The paper will also summarise R&D undertaken by the NDA on graphite waste management and identify at a high level what R&D may be needed to support the programme in the future.

This work represents one part of the NDA's wider programme for management of graphite wastes. A separate paper will set out the strategic framework for the management of operational graphite waste [Ref. i]. This approach, separating the strategy for reactor decommissioning waste from operational arisings, was determined following engagement with stakeholders within the regulator community. A key factor that influenced this decision was learning from the investigation of feasibility for near surface disposal of graphite sleeve wastes at the Hunterston A site [Ref. xi]. It was clear from this work the factors that would determine a coherent strategy for operational arisings are different to those for reactor decommissioning wastes and that progress in strategy development would be improved by separating the two.

Another important factor in setting out on this approach is that there is an established strategy for managing reactor core graphite that is embedded in site lifetime plans and is broadly similar across them, with the vast majority of the inventory from the final decommissioning of the Magnox and AGR reactors not planned to be generated for several decades. For operational arisings, different approaches are being undertaken at different sites for a range of operational and site-specific reasons.

This work is being delivered using NDA's Strategy Management System (SMS); this Gate A paper will establish the credible options for the management of core graphite waste streams arising from the decommissioning of graphite moderated reactors.

1.2 Scope

The scope of this paper covers strategic waste management options for all reactor graphite. This is typically in the form of irradiated graphite core bricks, used as a moderator or reflector assembly and will arise from the final dismantling of reactor cores in the UK. It includes currently stored, packaged waste and future arisings of such waste streams that will arise from reactor core dismantling.

As stated above, the strategic framework for the management of operational graphite waste such as Magnox fuel sleeve and AGR sleeve wastes that require management decisions to be made in the short term will be described in a separate paper.

Table 1 on the next page provides an overview of the scope and aims of these two pieces of strategic assessment work.

Table 1 – Summary of Approach for Addressing Graphite Waste Strategy

Title	**Core graphite waste from reactor decommissioning**	**Current operational graphite waste arisings**
SMS Stage	Stage A – Credible Options	Stage B – Preferred Option
Inventory	• NDA Magnox reactors • EDF Energy AGR reactors • NDA Sellafield reactors • NDA RSRL research reactors • NDA DSRL research reactors	• Magnox fuel sleeves at Hunterston • AGR fuel sleeves at Sellafield • Berkeley vault waste (as an example mixed waste stream)

Arisings timescale	• NDA Magnox reactors
	  » 2070-2101
	• EDF Energy AGR reactors
	  » 2105-2114
	• NDA Sellafield reactors
	  » In storage (WAGR waste)
	  » 2030-2043 (Pile 1 & 2)
	• NDA RSRL research reactors
	  » 2016-2030 (BEPO, DIDO, PLUTO & DRAGON research reactors)
	• NDA DSRL research reactors
	  » Decommissioning from 2017 (DMTR) & 2021 (DFR) research reactors
		• Magnox fuel sleeves at Hunterston
		  » 2013-2019
		• AGR fuel sleeves at Sellafield
		  » Now - 2025
		• Berkeley vault waste (as an example mixed waste stream)
		  » 2013-2017

Target level of strategy development	Gate A – Credible options	Gate B – Preferred option (Gate C decisions made at waste stream/ SLC level)
Purpose	• Determine the credible options for reactor graphite management and the effect of alternative site restoration scenarios • Clearly describe the relationship between site restoration strategy and reactor graphite waste management • Describe at a high level what R&D may be needed to support the programme going forward • Establish a planning position for nuclear provision, demonstrating that there are a range of credible management options	• Provide a strategic context within which SLCs can make waste stream level decisions (i.e. prevent an absence of strategy from unduly influencing decision making)

1.3 Topic background and context

The decommissioning of reactors in the UK will generate substantial amounts of higher activity radioactive waste. A significant proportion of these wastes will be graphite. The UK graphite inventory comprises operational and reactor decommissioning waste streams. Core graphite waste streams amount to circa 22 % on a packaged volume basis assuming baseline packaging plans of the total UK ILW inventory; by comparison, operational graphite waste streams comprise a further 6 % of the UK ILW inventory. In total, these graphite wastes comprise about 136,000 m^3, or almost 30% on a packaged volume basis of the total inventory of ILW forecast to arise across the UK of 488,000 m^3.

If consigned to the planned Geological Disposal Facility (GDF) it is estimated by RWMD that graphite wastes would occupy less than 2 % of the facility footprint. This is a consequence of the GDF footprint being dominated by galleries for the disposal of HLW, which must be suitably spaced to allow for heat dissipation, along with the ability to package graphite wastes efficiently for disposal [Ref. ii]. It is however recognised that there are other factors which need to be considered in relation to off-site geological disposal including the need to transport packages to the facility.

1.3.1 Summary of core graphite inventory

UK Radioactive Waste Inventory 2010 (UKRWI 2010) data have been used consistently in this paper to describe the inventory volumes, as a widely available data set that can be referenced. The total graphite mass, raw volume and packaged volume of reactor graphite streams are summarised in Table 2 below, corrected for the proportion of graphite present in mixed waste streams (in a number of cases, specifically for the research reactors, the graphite component of the stream is a proportion of the wider decommissioning waste stream reported in UKRWI 2010).

Appendix A is derived from UKRWI 2010 data and describes the waste streams in greater detail. It should also be noted that for some sites, inventory volume estimates have since changed, and may change in the future, albeit likely to a relatively minor extent. This is particularly true for the research reactor sites, where implementation plans have been further developed, for example in relation to conditioning and waste packaging. Changes from UKRWI 2010 are described in Appendix B.

Table 2 Mass and Volume of Core Graphite Wastes based on UKRWI 2010 Data

	Graphite mass t(e)	**Raw graphite volume (m^3)**	**Graphite packaged volume assuming packaging plans from UKRWI 2010 (m^3)**
Magnox reactors	56,555	45,244	59,190
EDF Energy AGR reactors	24,307	20,069	42,130
Sellafield reactors	3,967	2,890	6,493
RSRL research reactors	693	397	1,058
DSRL research reactors	296	124	623
Totals for all UK	**85,818**	**68,724**	**109,494**

The core graphite waste inventory is illustrated in Figures 1 and 2.

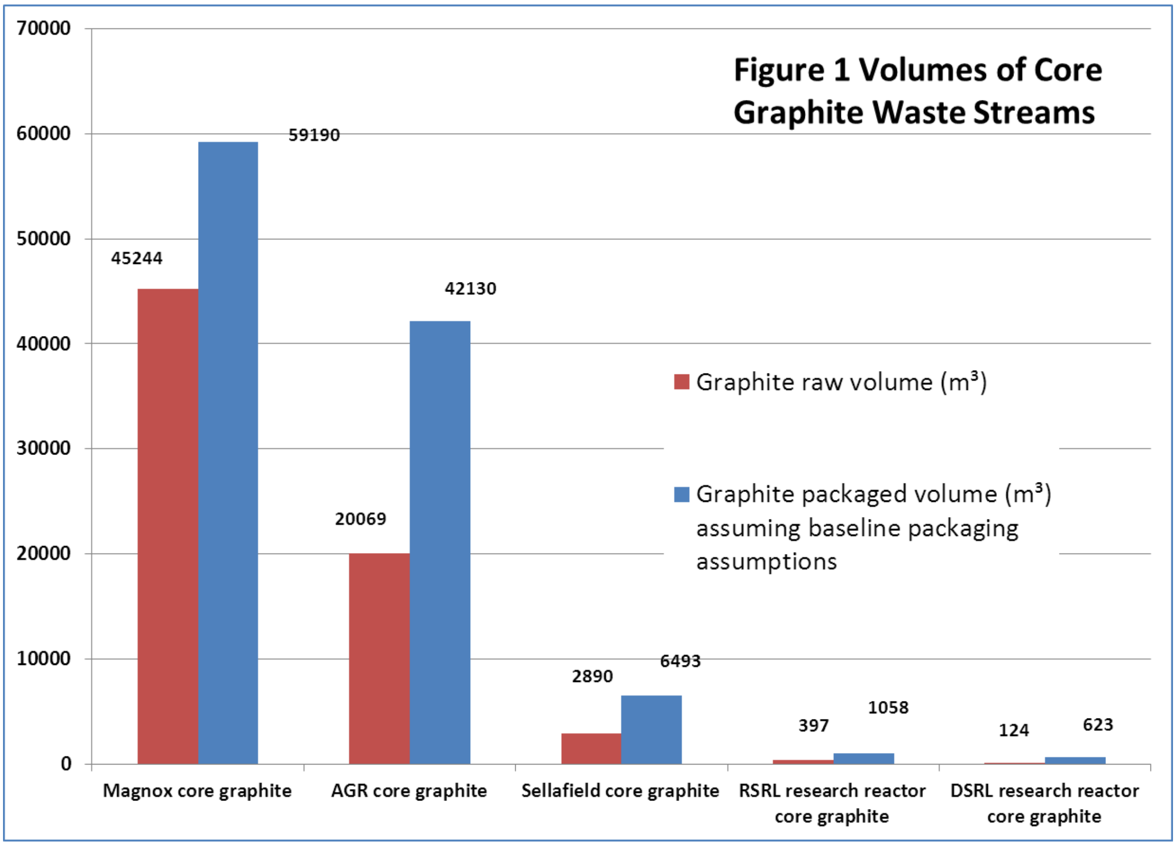
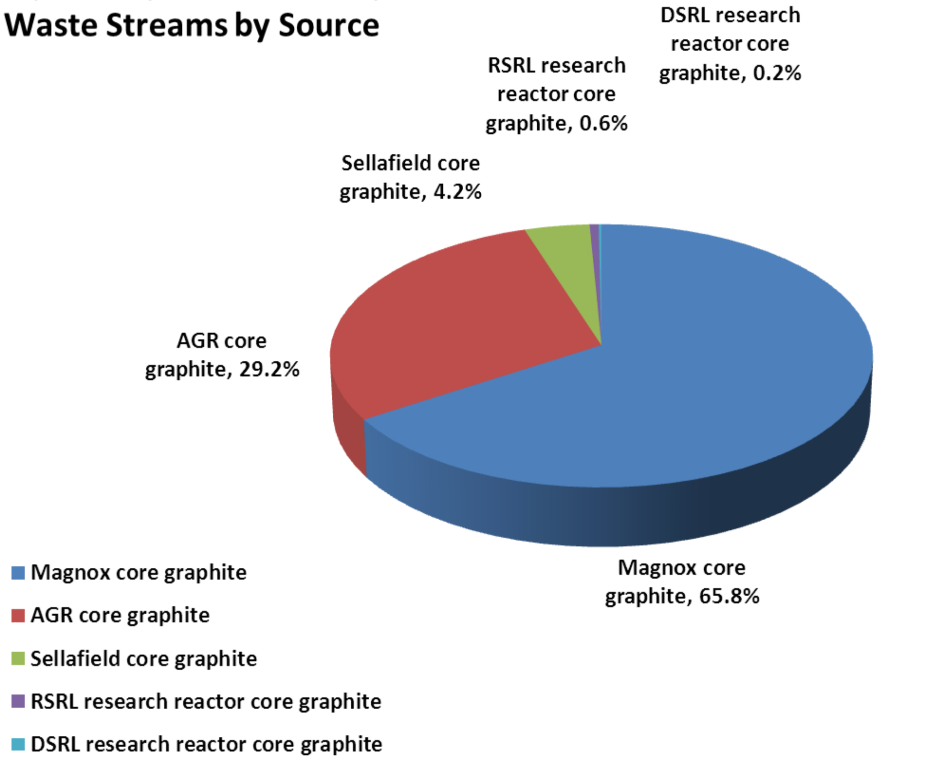


