

# Research and Development

## NDA Technical Baseline Issue 1

October 2016



## Executive Summary

The UK's nuclear energy programme, dating from the post-war years, has left a challenging decommissioning legacy to the country: numerous prototype reactors, fuel-manufacturing plants, research centres, reprocessing plants and 11 power stations. The Sellafield site in west Cumbria houses more than 200 nuclear facilities and 1,000 buildings, making it one of the world's most complex environmental decommissioning challenges. Across the UK many 'never-done-before' decommissioning projects will need to be completed. The Nuclear Decommissioning Authority (NDA) was established under the Energy Act (2004) [1] to ensure that the UK's nuclear legacy sites are decommissioned and cleaned up safely, securely, cost-effectively and in ways that protect people and the environment.

This document provides a high-level overview of the processes and associated technologies used or planned to be used to deliver our mission (i.e. Technical Baseline) and the organisations responsible for their development and implementation. It is based upon NDA estate information available up to the end of August 2016. It is aimed at a technical audience (e.g. experience in Science, Technology, Engineering or Mathematics) who have a general understanding of the challenges associated with decommissioning nuclear facilities. It is designed to provide the technical community, both academic and industrial, with information regarding the approaches and technologies being developed and adopted. It also highlights opportunities that the NDA estate have identified for developing improved technical solutions to their wide range of challenging technical issues.

Research and development (R&D) is fundamental to ensuring the cost-effective delivery of our mission. It generates new knowledge that allows the NDA estate to develop robust technical plans and develops new technologies to deliver the decommissioning activities. New ideas come from a range of sources, including NDA estate employees, the NDA estate's supply chain, related industries (e.g. oil and gas decommissioning) and academia. This document provides information on the existing approaches and allows individuals and organisations to identify the benefits associated with their new approaches and technologies compared with the existing situation.

The Technical Baseline is structured around NDA's four driving Strategic Themes:

- Nuclear Materials;
- Spent Fuels;
- Integrated Waste Management; and
- Site Decommissioning & Remediation.

Key areas of significant future R&D that have been identified by the NDA estate include:

- Treatment, reuse and disposal of plutonium;
- Geological disposal of waste;
- Management of legacy wastes and in particular their retrieval, treatment, packaging and disposal;
- POCO and treatment associated with decommissioning;
- Characterisation of ground, groundwater, facilities and waste; and

- *Ex situ* and *in situ* treatment of ground and groundwater.

The timing and scale of these R&D needs varies. For example, R&D associated with management of legacy waste is ongoing whereas the majority of R&D needs associated with *ex situ* and *in situ* treatment of ground and groundwater are at Sellafield and significantly in the future (typically after 2025).

Significant technology opportunities have also been identified. The implementation time for the technology opportunities varies considerably. For example, there is a relatively short timescale for implementation of any technology opportunities for reprocessing NDA's spent fuels whereas technology opportunities associated with decommissioning the Sellafield site will exist for at least 50 years.

Delivery of the R&D is through a variety of mechanisms including:

- R&D contracted by the NDA estate (e.g. SLC Framework Contracts, NDA's Direct Research Portfolio);
- Open calls (e.g. NDA's annual Ph.D. Bursary Call);
- Themed calls (e.g. Energy Game Changer call in collaboration with Innovate UK and support from Sellafield Ltd); and
- R&D funded by the supply chain to develop a product or service for sale to the NDA estate.

Future versions of this document will include any changes to the Technical Baseline and highlight the impact of R&D on the delivery of the NDA's mission. If you have any feedback on the current Technical Baseline or the report itself, please send it to [research@nda.gov.uk](mailto:research@nda.gov.uk).

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## 1 Introduction

The UK's nuclear energy programme, dating from the post-war years, has left a challenging decommissioning legacy to the country: numerous prototype reactors, fuel-manufacturing plants, research centres, reprocessing plants and 11 power stations. The Sellafield site in west Cumbria houses more than 200 nuclear facilities and 1,000 buildings, making it one of the world's most complex environmental decommissioning challenges. Across the UK many 'never-done-before' decommissioning projects will need to be completed. The Nuclear Decommissioning Authority (NDA<sup>1</sup>) was established under the Energy Act (2004) [1] to ensure that the UK's nuclear legacy sites are decommissioned and cleaned up safely, securely, cost-effectively and in ways that protect people and the environment. Since our establishment significant progress on decommissioning the civil nuclear legacy has been made [2]. Recent technical highlights include:

- Reduced radioactivity levels by 70 per cent in Sellafield Ltd's Pile Fuel Storage Pond (PFSP), through removal of the entire bulk stock of metal fuel.<sup>2</sup>
- For the very first time, begun removing bulk quantities of radioactive sludge from Sellafield Ltd's First Generation Magnox Storage Pond (FGMSP).<sup>3</sup>
- Completed the removal of spent fuel from the nuclear power station at Magnox Ltd's Oldbury site, thus removing 99 per cent of the radioactive hazard from the site.<sup>4</sup>
- Decontaminated more than 10,000 m<sup>2</sup> of walls, floors and ceilings at Magnox Ltd's Bradwell site.<sup>5</sup>
- Made good progress on transferring nuclear material from Dounreay to Sellafield, where it will be consolidated with similar material in safe, secure storage until a long-term disposal route is agreed.<sup>6</sup>
- Made safe the last of the higher activity liquid waste produced during Dounreay Fast Reactor (DFR) fuel reprocessing.<sup>7</sup>
- Continued to divert material away from the Low Level Waste Repository (LLWR) to alternative treatments such as recycling, combustion and use of licensed landfill sites, bringing the total diverted to 89 per cent of material, reducing demand for space at the facility.

Under the Energy Act NDA is required to promote and, where necessary, carry out research in relation to its primary function of decommissioning and clean-up. Our Research & Development (R&D) strategic objective [3] is therefore to ensure that the delivery of the NDA's

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<sup>1</sup> Many abbreviations are used within the nuclear decommissioning industry. A full list of abbreviations used in this report is included in Section 8.

<sup>2</sup> 'Nuclear clean-up milestone makes Sellafield safer', NDA website, 2016

<sup>3</sup> 'Sludge removal marks significant step in Sellafield clean-up', Sellafield Ltd website, 2015

<sup>4</sup> 'Last fuel leaves Oldbury site', NDA website, 2016

<sup>5</sup> 'Decontamination milestone reached at Bradwell', NDA website, 2016

<sup>6</sup> 'Dounreay fuel arrives safely at Sellafield', NDA website, 2015

<sup>7</sup> 'Dounreay meets target for liquid hazard reduction', DSRL website, 2016

mission is technically underpinned by sufficient and appropriate R&D. Our strategy is that, where possible, R&D is undertaken by our Site Licence Companies (SLCs), subsidiaries and their supply chain. Where necessary the NDA will directly maintain a strategic R&D programme. Overall strategic coordination is provided by us.

This report provides a high-level overview of the processes and associated technologies used or planned to be used to deliver the NDA's mission i.e. Technical Baseline. It is based upon NDA estate information available up to the end of August 2016. It therefore provides the supply chain with information about areas where the NDA estate will require R&D to develop the Technical Baseline and areas where the NDA estate has identified opportunities for R&D to improve our current Technical Baseline. Through a better understanding of our current approach the supply chain may also be able to identify further opportunities to improve our Technical Baseline and new commercial products and services that would improve our Technical Baseline.

## 1.1. Delivery of R&D

The main NDA estate organisations associated with the delivery of the R&D to technically underpin our mission are:

- Dounreay Site Restoration Ltd (DSRL);
- Low Level Waste Repository Ltd (LLWR);
- Magnox Ltd (MxL);
- Nuclear Decommissioning Authority (NDA);
- Radioactive Waste Management Ltd (RWM); and
- Sellafield Ltd (SL).

A large proportion of the R&D is carried out by their supply chain, which includes national laboratories, large technical organisations and a wide range of Small and Medium-sized Enterprises (SMEs).

Delivery of the R&D is through a variety of mechanisms including:

- R&D contracted by the NDA estate (e.g. SLC Framework Contracts, NDA's Direct Research Portfolio);
- Open calls (e.g. NDA's annual Ph.D. Bursary Call);
- Themed calls (e.g. Energy Game Changer call co-funded with Innovate UK with support from Sellafield Ltd); and
- R&D funded by the supply chain to develop a product or service for sale to the NDA estate.

Within the NDA estate, a gated approach to sanctioning which specifically addresses technology and engineering aspects is used. Technology Readiness Levels (TRLs) are used to ensure a consistent system for assessing technology maturity[4].

To facilitate communication within the NDA estate's technical community, the Nuclear Waste and Decommissioning Research Forum (NWDRF) has been established. This forum, along

with a number of Working Groups that it has established, aims to identify and share common R&D needs, risks and opportunities, share good practice and work collaboratively on innovation. The NDA and our estate also attend other key nuclear R&D meetings (e.g. Nuclear Innovation and Research Advisory Board (NIRAB), Low Carbon Innovation Coordination Group (LCICG) – Nuclear Sub-group) to ensure opportunities for collaboration are maximised and the potential for duplication is reduced.

### 1.2. Construction of Technical Baseline Report

The SLCs inform the NDA of their individual Technical Baselines through the Technical Baseline and underpinning Research and Development (TBuRD) documents [5]. The SLC supplied information when combined with NDA’s Strategy [3] and the associated NDA strategic R&D programme [6] provides the overall Technical Baseline (Figure 1).