Figure 2 Split of Core Graphite Waste Streams by Source



Magnox core graphite dominates the inventory (about 65% by raw volume), with AGR core graphite contributing a significant proportion (about 30%) and Sellafield (circa 4%) and the RSRL and DSRL research reactors (both less than 1%) making up the remainder of the inventory.

1.3.2 Drivers for the work

There are a range of identified drivers to better underpin strategy for core graphite wastes from reactor decommissioning:

- **Government policy framework**

  The Committee on Radioactive Waste Management (CoRWM) considered a broad range of options for the management of higher activity waste (HAW) and recommended geological disposal as the preferred solution. CoRWM also made a specific recommendation (CoRWM 8) that other management options for reactor decommissioning wastes should be considered[1] because of the nature of the waste [Ref. iii]. CoRWM noted that some stakeholders

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[1] Reactor decommissioning wastes generated from the final decommissioning of graphite moderated reactors in the UK principally comprise reactor graphite, metals and concrete waste streams.

favoured non-geological (on-site) disposal of reactor decommissioning wastes, as it avoids the transport impacts associated with consigning large quantities of wastes to an off-site disposal facility. Government accepted CoRWM's recommendations (see below for Scottish Government policy). In relation to CoRWM 8, Government requested that NDA undertake a review of whether or not a safety case could be made for non-geological disposal of reactor decommissioning wastes, including on-site, or near site, disposal in order to minimise transport [Ref. iv]. The white paper on the framework for implementing geological disposal [Ref. v] recognises the need to take account of developments in storage and disposal options, as well as possible new technologies and solutions, including application of the waste hierarchy, which could reduce the amount of waste requiring geological disposal.

- **Scottish Government policy**

  Scottish Government policy [Ref. vi] does not support use of the planned Geological Disposal Facility (GDF) for Scottish HAW. Scottish Government policy is for "the near surface, near site storage or disposal of Scottish HAW." The policy also supports treatment options higher in the waste management hierarchy, potentially at facilities outside of Scotland. This means that a different approach to managing reactor core graphite in Scotland is needed.

- **NDA statements on strategy for reactor graphite**

  Previously published NDA documents acknowledged the link between reactor decommissioning strategy and the availability of a waste route for reactor graphite. They also highlighted the possibility for alternative management options which could avoid the need to consign large volumes of graphite to the GDF. There are a number of more recent statements in the current NDA Strategy of direct relevance to strategy for reactor graphite [Ref. vii]. Plans for decommissioning reactors rely upon the availability of a final disposal solution for the waste. It is recognised that reactor decommissioning will generate substantial amounts of radioactive waste and that a significant proportion will be graphite waste. The NDA has a commitment to consider the best way to manage these wastes. The NDA is considering alternative options for some HAW, such as near surface disposal for reactor decommissioning wastes. The NDA is also investigating waste treatment options, such as thermal treatment, which could lead to benefits such as waste volume reduction. The NDA is undertaking a programme of work considering the various strategic options. This includes improvements to the current strategy of geological disposal, treatment of graphite waste and alternative disposal options[2].

- **Site restoration strategies**

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[2] Specific reference is made in NDA Strategy 2 to the study at Hunterston A which considered the feasibility of near surface disposal of some operational graphite wastes that require management in the near term, which in addition to addressing a specific requirement at the site, would inform the NDA's wider strategy for reactor graphite.

There is an interface and dependency between the timing and strategy for site restoration of Magnox and AGR reactor sites and the availability of waste routes for the reactor decommissioning wastes that will be produced. The availability of a waste route for reactor graphite is a key enabler for final reactor decommissioning. If this waste were to be generated prior to the availability of a suitable route, such as the GDF or a near surface facility in Scotland, an alternative strategy for reactor graphite would be needed.

- **R&D to underpin treatment technologies**

  There is a view within the regulatory community, amongst some stakeholders in academia and companies involved in developing waste treatment technologies that further R&D should be undertaken on treatment options for reactor graphite to support application of higher levels of the waste hierarchy e.g. thermal treatment, recycling opportunities, etc.

- **International work on graphite waste options**

  Investigation of graphite management options outside of the NDA has been ongoing for a considerable time including various R&D programmes and studies e.g. CarboWaste [Ref. viii], EPRI [Ref. ix] and IAEA [Ref x]. There has also been considerable international collaboration on graphite waste options, which the NDA and some SLCs have participated in[3]. The large volume of this waste in countries with graphite moderated reactors is an important driver. There is a view in some countries that the lack of an available waste route prevents decommissioning of such reactors. Although it is recognised that geological disposal is the planned waste route for much of this waste, there are issues surrounding timing and whether or not geological disposal of this waste represents the BPEO/ BAT for a waste that whilst long-lived is considered to pose a relatively low level of risk; there is also an aspiration to apply higher levels of the waste hierarchy to this waste. Considerable work has been undertaken on alternative options to GDF disposal.

  Core graphite waste from the Brookhaven Graphite Research Reactor (BGGR) with broadly similar activity concentrations of C-14 to Magnox core graphite has been disposed of to a near surface disposal facility in the US. A test cavern at 50–100 m depth has been excavated at Rokkasho in Japan, for a facility designed for the disposal of long-lived reactor wastes. There is a programme of work in France for the disposal of reactor graphite to a proposed national disposal facility sited at a minimum of 50–100 m depth within a thick, low permeability clay formation. In the US, there are plans for the prompt decommissioning of the K-reactors that include the disposal of the core graphite to a near surface disposal facility. A considerable amount of work has also been undertaken in the US, Germany, France and Japan on the application of thermal treatment technologies to core graphite wastes.

- **Integrated Waste Management Theme Overview Group (IWM TOG)**

[3] EDF Energy is planning to review graphite waste management strategies, treatment and disposal options in 2013 in France and the UK, considering potential synergies across the wider EDF group.

In November 2011, the NDA produced a forward programme [Ref. xi] setting out examples of drivers for work on further developing a strategy for the management of reactor graphite and questions that should be considered in establishing whether there is a case for changing strategy. These were discussed at the IWM TOG in December 2011 [Ref. xii], where strong views were expressed that further work should be undertaken to robustly underpin the strategy for reactor graphite. This would involve preparation of a credible options paper for operational and reactor core graphite to test the current baseline, to establish whether there is a case for a change in strategy and to identify any work needed to move to a more mature strategy position.

1.3.3 Summary of NDA work supporting graphite waste strategy

Graphite strategy has been under development within the NDA for several years as the main element of work under the reactor decommissioning work stream. To date NDA's work has focussed on developing understanding of technical options for the management of graphite waste, essentially answering the question "what can be done with graphite wastes?" More recently, NDA has shifted attention to addressing the question "what should be done with graphite wastes?"

R&D on graphite management options carried out to date by the NDA includes:

- **Graphite characterisation study**

The objective of this work (which has been performed by UKAEA and Babcock) [Refs. xiii, xiv] is to improve understanding of the inventory of Magnox reactor graphite. It involved definition of data requirements, the acquisition and analysis of inactive and active samples of graphite from the national archive and comparison of the results against theoretical models. The work suggests that the UK RWI data are reasonable, that the model developed is able to predict the inventory of samples and that much of the radionuclide inventory of C-14 is bound within the graphite matrix. It was also noted that contemporary sampling of reactor core graphite for characterisation purposes would increase confidence. The study is due to be completed by April 2013.