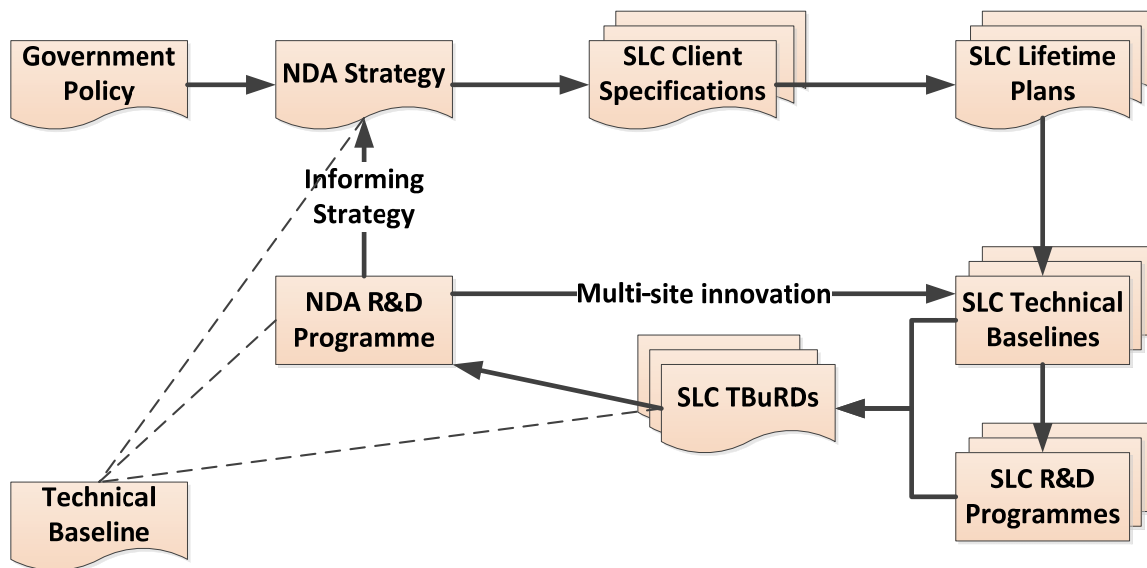
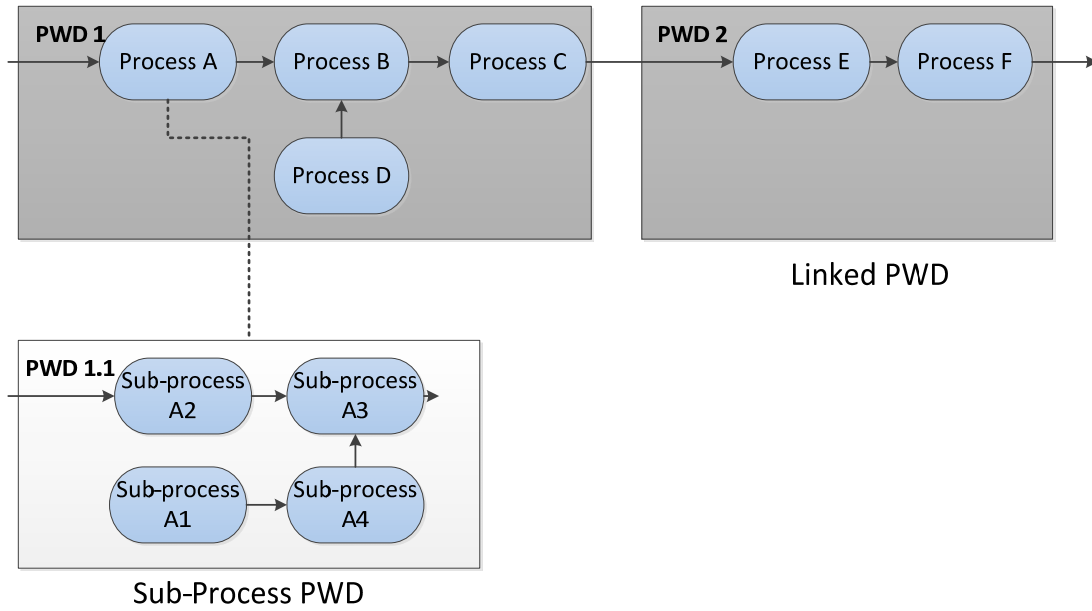


Figure 1: Construction of Technical Baseline

The key components of the TBuRD documents with respect to the Technical Baseline are the Process Wiring Diagrams (PWDs), R&D Table and Annual Technical Report (ATR).

SLC PWDs are a high-level overview of the systems or activities that make up the SLC’s overall programme, highlighting key interactions between different systems. Site or operating unit PWDs are a visual representation of the processes and associated technologies for a particular system within an SLC’s programme. They highlight the flow of material through processes or system elements, the current maturity of the associated technology and identified R&D tasks. A complex activity or system may be built up of multiple, linked PWDs, often with particularly complex processes broken down into simpler processes in a separate sub-process PWD (Figure 2). An example of a site PWD is given in Figure 3 and an example of an operating unit PWD is given in Figure 4.



**Figure 2:** Structure of linked and sub-process PWDs



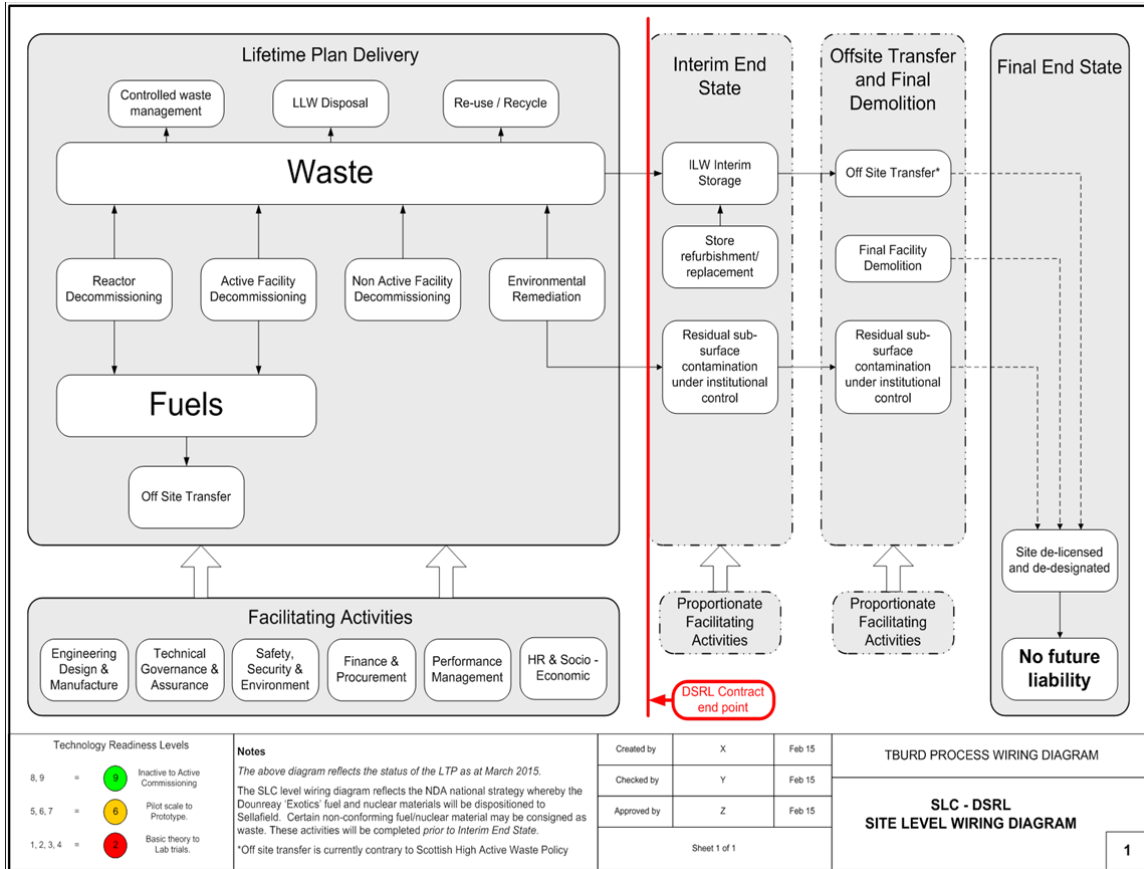
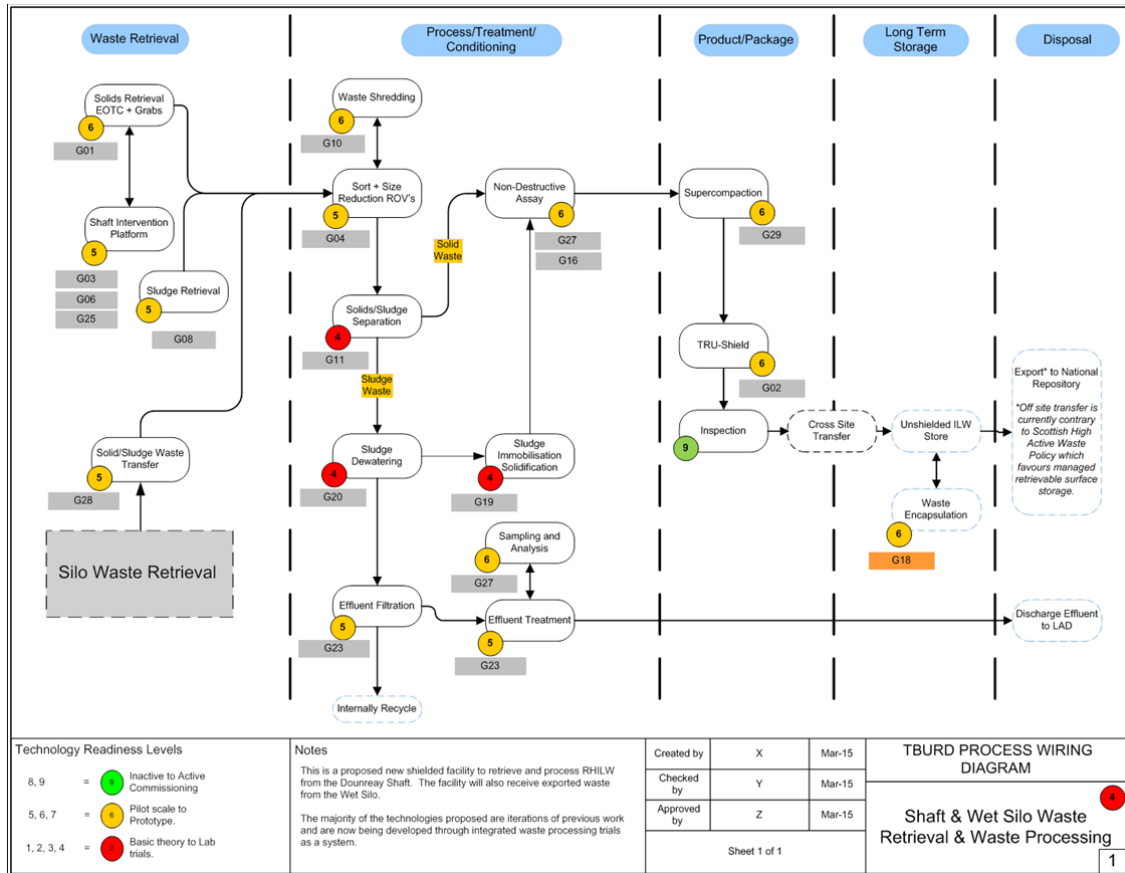


Figure 3: Example of a site PWD – DSRL



**Figure 4:** Example of an operating unit PWD – Shaft & Silo Waste Retrieval & Waste Processing at DSRL

The R&D Table is a spreadsheet containing a wide variety of information (e.g. timing, cost, target technical maturity) on the R&D tasks that will underpin the SLC's Technical Baseline. The R&D Table is linked to PWDs through the use of common R&D identification numbers.