- **Graphite behaviour study**

This work [Ref. xv] identified the fundamental graphite behaviours likely to influence treatment and disposability considerations along with a programme of experimental work and analysis to establish a baseline of information. The work also included thermal treatment studies and leaching trials to investigate short term releases of C-14. The study is due to be completed by April 2013.

- **Review of baseline assumptions for geological disposal**

A review of the baseline assumptions for managing reactor graphite through disposal to the GDF [Ref. ii] has been carried out by RWMD, identifying opportunities to enhance the baseline through consideration of more optimal approaches. The review focussed on alternative conditioning and packaging options and included disposability assessments, a cost-benefit analysis and a discussion of the implications of consigning graphite wastes to the GDF. The review highlights that the use of the GDF option for graphite waste arising in England and Wales would avoid the need to identify a separate disposal site or sites for such waste and would result in only the marginal costs of disposal of such waste to this planned facility being incurred. The review has gone some way to demonstrate that the baseline for graphite arising in England and Wales of GDF disposal is robust and that it may be possible to further optimise it through alternative packaging and conditioning approaches.

- **Work on near surface disposal of reactor graphite**

Magnox carried out a study on behalf of the NDA to assess the feasibility for disposing of an operational graphite waste stream by means of near surface disposal at the Hunterston A site. A sensitivity study was carried out to assess the applicability of this approach to reactor core graphite. A design for the disposal facility, a preliminary Environment Safety Case and a suite of supporting reports were produced. The work has improved NDA's understanding of this option and provided insight into its applicability to reactor core graphite. A decision was made not to implement this option for the operational waste at Hunterston because a compelling business case for changing from the baseline to this alternative at the time could not be made. This was not related to feasibility but rather to the balance of risks and benefits given that an ILW Store had been built at the site and plans for an encapsulation plant were well progressed.

- **Summary of treatment options**

A report on treatment options that could be applied to reactor graphite waste [Ref. xvi] has been prepared by the Nuclear Graphite Research Group of the University of Manchester on behalf of the NDA. This includes a summary of the latest knowledge and research, encompassing UK and international experience of current and emerging treatment technologies that could be applied to the waste.

1.3.4 Strategic objective for graphite waste from final reactor decommissioning

The strategic objective of the NDA's strategy for reactor graphite is to –

> **Ensure safe, secure and environmentally protective management and disposition of graphite waste streams from final reactor decommissioning in a cost-effective and timely manner**

This work should help to identify what work is needed to support future strategy development for reactor core graphite, including any necessary underpinning R&D. It should also consider under what circumstances a case for a change in strategy for reactor core graphite might be made; the timing for preparation of such a case, depending on the drivers and related work programmes; and the strategic tolerances surrounding such a case. The forward programme of work on graphite strategy should be designed to provide strategic input at the appropriate time to support selection and implementation of the preferred site restoration strategy.

1.4 Current Situation

The final decommissioning of the NDA Magnox reactors is assumed to take place between 2074 and 2101. The reactors will be finally dismantled in a sequenced programme with a start date and duration to be agreed. The current strategy is to begin this work 85 years after the cessation of generation.

The final decommissioning of the EDF Energy AGR reactors is currently assumed to take place between 2105 and 2114.

Much smaller volumes of core graphite waste will be produced earlier from the decommissioning of the BEPO, DIDO, PLUTO and DRAGON research reactors by RSRL from 2016, the DFR and MTR research reactors by DSRL from 2017 and the Windscale Piles 1 and 2 from 2030 by Sellafield Ltd.

Final decommissioning of both the Magnox and the AGR reactors will not commence until well after the start date for first emplacement of waste in the GDF which is assumed to be 2040.

Final decommissioning of Sellafield, RSRL and DSRL reactors will commence before planned GDF availability and the graphite wastes produced will consequently require a period of interim storage

The baseline strategy for reactor graphite wastes arising in England and Wales is for consignment to the planned GDF, with a national prioritised programme for waste emplacement.

Scottish Government policy is for the long term management of Scottish HAW in near surface facilities. It is assumed that a near surface, near site facility or facilities for the long term management of Scottish HAW will become available prior to the commencement of final reactor decommissioning in Scotland.

The baseline strategy for core graphite wastes is summarised in Table 3.

Table 3 Summary of Baseline Strategy for Core Graphite Wastes

	Summary of Strategy
Magnox reactors	Upon Magnox reactor final decommissioning 2074 – 2101**, cementitious encapsulation in RWMD 4 m boxes for GDF disposal** (**or consignment to an appropriate near surface facility for waste arising in Scotland)**
EDF Energy AGR reactors	Upon EDF Energy AGR final decommissioning 2105 – 2114, **cementitious encapsulation in RWMD 4 m boxes for GDF disposal** (**or consignment to an appropriate near surface facility for waste arising in Scotland)**
Sellafield reactors	Pile waste – upon pile decommissioning 2030 – 2043, **packaging unencapsulated in RWMD 4 m boxes for interim storage where necessary pending GDF disposal** WAGR waste – **encapsulated in WAGR boxes, in interim storage at Sellafield pending GDF disposal**
RSRL research reactors	Upon RSRL research reactor decommissioning 2016 – 2030, **cementitious encapsulation in Robust Concrete Boxes (RCBs) for interim storage pending GDF disposal**

	Summary of Strategy
DSRL research reactors	Upon DSRL research reactor decommissioning commencing 2017, **cementitious encapsulation in Robust Concrete Boxes (RCBs) for interim storage pending consignment to anoff-site facility**

1.5 The Case for Change

1.5.1 Magnox and AGR reactor sites

The vast majority of the reactor core graphite wastes in the UK are not due to be generated for several decades. Whilst there are uncertainties regarding the siting and design of the GDF, the baseline plan for wastes arising in England and Wales of GDF disposal is reasonably developed and robust against a planned date for availability of this facility from 2040. By contrast, in Scotland there may be a case to undertake further development work to better underpin the Scottish policy of consignment of the waste to an appropriate near surface facility, perhaps to the same level of underpinning as the GDF baseline. This reflects the relatively undeveloped status of the Scottish policy option, in comparison with the GDF disposal option.

Magnox and AGR baseline decommissioning plans provide time for the maturity and technical readiness level (TRL) of alternative management options to improve, before there is a need to identify the preferred option for such waste. During this period, advances in technology will be made that may result in treatment options or those involving recovery for beneficial re-use becoming candidates for implementation. Society's attitude toward radioactive waste and the availability of waste routes are both likely to change over such time periods. The case to further develop strategy for reactor graphite waste based on Magnox and AGR baseline decommissioning plans is consequently relatively weak over the short term (the next decade or so), perhaps with the exceptions of improving the underpinning of the Scottish policy option and reducing uncertainties on the characterisation and behaviour of graphite. As time progresses and baseline implementation plans for GDF disposal or consignment to a near surface facility in Scotland are further developed, there may be a driver to move to a preferred option for Magnox and AGR graphite wastes to ensure that the design of the disposal vaults for ILW in these facilities is appropriately sized (graphite waste represents a relatively high proportion of the English & Welsh ILW and the Scottish ILW inventories). This would also help to avoid any potential nugatory costs.

The only circumstances over the short term in which there is likely to be a need to further develop the underpinning for strategic options for core graphite wastes, as well as wider reactor decommissioning wastes, is if the NDA decided to explore alternative site restoration scenarios for Magnox decommissioning i.e. acceleration of the timescale for the final decommissioning of one or more Magnox reactors. In this case, an alternative waste route to GDF disposal for such a site in England & Wales might be needed to support the wider business case (on-site interim storage of the large volume of waste that would be produced would be more costly than the current baseline); in Scotland, it would be necessary to underpin the Scottish policy option for such wastes. In either case, there would be merit in developing strategy to identify the preferred waste option for such a scenario. Further work to better underpin the status of treatment and reuse/ recycling options might also be justified in this case.

1.5.2 Sellafield, RSRL and DSRL reactors

The WAGR graphite waste at Sellafield is encapsulated within WAGR boxes and is in interim storage at the Sellafield site. Treatment and re-use/ recycling options are not considered to be feasible for this waste. The Pile 1 graphite waste at Sellafield is fuel contaminated; as a consequence, it is considered unlikely that a change from the baseline GDF disposal plan could be justified. Given the fuel contamination, there may be merit in considering encapsulation of this waste. It is understood that Pile 2 waste is not fuel contaminated, however it represents only a small fraction of wider Sellafield higher activity wastes and its management may be driven by decisions taken for the management of other waste streams on the Sellafield site e.g. making use of available waste packaging and conditioning plants.

DSRL and RSRL plans for the management of research reactor graphite wastes have changed to encapsulation in Robust Concrete Boxes (RCBs) which have features identical to those for a WAGR box, instead of the 2m and 4m RWMD boxes assumed in UKRWI 2010. It is understood that graphite wastes will be segregated from other reactor decommissioning wastes. Interim storage facilities are planned at the sites of arising. There may be opportunities to improve knowledge of graphite retrieval, handling and waste management approaches. There is also potentially an opportunity to undertake treatment trials on these graphite wastes, although applicability of the results to the much larger and differing grade Magnox and AGR graphite waste streams would need to be considered. Where reactor decommissioning is planned to commence within the short – medium term, the opportunity to consider alternative options may be precluded, although it is noted that the case for a change of strategy to non-encapsulated storage could still be explored if there was considered to be benefit in doing so e.g. avoiding foreclosure of treatment and re-use/ recycling options. These research reactor graphite wastes are relatively low in volume and form part of larger reactor decommissioning waste streams; management decisions may be driven by the approach taken for these other wastes. There may be opportunities to improve knowledge of graphite retrieval, handling and waste management approaches. The planned generation of DFR and DMTR waste streams might provide the opportunity to better develop management arrangements consistent with Scottish policy.