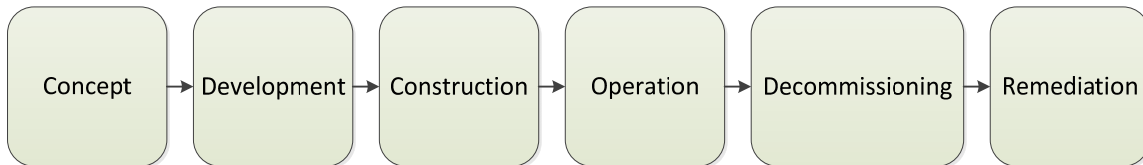
The ATR is a statement of any changes to the SLC's technical governance and assurance arrangements, significant changes to the SLC Technical Baseline, SLC R&D successes and challenges and annual R&D expenditure (current and future).

Together the PWDs, R&D Table and ATR enable the NDA to understand the processes and associated technologies that each SLC is using or plans to use to deliver their individual missions. They enable us to monitor the progress that the SLC is making to underpin its Technical Baseline. They also enable us to understand the overall scale of the SLC R&D programme and identify common issues or gaps across the NDA estate.

Where a technology is operational, the SLC TBuRD documents include any technical opportunities that the SLC is progressing to improve their individual Technical Baseline.

Where the technology has been selected but is not yet fully operational, the SLC TBoRD documents include the current maturity of the technology using TRLs [4] and the R&D necessary to technically underpin its deployment and enable delivery of their individual missions. Where no technology has yet been selected, the SLC TBoRD documents include information on the high-level processes that will be necessary to deliver their individual missions.

Every SLC activity or system has a life cycle. A typical life cycle for a nuclear decommissioning activity is given in Figure 5. Many of our SLCs have interacting activities at different life cycle stages and progress to the next life cycle stage is often dependent upon the progress of multiple other activities. This interconnected nature increases the complexity of the overall programme.



**Figure 5:** Typical life cycle stages of nuclear decommissioning activity

The NDA Technical Baseline could be categorised and sub-categorised in a number of different ways (e.g. by delivery organisation, by technology status). However, to best show how the overall programme aligns with NDA's Strategy, it has been categorised by our four driving Strategic Themes and further sub-categorised by Strategic Topic where necessary (Table 1).

There is considerable interaction between the different Strategic Themes and Strategic Topics. For example, the management of Spent Fuels generates Nuclear Materials and Radioactive Waste through reprocessing using facilities that will ultimately be subject to Decommissioning. Ultimately Site Decommissioning and Remediation is the driving theme supported by Integrated Waste Management with the need to manage Spent Fuels and Nuclear Materials as an early stage of the overall mission.






Strategic Theme	Strategic Topic
<b>Spent Fuels</b> - defines our approach to managing the diverse range of spent nuclear fuels for which we are responsible	Spent Magnox Fuel
	Spent Oxide Fuel
	Spent Exotic Fuel
<b>Nuclear Materials</b> - defines our approach to dealing with the inventory of uranics and plutonium currently stored on some of our sites	Plutonium
	Uranics
<b>Integrated Waste Management</b> - considers how we manage all forms of waste arising from operating and decommissioning our sites, including waste retrieved from legacy facilities	Radioactive Waste
	Liquid and Gaseous Discharges
	Non-Radioactive Waste
<b>Site Decommissioning &amp; Remediation</b> - defines our approach to decommissioning redundant facilities and managing land quality in order that each site can be released for its next planned use	Decommissioning
	Land Quality Management
	Site Interim and End States
	Land Use

**Table 1:** Strategic Themes and associated Strategic Topics [3]

For each area, a high-level PWD is included in this report:

- Figure 8 and 9 – PWDs for spent Magnox fuel;
- Figure 11 and 12 – PWDs for spent oxide fuel;
- Figure 14, 16 and 18 – Example PWDs for spent exotic fuel;
- Figure 20 – PWD for plutonium;
- Figure 22 – PWD for uranics;
- Figure 28, 35, 38 and 39 – PWDs for integrated waste management; and
- Figure 42 – PWD for site decommissioning and remediation.

For these high-level PWDs the process flow is broken down into the key process steps linked together to indicate the flow of material and any decision points. The colour of each box indicates the amount of R&D required to bring that process to full operation (Figure 6). The colour of the box was determined through a combination of information provided in the latest SLC TBUrd documents and discussions with the relevant NDA Strategic Authorities.

	Input or Output
	Existing technology in place that meets requirements
	Small amount of R&D required – 0-5 yrs and/or <£5M
	Medium amount of R&D required – 5-10 yrs and/or >£5M
	Large amount of R&D required – >10 yrs and/or >£10M

**Figure 6:** Colour coding used for high-level PWDs included in Technical Baseline report

For each area, a commentary is provided that highlights relevant historical information, the technology used, the relevant delivery organisations and key technology opportunities for the supply chain.

## 2. Spent Fuels

### 2.1. Spent Magnox Fuel

The Magnox reactors were the first generation of commercial nuclear power stations to operate in the UK. All of the twenty six reactors are no longer operating, with Reactor 1 at Wylfa stopping at the end of 2015.<sup>8</sup> Only two sites are left to defuel, Calder Hall and Wylfa, with the remainder having transferred their spent fuel to Sellafield for reprocessing. At Sellafield Ltd in the Fuel Handling Plant (FHP), the spent Magnox fuel is cooled further in water, decanned using remotely operated machinery and then reprocessed in the Magnox Reprocessing Plant. This is achieved by dissolving the spent fuel in nitric acid and extracting the uranium and plutonium streams using a solvent extraction process involving mixer-settler contactors. Following concentration and conversion to the oxide form the main outputs from the Magnox reprocessing process are plutonium oxide and uranium oxide along with a variety of radioactive wastes (e.g. fuel cladding and fission products in nitric acid).