1.6 The Aspirational Outcome and Potential Benefits

The aspirational outcome of this work is to progress development of graphite strategy in a cost effective and structured manner, addressing the drivers and strategic objective described in Section 1.3. Alternative waste management and disposal options could result in lifecycle cost savings in comparison with GDF disposal and may represent a more sustainable approach to the management of such waste. There is a range of potential benefits associated with alternative treatment options and those involving recovery for beneficial re-use that could result in higher levels of the waste hierarchy being applied to graphite wastes. It is also important to schedule further development of graphite strategy for Magnox and AGR reactor graphite wastes at the appropriate time to support the development of site restoration and decommissioning strategies e.g. any work on scenarios involving accelerated Magnox final decommissioning prior to GDF availability.

1.7 Boundaries including Interfaces with other Topic Strategies

This Gate A paper will consider long-term management options at a strategic level. The paper will not consider BAT/ BPM options for packaging, conditioning, etc. although will acknowledge that such matters will need consideration. The paper will fully describe the baseline plans for the various in-scope wastes and will reference work that has considered options for packaging, conditioning, etc. There are interfaces with a range of other Topic Strategies and NDA work areas –

- **Site restoration and decommissioning** – alternative waste options are a potential enabler, along with a range of other considerations such as business case and the availability of funding, for alternative decommissioning strategies.
- **Land quality management** – possible presence of disposal facilities at local, regional or national level for some graphite waste options; interface with wider site restoration programme dependent on decommissioning strategy.
- **Site end states** – timing of achieving site end states is dependent on decommissioning strategy; possible presence of disposal facilities at local, regional or national level for some graphite waste options.
- **Higher activity waste** – interface with management of other reactor decommissioning wastes e.g. common waste conditioning/ packaging plants for core graphite and other FSC wastes assumed in Magnox plans, opportunity for use of shared alternative disposal options for core graphite and other reactor decommissioning wastes, etc.
- **Research and development** – a considerable R&D programme has been undertaken by NDA, further work may be justified.

1.8 Constraints and Dependencies

This Topic Strategy is subject to the constraints and dependencies set out in Table 4.

Table 4 Constraints, dependencies and potential impacts

Constraint/ Dependency	Potential Impact
Government policy, standards, legislative, planning and regulatory environment	Constraint
Site restoration and decommissioning strategies	Constraint and dependency – an alternative waste strategy would be needed for Magnox site restoration timescales prior to GDF availability
GDF availability and timing	Constraint and dependency for baseline option for waste arising in England and Wales
Regulatory guidance on geological disposal and on near surface disposal	Constraint
The RWMD Letter of Compliance process	Constraint

Constraint/ Dependency	Potential Impact
Joint regulatory guidance on management of higher activity waste	Constraint
Scottish higher activity waste policy, for Scottish wastes	Constraint
Scottish higher activity waste implementation strategy, for Scottish wastes	Dependency
NDA reactor decommissioning waste strategy	Dependency
Magnox Ltd., EDF Energy, Sellafield Ltd., RSRL and DSRL strategy and plans	Dependency
Site end states	Dependency – for options involving disposition of waste at a site
De-licensing/ de-designation/ divestment	Dependency – for options involving disposition of waste at a site
Discharge limits for treatment technologies	Dependency – for options involving environmental discharges
Interface between site decommissioning and on- and off-site waste management, transport and disposal steps	Dependency – optimisation waste management and decommissioning on a lifecycle basis to mimimise estate and UK wide costs
Availability of appropriate packages, conditioning and interim storage facilities	Dependency – particularly relevant to Sellafield, RSRL and DSRL
Availability of suitable transport containers and logistics	Dependency – for options involving off-site waste transport

1.9 Risks, Issues, Concerns and Key Assumptions

1.9.1 *Risks*

There are a number of risks which are posed to the successful delivery of a reactor graphite waste management strategy. The key risks are detailed below with a more comprehensive list provided in Appendix C.

- There is a risk that the regulators do not consider the extent of planned strategic development work and R&D for graphite waste to be adequate.
- There is a risk that the legal, policy, planning or regulatory framework changes, resulting in increased costs and or timescales to implement the preferred options e.g. standards become more restrictive.
- There is a risk that the marginal cost for consigning graphite waste to the GDF is higher than currently estimated.

1.9.2 Opportunities

There are a number of opportunities which could be realised to support the successful delivery of a reactor graphite waste management strategy. The key opportunities are detailed below with a more comprehensive list provided in Appendix C.

- There is an opportunity to apply learning gained from other sources such as international experience, Carbowaste and EDF Energy to improve graphite management strategy.
- There is an opportunity to assess alternative options which could be enablers for alternative site restoration strategies e.g. alternative timescales for final decommissioning of one or more Magnox reactors.
- There is an opportunity to trial alternative waste management options using research reactor graphite.
- There is an opportunity to improve knowledge of graphite retrieval, handling and waste management approaches during management of research reactor and Sellafield wastes.

1.9.3 Issues and concerns

- Perception about transport of large volumes of graphite and wider reactor decommissioning wastes to an off-site facility c.f. CoRWM 8.
- De-licensing, de-designation, divestment and Paris & Brussels liability implications in relation to disposal facilities for some options.
- Status of environmental safety case work for near surface disposal of graphite - a small number of environmental safety case issues were not closed out with SEPA following completion of the Graphite Pathfinder Project.
- Understanding under what circumstances near surface disposal may be preferable to geological disposal.
- Perceptions concerning any treatment options involving the release of large inventories of C-14 or Cl-36 to the environment in gaseous or liquid form.
- The acceptability of in-situ disposal options, particularly at coastal sites where reactor mounding would eventually be impacted by coastal evolution.
- Do treatment options deliver any net benefit over disposal for reactor graphite wastes, given the suitability of the waste form for direct disposal and the need to manage any secondary wastes stemming from treatment.

1.9.4 Key assumptions

- Baseline decommissioning plans and site end states assumed (alternative site restoration strategies considered in terms of strategic tolerances).
- Core reactor graphite wastes have a C-14 inventory which precludes its disposal to the LLWR and to landfill.
- An environmental safety case for either near surface disposal to a purpose designed facility for graphite (possibly at intermediate depth) or to the GDF can be made.
- Public and stakeholder acceptance for development of any necessary waste treatment or disposal facilities can be achieved.

- Graphite core bricks at Magnox and AGR reactor sites are of various dimensions and shape (varies across different sites, for reflector/ moderator graphite and with location in the reactor).
- There is no benefit in terms of disposal routes in segregating graphite waste according to its activity concentration for the vast proportion of the UK graphite inventory (a small proportion, such as reflector graphite that may have lower C-14 concentrations, may be suitable for LLWR disposal).
- Graphite core bricks are retrieved in air whole and dry during decommissioning i.e. as opposed to “nibble and vacuum” - consider latter as R&D development opportunity for research reactor waste.
- Scottish implementation strategy is published by Scottish Government to enable implementation of the Scottish policy option for higher activity wastes on timescales to support decommissioning strategies for Scottish sites.

2 The Economic Case Part I (Gate A) Credible Options

A long list of potential options that address the strategic drivers and objectives for the work set out in Section 1 will be assessed against a range of screening criteria developed for the study to produce a list of credible options that are legal, potentially feasible and meet the strategic objective set out in Section 1.3.

2.1 List of Potential Options

The list of potential options has been grouped according to whether they are disposal options, treatment options or re-use/ recycling options.

Disposal options

1. **GDF disposal** to the planned disposal facility for higher activity wastes arising in England & Wales.
2. **Near surface disposal** [4] to a new specialised facility Permitted in line with the Near Surface Guidance for Requirement on Authorisation (GRA).
3. **In-situ disposal** (necessarily assumes reactor mounding is selected as an alternative site restoration and decommissioning strategy).
4. **LLWR disposal** (existing specialised facility).
5. **Permitted landfill disposal** (existing or future commercial facilities).

Treatment options

6. **Treatment to make subsequent management of the waste easier**, followed by consignment to appropriate waste routes e.g. decontamination to remove key radionuclides.
7. **Treatment to minimise the volume of solid waste for disposal**, followed by consignment to appropriate waste routes e.g. steam reformation, thermal treatment, etc.

Recovery for re-use or recycling

8. **Recovery for beneficial re-use or recycling**

2.1.1 Notes on potential options

It should be noted that the treatment and recovery/ recycling options could be applied in conjunction with disposal options for any remaining waste.

For disposal options 1 – 5

- The waste would be conditioned and packaged according to the waste acceptance criteria for the disposal route, and backfilled in the disposal facility, etc. as appropriate for the waste form and disposal option.

[4] Facility could be sited at intermediate depths up to about 100 m below ground

- There is the potential for a pre-treatment stage if it makes subsequent management easier or contributes to waste minimisation e.g. sorting of waste for different waste routes depending on radioactivity content, crushing of waste if there is considered to be benefit in doing so, etc.

For the treatment options 6 and 7

- Residual or secondary solid radioactive wastes would be consigned to an appropriate waste route e.g. disposal options 1, 2, 3, 4 or 5 and potentially recovery for beneficial re-use/ recycling option 8.
- Any secondary gaseous or liquid radioactive wastes stemming from treatment options would either be captured for future management or discharged to an appropriate Permitted discharge route, specific to the treatment option and the characteristics of the waste form e.g. carbon capture and sequestration.

For option 8

- There is the potential for pre-treatment of the waste, to facilitate beneficial re-use or recycling i.e. this option could be implemented in conjunction with treatment options 6 and 7.

2.1.2 *Notes on siting considerations for options*

Some of the options assume use of existing and planned facilities; whilst decisions on siting would be necessary for others that require new facilities not planned for.

For the disposal options

- Option 2 near surface disposal, facility siting could be undertaken at the local (on, or adjacent to the originating site), regional or national level.

For the treatment and recovery for beneficial re-use/ recycling options

- Implementation could be at the local, regional, national or international level, either involving new facilities or use of available facilities at the time of waste arising. There is the possibility for use of mobile or movable treatment plants.

A strategic options diagram (SOD) is provided on the next page for these options.

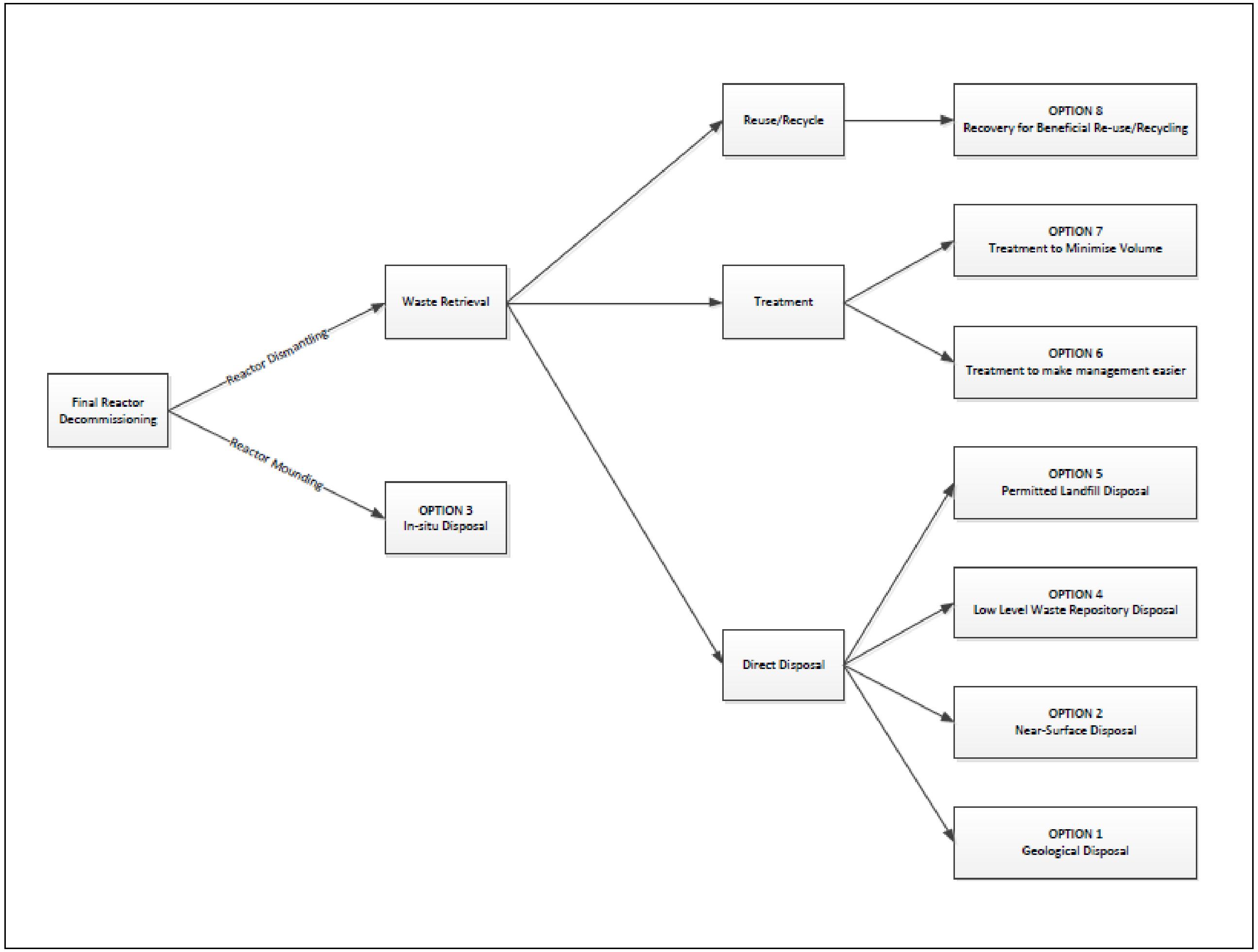

Figure 3 Strategic options diagram for core graphite waste

2.2 Initial Screening Criteria

A small number of screening criteria have been developed to assess the potential options against and to move to a credible options list.

Table 5 Screening criteria

	Screening Criteria
1.	**The option must be legal and compliant with policy -** the option must be legal under national and international law; options not consistent with Scottish policy will also be screened out
2.	**Compliance with facility waste acceptance criteria -** the option must meet the waste route WAC, or be considered to have a reasonable chance of meeting them if they are either not known at this time or could change in the future
3.	**Ability to meet timescale -** screen options against the ability to meet baseline decommissioning and site restoration plans (and explore strategic tolerances against different site restoration scenarios and GDF availability variants); this criterion implicitly includes consideration of technical readiness at the time of implementation
4.	**The option must meet the Strategic Objective** – to ensure safe, secure and environmentally protective management and disposition of reactor graphite waste in a cost effective and timely manner

2.3 Identification of Credible Options and Strategic Tolerances

2.3.1 Magnox and AGR graphite wastes

The high C-14 content of the Magnox and AGR graphite wastes results in option 4 LLWR disposal and option 5 permitted landfill disposal being screened out on the basis that they would not meet current WAC and are highly unlikely to meet future WAC for such facilities[5].

GDF disposal, near surface disposal and *in-situ* disposal options (1, 2 & 3) satisfy the screening criteria and are considered to be credible options.

[5] See [Ref. ii] which demonstrated that operational graphite waste streams that have a lower activity concentration and total inventory are highly unlikely to meet current or future WAC for disposal to the LLWR based on their C-14 content. However, is possible that a small proportion of such reactor wastes, for example reflector graphite waste surrounding some reactors, may have a relatively low C-14 activity concentration and might meet the WAC for LLWR disposal. Site specific assessments against the LLWR WAC should be undertaken by the site operators to confirm if LLWR disposal is a credible option for a portion of such waste.

The treatment options (6 and 7) and recovery for beneficial re-use/ recycling option (8) also satisfy the screening criteria and are considered to be credible, given that the reactor decommissioning wastes are not due to be generated according to baseline decommissioning plans for several decades and the potential treatment and recycling technologies may mature over these timescales to be feasible for industrial scale application to such wastes.

It should be noted that Option 1 GDF disposal is not compliant with Scottish Government policy and could be rejected on this basis for the Scottish Magnox and EDF Energy sites at Hunterston A, Chapelcross, Hunterston B and Torness.

Table 6 Summary of credible options for Magnox and EDF Energy wastes

	Magnox waste	EDF Energy AGR waste
1. **GDF disposal**	✓ for English & Welsh sites X for Scottish sites (Scottish policy compliance)	✓ for English & Welsh sites X for Scottish sites (Scottish policy compliance)
2. **Near surface disposal**	✓	✓
3. **In-situ disposal**	✓	✓
4. **LLWR disposal**	X (compliance with WAC)	X (compliance with WAC)
5. **Permitted landfill disposal**	X (compliance with WAC)	X (compliance with WAC)
6. **Treatment to make management easier**	✓	✓
7. **Treatment to minimise volume**	✓	✓
8. **Re-use/ recycling**	✓	✓

2.3.2 Strategic tolerances for Magnox and AGR graphite wastes

An alternative Magnox site restoration scenario for one or more Magnox sites that involved reactor decommissioning prior to GDF availability would necessitate interim storage of such wastes in a suitable storage facility for a period. Depending on the maturity of the technologies involved at the time, such a scenario might result in the treatment and recycling options 6, 7 and 8 being screened out.

2.3.3 Sellafield, RSRL and DSRL graphite wastes

The C-14 content of the Sellafield, RSRL and DSRL graphite wastes result in option 4 LLWR disposal and option 5 Permitted landfill disposal being screened out on the basis that they would not meet current WAC and are highly unlikely to meet future WAC for such facilities[6].

Only the GDF disposal and near surface disposal options are considered to be credible for the WAGR waste (options 1 and 2). In-situ disposal (option 3) is precluded because the reactor wastes have already been generated. The treatment and recycling options (6, 7 and 8) are also not considered to be credible because the waste has been encapsulated within the waste packages.

Sellafield Pile 1 waste is fuel contaminated and consequently the in-situ disposal option has been screened out on practicality grounds. It is considered highly unlikely that such waste would be suitable for recovery for beneficial re-use or recycling even after pre-treatment, so option 8 has also been screened out for Pile 1 waste.

Options 1, 2, 3, 6, 7, and 8 are all considered to be credible for the research reactor wastes to be produced by RSRL and DSRL. It is noted that encapsulation of any of these wastes would foreclose opportunities to apply treatment and recycling options to such wastes at a later stage (options 6, 7 and 8).

Whilst credible, it should be noted that in-situ disposal (option 3) is inconsistent with preferred site end states for some of the research reactors and that as the commencement of final reactor decommissioning approaches the opportunity to implement this option will start to close. This option might be screened out for such sites at some point in the near future (e.g. for RSRL and DSRL research reactors).