**Figure 7:** Aerial view of the Wylfa Magnox power station

As of March 2016 there remains less than 2,100 tU of Magnox fuel to reprocess. Reprocessing of spent Magnox fuel has been the preferred approach because of Magnox fuel's susceptibility to corrosion when stored for long periods in water. Magnox reprocessing operations began in 1964 and the facility is therefore relatively old. Gradual loss of performance or sudden, acute failure would require a different approach and a contingency

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<sup>8</sup> 'The last Magnox power station in the world, Wylfa, stopped generating electricity on 30 December 2015.', Magnox Ltd website, 2015

Technical Baseline has therefore been developed. This contingency approach involves drying the wetted Magnox spent fuel followed by interim dry storage and ultimately disposal in a Geological Disposal Facility (GDF). The development of drying technology to manage wetted spent Magnox fuel is now at an advanced stage and there is high confidence that this option is deployable if required.

When Magnox reprocessing operations cease (current estimate is December 2020) there are likely to be relatively small amounts of fuel left over to manage. Projections of this inventory range from a few tonnes to a few hundred tonnes of fuel depending on a number of factors including reprocessing performance and the amounts of fuel recovered from legacy facilities. Further R&D is required to treat this fuel, so that any remaining fuel can be safely and cost-effectively managed to the point of disposal.

Once defueled the reactors are covered by the Site Decommissioning and Remediation Theme. Similarly, once Magnox reprocessing has completed the facilities are covered by the Site Decommissioning and Remediation Theme.

### Relevant organisations

MxL:	All Magnox reactors with the exception of Calder Hall. Only Wylfa of the MxL reactors still has fuel.
SL:	Calder Hall, which is partially defuelled; Reprocessing of Magnox spent fuel. Dry storage of spent Magnox fuel – Contingency
RWM:	Disposal of spent Magnox fuel – Contingency
NDA:	Strategic decisions regarding the most appropriate time to cease Magnox reprocessing operations.

### Technology Opportunities

Magnox spent fuel management is an established operation that is nearing completion. There is therefore limited opportunity to improve the existing technology. Due to the ageing condition of the reprocessing facilities there are some opportunities for improved characterisation technologies that would provide Sellafield Ltd with a better understanding of the condition of the reprocessing facility. Again as operations are nearing completion, there is only a limited timeframe for any new technologies to be used.

There are opportunities to develop technologies to treat the small amounts of fuels left over once Magnox reprocessing operations cease. Further technologies to dry store and/or immobilise legacy Magnox fuels continue to be developed as part of the programmes to manage materials held within Legacy Ponds and Silos (LP&S) at Sellafield.