A summary of the credible options for Sellafield, RSRL and DSRL wastes is illustrated in Table 7 on the next page.

[6] It is possible that a proportion of such wastes, for example reflector graphite waste surrounding research reactors that may have a relatively low C-14 activity concentration, might meet the WAC for LLWR disposal. Site specific assessments against the LLWR WAC should be undertaken by the site operators to confirm if LLWR disposal is a credible option for a portion of such waste.

Table 7 Summary of credible options for Sellafield, RSRL and DSRL wastes

	Sellafield waste	RSRL waste	DSRL waste
1. **GDF disposal**	✓	✓	X (Scottish policy compliance)
2. **Near surface disposal**	✓	✓	✓
3. **In-situ disposal**	✓ for Pile 2 waste X for WAGR & Pile 1 waste (feasibility)	✓ ? (ability to meet timescales)	✓ ? (ability to meet timescales)
4. **LLWR disposal**	X (compliance with WAC)	X (compliance with WAC)	X (compliance with WAC)
5. **Permitted landfill disposal**	X (compliance with WAC)	X (compliance with WAC)	X (compliance with WAC)
6. **Treatment to make management easier**	✓ for Pile waste X for WAGR waste (feasibility)	✓	✓
7. **Treatment to minimise volume**	✓ for Pile waste X for WAGR waste (feasibility)	✓	✓
8. **Re-use/ recycling**	✓ for Pile waste X for WAGR waste (feasibility)	✓	✓

2.3.4 Strategic tolerances for Sellafield, RSRL and DSRL wastes

Screening against the ability to meet timescales for baseline decommissioning and site restoration plans for a number of the research reactors managed by RSRL and DSRL calls into question the applicability of the in-situ disposal option (option 3) for these graphite wastes as the commencement of decommissioning approaches at these sites. This also applies to the treatment and re-use/ recycling options (options 6, 7 and 8) if the waste is encapsulated, which would effectively foreclose any future opportunity to apply such options.

2.4 Plan for Delivering the Topic Strategy

2.4.1 Magnox and AGR graphite wastes

It is not clear that there is a strategic driver to progress to Gate B (preferred option) for strategy for the management of reactor graphite arising from Magnox and AGR reactor sites at this time, given that final decommissioning will not commence for several decades according to baseline plans.

Further work on the development of strategy for Magnox reactor graphite wastes could be scheduled at the appropriate time to support consideration of alternative site restoration strategies, perhaps undertaking an assessment of preferred options as an input to the site restoration work stream if this work is progressed to consider alternative Magnox decommissioning scenarios.

In terms of supporting R&D –

- There may be a case to undertake further development work to better underpin the Scottish policy of consignment of the waste to an appropriate near surface facility and/or investigate extended storage periods, perhaps to the same level of underpinning as the GDF baseline. This reflects the relatively undeveloped status and underpinning for the Scottish policy option, in comparison with the GDF disposal option. Likewise, further development of the underpinning for the GDF baseline might be warranted.

- There may be merit in seeking to close out the environmental safety case issues outstanding with SEPA following completion of the Graphite Pathfinder Project and to capture the learning from this project relevant to the near surface disposal option for core reactor graphite.

- Contemporary sampling of reactor core graphite for characterisation purposes would enable further comparison with models and increase confidence in the inventory data; such samples could also be subject to laboratory studies to improve understanding of graphite behaviour relevant to various treatment and disposal options.
- Unless significant work on alternative Magnox site restoration strategies that could bring forward the date for the final decommissioning of one or more Magnox reactor sites is initiated, a watching brief might be kept on

the development and maturity of technologies supporting treatment and reuse/ recycling options that might be applied to graphite wastes.

A watching brief should be maintained on wider international developments e.g. CarboWaste, graphite programmes in other countries, etc. EDF Energy plans to review graphite waste management strategies, treatment and disposal options in 2013 in France and the UK, considering potential synergies across the wider EDF group; there may be merit in NDA collaborating with EDF Energy to share experience and lessons learned to date in the development of graphite waste strategy.

2.4.2 Sellafield, RSRL and DSRL wastes

Given the range of waste stream specific considerations that apply to these research reactor waste streams wastes, their relatively low volume as a proportion of the total UK inventory of graphite, and that they comprise a proportion of larger decommissioning waste streams for which strategic decisions will be driven by other considerations, it may be more appropriate for the various SLCs to develop their implementation strategies and plans for the management of such waste at the SLC level rather than progressing to Gate B/ C at NDA level.

For waste streams for which encapsulation is planned, there may be merit in the respective SLCs considering the merits for making a safety case for non-encapsulation of such wastes in order to avoid foreclosing options. Site and waste stream specific considerations will likely determine whether or not there is merit in doing so. Likewise, particularly if encapsulation is not undertaken, consideration should be given to segregating graphite wastes from the wider reactor decommissioning wastes as this would support opportunities to apply treatment and reuse/ recycling options to such waste in the future.

In terms of supporting R&D -

- There is an opportunity to undertake treatment trials on samples of graphite waste which will arise over the medium term from the decommissioning of research reactors. This could contribute toward improved understanding of options 6, 7 and possibly option 8. Such samples could also be subject to behaviour studies to provide information that would support the range of treatment and disposal options.

  The applicability of the results to the much larger and different grade Magnox and AGR graphite waste streams would need to be considered to determine if there is any merit in undertaking such studies.

- There is also an opportunity to trial alternative decommissioning and waste retrieval techniques e.g. nibble and vacuum. This would improve knowledge of graphite retrieval, handling and waste management for this alternative decommissioning technique. Treatment trials could be undertaken on the waste samples that are produced (the waste form may be in a more suitable form for some treatment technologies, such as steam reformation and thermal treatment).

- The planned generation of DFR and DMTR waste streams might provide the opportunity to better develop management arrangements for such wastes to help to better underpin the Scottish policy option.

2.5 Stakeholder Engagement and Forward Communications Plan

The specification for this work was developed with input from the regulatory community.

Regular progress updates have also been provided to TOG participants and to representatives of the IAEA alongside wider updates on NDA's graphite waste strategy programme.

Data review of waste inventory and baseline plans used in this report were sought from EDF Energy, Sellafield Ltd., DSRL and RSRL and input provided has been incorporated within Draft 1 of this paper was forwarded for review by these operators.

Following addressing of comments, it is planned to share this report with TOG participants and regulators for review and comment.

There may be merit in arranging a meeting with regulators and other SLCs to discuss the interim outcome of this work and any work in this area that may be planned in the future. Existing routes should be used as appropriate e.g. the IWM ToG.

A summary position statement is being prepared by the NDA for wider stakeholder comment.

3 Conclusion

This paper establishes the credible options for the long term management of graphite wastes arising from the final decommissioning of reactors. The scope of the paper includes core and reflector graphite wastes arising from the final decommissioning of the Magnox and AGR reactors, and from the Sellafield Ltd., RSRL and DSRL research reactors. There is an established strategy for managing reactor core graphite that is embedded in site lifetime plans and is broadly similar across them, with the vast majority of the inventory from the final decommissioning of the Magnox and AGR reactors not planned to be generated for several decades. As such, there will be frequent opportunities to review the credible options set out in this paper as time progresses. The strategic tolerances to alternative site restoration strategies and GDF availability scenarios are explored in this paper. A high level plan for progressing the topic strategy and options for supporting R&D that there may be merit in undertaking is also described.

This paper identifies a number of potential options for the management of reactor graphite including both direct disposal and pre-disposal treatment options. These options are screened against four criteria for each of the Site Licence Companies (SLCs) within scope. The conclusion of this screening exercise is that it is not currently considered credible to directly dispose of reactor graphite to either the Low Level Waste Repository (LLWR) or to other radioactive waste permitted landfill sites. Opportunities are highlighted for the use of near-term waste arising (for example RSRL and DSRL research reactor graphite) as pathfinder material for core dismantling or treatment trials to inform decisions on the management of larger volume, later arising Magnox, Sellafield and EDF Energy reactor graphite.

4 Recommendations

The following recommendations for further work are made:

(1) The NDA should continue involvement in international work on graphite management to keep a watching brief over developments in graphite management technologies;

(2) An independent review should be undertaken of the NDA funded work which will be reported on in April 2013 on graphite behaviour and characterisation;

(3) The UK Radioactive Waste Inventory graphite radionuclide inventory should be reviewed to take account of the NDA funded work on graphite characterisation.

Opportunities to undertake further R&D to support strategy development in relation to specific licensees are made in Section 2.4.

Appendix A - UKRWI 2010 Inventory Data on Reactor Graphite Wastes from Final Reactor Decommissioning

Site	Waste stream identifier	Waste stream description	Waste type	Stream stock volume (m^3)	Stream future arising volume (m^3)	Total stream volume (m^3)	Graphite raw volume	Stream packaged volume	Graphite packaged volume	Package Type for Graphite Waste	Density (t/m^3)	Graphite Total material mass (t)	% of Graphite in Stream	Comments and baseline assumptions
Magnox reactors														
Berkeley	9A316	Graphite LLW	LLW	0	33	33	33	41	41	4m box (no shielding)	1.25	41	100	Cementitous encapsulation using FSC plant assumed
Berkeley	9A321	Graphite ILW	ILW	0	3121	3121	3121	3858	3858	4m box (no shielding)	1.25	3901	100	Cementitous encapsulation using FSC plant assumed
Bradwell	9B312	Graphite ILW	ILW	0	3025	3025	3025	3739	3739	4m box (no shielding)	1.25	3781	100	Cementitous encapsulation using FSC plant assumed
Bradwell	9B316	Graphite LLW	LLW	0	215	215	215	266	266	4m box (no shielding)	1.25	269	100	Cementitous encapsulation using FSC plant assumed
Calder Hall	2A310	Final Dismantling & Site Clearance : Graphite ILW	ILW	0	3633	3633	3633	7752	7752	4m box (200mm concrete shielding)	1.25	4542	100	Cementitous encapsulation using FSC plant assumed
Chapelcross	2C304	Final Dismantling & Site Clearance : Graphite LLW	LLW	0	6	6	6	7	7	4m box (no shielding)	1.25	8	100	Cementitous encapsulation using FSC plant assumed
Chapelcross	2C311	Final Dismantling & Site Clearance : Graphite ILW	ILW	0	3647	3647	3647	4508	4508	4m box (no shielding)	1.25	4559	100	Cementitous encapsulation using FSC plant assumed
Dungeness	9C312	Graphite ILW	ILW	0	3424	3424	3424	4233	4233	4m box (no shielding)	1.25	4280	100	Cementitous encapsulation using FSC plant assumed
Hinkley Point A	9D312	Graphite ILW	ILW	0	3555	3555	3555	4395	4395	4m box (no shielding)	1.25	4444	100	Cementitous encapsulation using FSC plant assumed
Hinkley Point A	9D316	Graphite LLW	LLW	0	47	47	47	58	58	4m box (no shielding)	1.25	59	100	Cementitous encapsulation using FSC plant assumed
Hunterston	9J301	Final Dismantling & Site Clearance : Graphite ILW	ILW	0	3434	3434	3434	4245	4245	4m box (no shielding)	1.25	4293	100	Cementitous encapsulation using FSC plant assumed
Hunterston	9J313	Final Dismantling & Site Clearance : Graphite LLW	LLW	0	7	7	7	9	9	4m box (no shielding)	1.25	9	100	Cementitous encapsulation using FSC plant assumed
Oldbury	9E315	Final Dismantling & Site Clearance : Graphite LLW	LLW	0	1890	1890	1890	2336	2336	4m box (no shielding)	1.25	2363	100	Cementitous encapsulation using FSC plant assumed
Oldbury	9E319	Final Dismantling & Site Clearance : Graphite ILW	ILW	0	3303	3303	3303	4083	4083	4m box (no shielding)	1.25	4129	100	Cementitous encapsulation using FSC plant assumed
Sizewell	9F312	Graphite ILW	ILW	0	3606	3606	3606	4458	4458	4m box (no shielding)	1.25	4508	100	Cementitous encapsulation using FSC plant assumed
Trawsfynydd	9G311	Final Dismantling & Site Clearance : Graphite ILW	ILW	0	3432	3432	3432	4243	4243	4m box (no shielding)	1.25	4290	100	Cementitous encapsulation using FSC plant assumed
Trawsfynydd	9G316	Final Dismantling & Site Clearance : Graphite LLW	LLW	0	48	48	48	59	59	4m box (no shielding)	1.25	60	100	Cementitous encapsulation using FSC plant assumed
Wylfa	9H311	Final Dismantling & Site Clearance : Graphite ILW	ILW	0	5493	5493	5493	6790	6790	4m box (no shielding)	1.25	6866	100	Cementitous encapsulation using FSC plant assumed
Wylfa	9H315	Final Dismantling & Site Clearance : Graphite LLW	LLW	0	3325	3325	3325	4110	4110	4m box (no shielding)	1.25	4156	100	Cementitous encapsulation using FSC plant assumed
AGR reactors														
Dungeness B	3J313	Decommissioning Stage 3: Graphite ILW	ILW	0	2015	2015	2015	4719	4719	4m box (100mm concrete shielding)	1.25	2519	100	Cementitous encapsulation using FSC plant assumed
Dungeness B	3J317	Decommissioning Stage 3: Graphite LLW	LLW	0	1694	1694	1694	2261	2261	4m box (no shielding)	1.25	2117	100	Cementitous encapsulation using FSC plant assumed
Hartlepool	3K313	Decommissioning Stage 3: Graphite ILW	ILW	0	2534	2534	2534	5935	5935	4m box (100mm concrete shielding)	1.25	3168	100	Cementitous encapsulation using FSC plant assumed
Hartlepool	3K317	Decommissioning Stage 3: Graphite LLW	LLW	0	453	453	453	605	605	4m box (no shielding)	1.25	566	100	Cementitous encapsulation using FSC plant assumed
Heysham	3L313	Decommissioning Stage 3: Graphite ILW	ILW	0	2534	2534	2534	5935	5935	4m box (100mm concrete shielding)	1.25	3167	100	Cementitous encapsulation using FSC plant assumed
Heysham	3L317	Decommissioning Stage 3: Graphite LLW	LLW	0	453	453	453	605	605	4m box (no shielding)	1.25	566	100	Cementitous encapsulation using FSC plant assumed
Heysham 3	3M313	Decommissioning Stage 3: Graphite ILW	ILW	0	2191	2191	2191	5132	5132	4m box (100mm concrete shielding)	1.25	2739	100	Cementitous encapsulation using FSC plant assumed
Heysham 4	3M317	Decommissioning Stage 3: Graphite LLW	LLW	0	654	654	654	873	873	4m box (no shielding)	1.25	818	100	Cementitous encapsulation using FSC plant assumed
Hinkley Point B	3N313	Decommissioning Stage 3: Graphite ILW	ILW	0	1882	1882	1882	4407	4407	4m box (100mm concrete shielding)	1.25	2352	100	Cementitous encapsulation using FSC plant assumed
Hinkley Point B	3N317	Decommissioning Stage 3: Graphite LLW	LLW	0	467	467	467	623	623	4m box (no shielding)	1.25	583	100	Cementitous encapsulation using FSC plant assumed
Hunterston B	4B313	Decommissioning Stage 3: Graphite ILW	ILW	0	1882	1882	1882	4407	4407	4m box (100mm concrete shielding)	1.1	2070	100	Cementitous encapsulation using FSC plant assumed
Hunterston B	4B317	Decommissioning Stage 3: Graphite LLW	LLW	0	467	467	467	623	623	4m box (no shielding)	1.1	513	100	Cementitous encapsulation using FSC plant assumed
Torness	4C313	Decommissioning Stage 3: Graphite ILW	ILW	0	2191	2191	2191	5132	5132	4m box (100mm concrete shielding)	1.1	2410	100	Cementitous encapsulation using FSC plant assumed
Torness	4C317	Decommissioning Stage 3: Graphite LLW	LLW	0	654	654	654	873	873	4m box (no shielding)	1.1	719	100	Cementitous encapsulation using FSC plant assumed
Sellafield reactors and piles														
Windscale	2S308/C	Conditioned WAGR Decommissioning ILW	ILW	610.56	6	616	68	1263	139	WAGR Box	2.73	185	11	Waste is already encapsulated and in interim storage at Sellafield.
Windscale	2S302	Windscale Pile1 and Pile 2 Graphite and Aluminium Ch	ILW	0	2826	2826	2823	6362	6354	Sellafield 3m³ box	1.34	3782	99.9	No graphite annealing planned; Pile 1 waste is fuel contaminated.
RSRL research reactors														
Harwell	5C302	BEPO Research Reactor ILW	ILW	0	363	363	356	941	922	2m box (no shielding)	1.66	591	98	Graphite to be segregated and annealed; conditioning not specified.
Harwell	5C306	Dido Reactor Decommissioning ILW	ILW	0.2	60	60	10	304	49	2m box (200 - 300mm concrete shielding)	6	58	16	Conditioning not specified.
Harwell	5C308	Pluto Reactor Decommissioning ILW	ILW	0	47	47	4	238	21	2m box (200 - 300mm concrete shielding)	6	25	9	Conditioning not specified.
Winfrith	5G304	Dragon Reactor Decommissioning ILW	ILW	0	80	80	27	194	66	2m box (150mm shielding)	0.7	19	33.81	Cementitous encapsulation assumed.
DSRL research reactors														
Dounreay	5B304	Dounreay Fast Reactor ILW	ILW	0	285	285	122	1432	616	4m box (100mm concrete shielding)	2.4	294	43	Cementitous encapsulation using DFR processing plant likely.
Dounreay	5B310	Materials Test Reactor ILW	ILW	0	10	10	2	40	7	4m box (0 - 300mm concrete shielding)	1.24	2	17.92	Cementitous encapsulation likely.

Appendix A Notes

Plans and data for the management of some waste streams have changed since UKRWI 2010 publication (e.g. for RSRL research reactors). Appendix B includes more up to date information based on the most recent plans of the various waste producers.

The stream packaged volume is that stated in UKRWI 2010 for the stated stream, which in some cases include both graphite and other decommissioning wastes. The graphite packaged volume column takes into account the proportion of graphite in the waste stream and consequently is an indication of the packaged graphite volume if segregation of graphite from other wastes were to be undertaken.