Process Wiring Diagrams

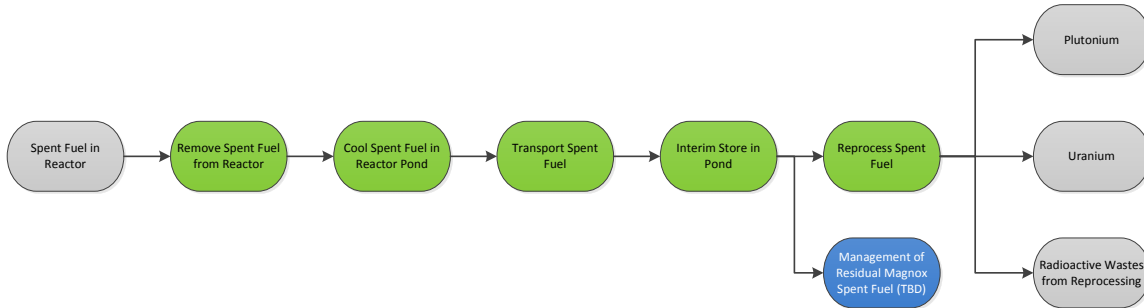


Figure 8: Baseline PWD for spent Magnox fuel

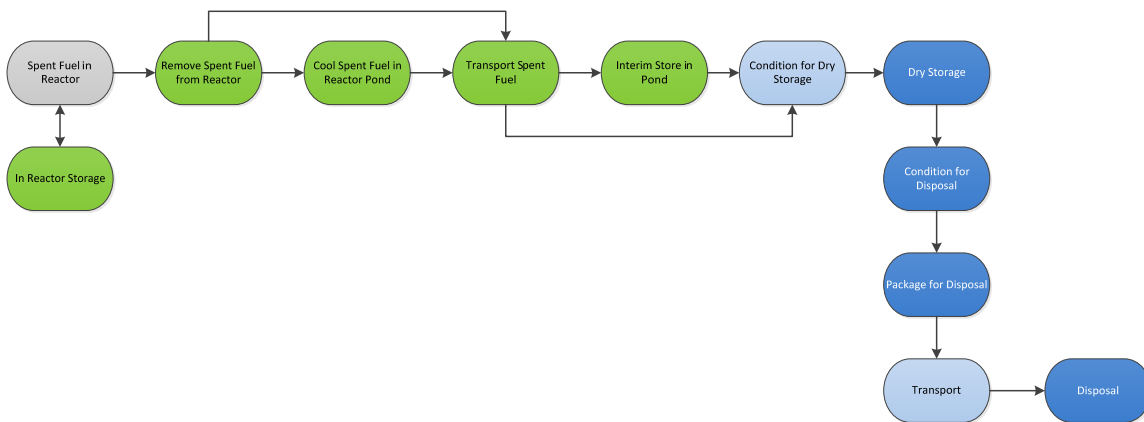


Figure 9: Contingency PWD for spent Magnox fuel

2.2 Spent Oxide Fuel

There are currently seven Advanced Gas-cooled Reactor (AGR) power stations operating in the UK. These reactors are owned by EDF Energy (EDFE) and NDA is contractually committed to receive and manage all of the spent fuel arising from these reactors. EDFE has publicly declared its intention to operate these stations for as long as it is safe and economic to do so and to seek significant life extensions for its AGR reactors. NDA must therefore maintain the capability to receive and manage spent oxide fuel until the late 2020s and potentially beyond. The current approach is for the spent oxide fuel to be transferred to Sellafield, further cooled in a storage pond, decanned using remotely operated machinery and then reprocessed in the Thermal Oxide Reprocessing Plant (THORP). This is achieved by dissolving the spent fuel in nitric acid and extracting the uranium and plutonium streams using a solvent extraction process involving both pulsed columns and mixer-settler contactors. Following concentration and conversion to the oxide form the main outputs from the THORP reprocessing process are plutonium oxide and uranium oxide along with a variety of radioactive wastes (e.g. fuel cladding and fission products in nitric acid).





**Figure 10:** The Thermal Oxide Reprocessing Plant (THORP) at Sellafield

In 2012 NDA confirmed that its preferred strategy for managing the spent oxide fuel and small amounts of overseas origin Light Water Reactor (LWR) fuels currently scheduled for reprocessing at Sellafield through THORP was to complete the contractual commitments and then to close THORP [7]. The remaining spent oxide fuel would then be managed, at least for 20 years, through pond storage. For some of these overseas origin fuels it will not be economic or not possible to reprocess them before the closure of THORP. The agreed approach for these fuels is that they should be retained in the UK and that products and wastes allocated and, where appropriate, returned to customers in line with contractual commitments. The approach of pond storage of spent oxide fuel is based on the considerable operational experience and technical knowledge base which Sellafield Ltd has accumulated over 30 years of managing spent oxide fuel. Further R&D is required to underpin the full duration of wet storage that is possible for these fuels, to develop an alternative long-term storage option to wet storage such as dry storage and to technically underpin the disposal of the fuel. If in the future the economics of spent fuel recycling were to change, due to pressures with uranium supply or concerns over energy security, then the spent oxide fuel could be removed from storage and reprocessed if a suitable facility was available.

Once THORP has completed its contractual reprocessing commitments the facility and the associated infrastructure not essential to pond storage of spent oxide fuels are covered by the Site Decommissioning and Remediation Theme.

### Relevant Organisations

- NDA: Strategic decisions regarding the most appropriate duration for wet storage of spent oxide fuels.
- RWM: Disposal of spent oxide fuel.
- SL: Reprocessing of spent oxide fuel and following closure of THORP long-term storage of spent oxide fuel followed by preparation for disposal.

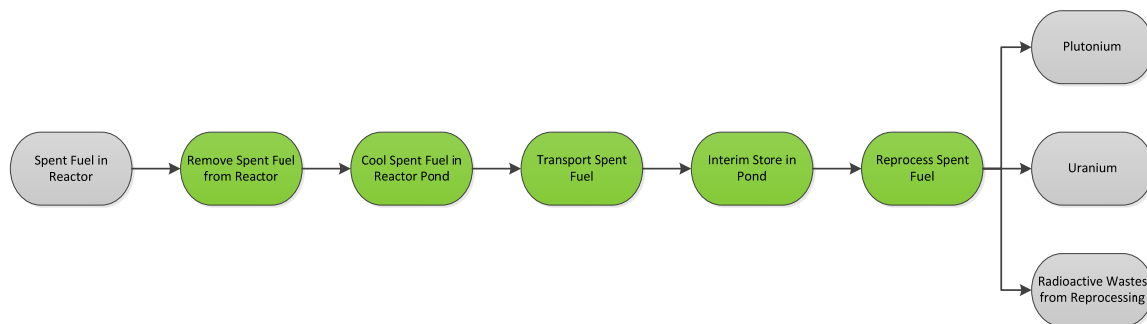
**Technology Opportunities**

Oxide spent fuel management is an established operation that is nearing completion. There is therefore limited opportunity to improve the existing technology. Due to the ageing condition of the reprocessing facilities there are some opportunities for improved characterisation technologies that would provide Sellafield Ltd with a better understanding of the condition of the reprocessing facility. Again as operations are nearing completion, there is only a limited timeframe for any new technologies to be used.