Appendix B – Baseline Plans for Graphite Wastes

Magnox reactor sites

Appendix B Table 1 Baseline Plan for Management of Magnox Reactor Graphite

	Current plan
Decommissioning	Assumed to take place 2074 – 2101 Reactor buildings dismantled and sites cleared for next use De-licensing of the sites is assumed
Waste form	Moderator and reflector graphite bricks (ILW & LLW)
Waste retrieval	Assumed to be in air, top entry, graphite bricks retrieved intact
Waste packaging	RWMD 4m stainless steel package (no internal shielding assumed)
Waste conditioning	Encapsulation to RWMD specifications in a cementitous grout assumed using the final site clearance waste management facility
Waste transport and disposal	Transport for disposal in the GDF (in Scotland, waste will be consigned to an appropriate near surface facility)

EDF Energy reactor sites

Appendix B Table 2 Baseline Plan for Management of AGR Reactor Graphite

	Current plan
Decommissioning	Assumed to take place 2102 – 2114 Reactor buildings dismantled and sites cleared for next use De-licensing of the sites is assumed
Waste form	Moderator and reflector graphite bricks (ILW & LLW)
Waste retrieval	Assumed to be in air, top entry, graphite bricks retrieved intact
Waste packaging	RWMD 4m stainless steel package (up to 100 mm internal concrete shielding assumed)
Waste conditioning	Encapsulation to RWMD specifications in a cementitous grout assumed using the final site clearance waste management facility
Waste transport and disposal	Transport for disposal in the GDF (in Scotland, waste will be consigned to an appropriate near surface facility)

Sellafield reactors

Conditioned WAGR decommissioning ILW (2S308/C)

The waste stream comprises graphite blocks and structural components which have been encapsulated in WAGR boxes. The waste comprises 30% by weight mild steel, 1 % stainless steel, 11% graphite and 58% cement grout. The waste stream amounts to a packaged volume of 1263 m^3.

Windscale Pile 1 and Pile 2 graphite and aluminium charge pans (2S302)

The waste stream is made up of graphite blocks, slats and tiles. It will arise upon pile decommissioning which will take place in two phases (2030 – 2034 and 2038 – 2043). The waste stream comprises 99.88% by weight graphite, 0.12% by volume aluminium and 0.002% by volume fuel. Pile 1 graphite is contaminated with fuel.

The graphite waste and aluminium charge pans will be placed into project wastes baskets before being placed into RWMD 4m stainless steel boxes. It is envisaged that four project waste baskets will fit into each 4m box. It is not planned to anneal the graphite or encapsulate the waste in the 4m boxes.

RSRL research reactors

BEPO research reactor graphite (5C302)

UKRWI 2010 states that BEPO research reactor decommissioning is assumed to take place 2019 – 2021.

UKRWI 2010 states that the waste stream comprises 98% by volume graphite moderator and reflector bricks with circa 2% steel plates. The graphite will be segregated and annealed prior to packaging in RWMD 2m stainless steel packages without internal shielding using the planned BEPO waste packaging plant. Conditioning is not specified.

It is understood from RSRL that BEPO decommissioning is now scheduled for 2016 - 2025. The packaging approach for this waste has been changed by RSRL to Robust Concrete Boxes (RCBs) which have features identical to those for a WAGR box. It is understood that graphite wastes will be segregated from metallic waste and encapsulated in the RCBs.

Latest volume estimates differ slightly from UKWRI 2010 data, with 260 m^3 core graphite and 497 m^3 reflector graphite forecast to arise, yielding a total packaged volume of 757 m^3 graphite waste, compared with the UKRWI 2010 derived estimate of 922 m^3 packaged waste for the assumption of packaging in 2 m RWMD boxes.

DIDO reactor decommissioning ILW (5C306)

UKRWI 2010 states that DIDO research reactor decommissioning is assumed to take place 2029 – 2030.

UKRWI 2010 states that the waste stream comprises 32% by volume graphite reflector bricks. The graphite will be packaged in RWMD 2m stainless steel packages with 200 – 300 mm internal shielding using the planned DIDO ILW processing plant. Conditioning is not specified.

It is understood from RSRL that DIDO decommissioning is now scheduled for 2019 - 2026. The packaging approach for this waste has been changed by RSRL to Robust Concrete Boxes (RCBs) which have features identical to those for a WAGR box. It is understood that graphite wastes will be segregated from metallic waste and encapsulated in the RCBs.

Latest volume estimates differ slightly from UKWRI 2010 data, with circa 31 m^3 graphite forecast to arise in total at DIDO and PLUTO, compared with the UKRWI 2010 derived estimate of 70 m^3 packaged waste for the assumption of packaging in 2 m RWMD boxes.

PLUTO reactor decommissioning ILW (5C308)

PLUTO research reactor decommissioning is assumed to take place 2026 – 2028.

UKRWI 2010 states that the waste stream comprises 17% by volume graphite reflector bricks. The graphite will be packaged in RWMD 2m stainless steel packages with 200 – 300 mm internal shielding using the planned PLUTO ILW processing plant. Conditioning is not specified.

It is understood from RSRL that PLUTO decommissioning is now scheduled for 2019 - 2026. The packaging approach for this waste has been changed by RSRL to Robust Concrete Boxes (RCBs) which have features identical to those for a WAGR box. It is understood that graphite wastes will be segregated from metallic waste and encapsulated in the RCBs.

Latest volume estimates differ slightly from UKWRI 2010 data, with circa 31 m^3 graphite forecast to arise in total at DIDO and PLUTO, compared with the UKRWI 2010 derived estimate of 70 m^3 packaged waste for the assumption of packaging in 2 m RWMD boxes.

Dragon reactor decommissioning ILW (5G304)

UKRWI 2010 states that Dragon research reactor decommissioning is assumed to take place 2028 – 2030.

UKRWI 2010 states that the waste stream comprises 33% by volume graphite. The graphite will be packaged in RWMD 2m stainless steel packages with 150 mm internal shielding using the planned Dragon ILW processing plant. The waste will be encapsulated using cementitous grout.

DSRL research reactors

Dounreay fast reactor ILW (5B304)

Dounreay fast reactor ILW is assumed in UKRWI 2010 to be generated from 2019 following start-up of the DFR processing plant.

UKRWI 2010 states that the waste stream comprises 43% by weight graphite. The graphite waste will be packaged in RWMD 4m stainless steel packages with 100mm internal shielding using the planned DFR processing plant. UK RWI 2010 states that it is likely that the waste will be encapsulated.

It is understood from DSRL that graphite waste will be retrieved from DFR from around 2021. The packaging approach for this waste has been changed. The reference strategy is for the graphite blocks to be packaged into Robust Concrete Boxes (RCBs) which have features identical to those for a WAGR box. It is understood that graphite wastes will be encapsulated in the RCBs. This has yet to be underpinned by the Letter of Compliance process. Some dust is anticipated but not quantified as yet, so there is a risk is that it may need a separate conditioning and packaging process. Tooling to take samples of the graphite have been developed and trialled inactively. Analysis of samples will be for radiological and chemical properties, physical/mechanical properties and Wigner energy level. The presence of Wigner energy may be a risk. The raw volume of graphite waste is around 128 m^3 similar to that derived from UKRWI 2010.

Materials test reactor ILW (5B310)

Dounreay materials test reactor ILW is assumed to be generated from 2020.

The waste stream comprises 37% by volume graphite. The graphite waste will be packaged in RWMD 4m stainless steel packages with either no internal shielding or 300mm internal shielding. UKRWI 2010 states that the waste is likely to be encapsulated using a cementitious grout.

It is understood from DSRL that graphite waste will be retrieved from DMTR to an accelerated schedule from around 2017. The packaging approach for this waste has been changed. The reference strategy is for the graphite blocks to be packaged into Robust Concrete Boxes (RCBs) which have features identical to those for a WAGR box. It is understood that graphite wastes will be encapsulated in the RCBs. This has yet to be underpinned by the Letter of Compliance process. Graphite dust may be present but not quantified as yet, so there is a risk is that it may need a separate conditioning and packaging process. Sample cores have already been taken through the reactor vessel including the graphite, this information can be shared with other SLCs. The raw volume of graphite waste is around 7 m^3, compared with an estimate of 2 m^3 that derived from UKRWI 2010.

Appendix C – Risk and Opportunities

Risks

- There is a risk that development work on enabling alternative graphite waste options is not available at the appropriate time to support strategic work on alternative site restoration and decommissioning strategies.
- There is a risk that the supply chain does not invest in R&D to develop alternative treatment options if there is perceived to be no strategic need for near or medium term solutions.
- There is a risk that the regulators do not consider the extent of planned strategic development work and R&D for graphite waste to be adequate.
- There is a risk that the legal, policy, planning or regulatory framework changes, resulting in increased costs and or timescales to implement the preferred options e.g. standards become more restrictive.
- There is a risk that societal views change, impacting upon the options which may be considered to be publicly acceptable.
- There is a risk that the costs and or availability of raw materials and energy change e.g. for manufacture of waste containers, or construction of facilities.
- There is a risk that the availability of the GDF is delayed.
- There is a risk that the marginal cost for consigning graphite waste to the GDF is higher than currently estimated.
- There is a risk that funding will not be available for development of options.
- There is a risk that the presence of graphite dust will require changes to assumed condition and packaging plans.

Opportunities

- There is an opportunity to apply learning gained from other sources such as international experience, Carbowaste and EDF Energy to improve graphite management strategy.
- There is an opportunity to assess alternative options which could be enablers for alternative site restoration strategies e.g. alternative timescales for final decommissioning of one or more Magnox reactors.
- There is an opportunity to undertake R&D on alternative management options which could contribute to the development of treatment technologies at a higher level of the waste hierarchy for such wastes.
- There is an opportunity to assess alternative management options which could contribute to lifecycle cost savings for the NDA and other waste owners.
- There is an opportunity to trial alternative waste management options using research reactor graphite.
- There is an opportunity to improve knowledge of graphite retrieval, handling and waste management approaches during management of research reactor and Sellafield wastes.

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