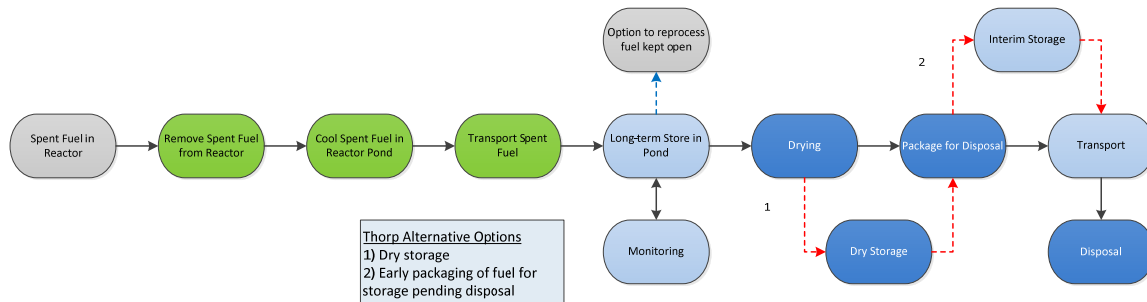
Pond storage of spent oxide fuel is planned for a significant period. Technologies that improve our existing approach to treating pond water are therefore of interest. Technologies that monitor spent oxide fuel and associated pond furniture under wet storage conditions will be required. Existing approaches focus on monitoring of the pond water and *ex situ* characterisation of the spent oxide fuel and pond furniture. *In situ* technologies that monitor the precursors of spent oxide fuel corrosion are of particular interest.

In the longer term technologies associated with drying, storage and disposal of spent oxide fuel are of interest to us.

**Process Wiring Diagrams**



**Figure 11:** Pre-closure of reprocessing in THORP PWD for spent oxide fuel



**Figure 12:** Post-closure of reprocessing in THORP PWD for spent oxide fuel

### 2.3 Spent Exotic Fuel

In addition to the bulk Magnox and oxide fuels we also manage a smaller inventory of non-standard fuels, commonly referred to as 'exotics'. These fuels include metallic, oxide and carbide materials. They are a legacy we inherited from earlier nuclear industry activities such as the development of research, experimental and prototype fuels and reactors.

Examples of exotic fuel types include fuels arising from the Dounreay Fast Reactor (DFR), the Prototype Fast Reactor (PFR) at Dounreay, the Dragon reactor at Winfrith and the Steam Generating Heavy Water Reactor (SGHWR) at Winfrith.

Some, but not all, of these fuels share common characteristics with our bulk Magnox and oxide fuels and can be managed in much the same way, for example through reprocessing. However, although much smaller in quantity than our bulk fuels, some of the exotic fuels present their own particular management challenges due to their diverse and sometimes unique properties. Currently all of our exotic fuels are being safely and securely stored while plans for their final disposition are implemented or developed. In some cases specifically tailored solutions for their long-term management and disposition will be required.

- **Dounreay Fast Reactor (DFR) Fuel** – The experimental fast breeder reactor<sup>9</sup> at Dounreay led British research and development of nuclear energy during the 1950s and 60s. Housed inside a steel sphere, it was built between 1955 and 1958 to test the breeder reactor concept. In 1962, it became the first fast reactor in the world to provide electricity to a national grid. It closed down in 1977. The fuel and a portion of the breeder material were removed from the reactor following its closure. The DFR breeder material that was removed from the reactor following closure was stored on site and has now been transported to Sellafield. One experimental assembly and the remaining breeder material in the reactor will be removed, packaged and transported to Sellafield for reprocessing alongside Magnox spent fuel.

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<sup>9</sup> A breeder reactor is a nuclear reactor that generates more fissile material than it consumes. A fast breeder reactor utilises fast rather than thermal neutrons to split the fissile atoms of the fuel.



Figure 13: Dounreay Fast Reactor (DFR)

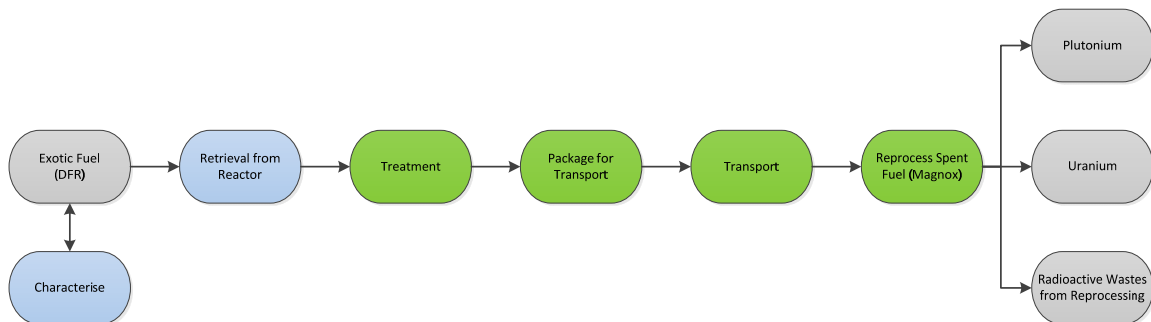


Figure 14: PWD for DFR fuel

- Prototype Fast Reactor (PFR) Fuel** – Dounreay's PFR was the second and last grid connected fast reactor to be built in the UK. It followed the successful demonstration of fast reactor technology by the DFR. Construction commenced in 1968 and PFR went critical in 1974. PFR had the dual role of providing power to the national grid and offering unique R&D facilities. The UK decided in the late 1980s that there was no immediate need to further develop fast reactor technology and discontinued the programme. The reactor closed in 1994 and it was de-fuelled between 1994 and 1996. The fuel which is currently being stored at Dounreay will be treated (e.g. simple size

reduction), packaged and transported to Sellafield for long-term storage whilst a plan for its final disposition is developed.<sup>10</sup>



Figure 15: Prototype Fast Reactor (PFR) at Dounreay

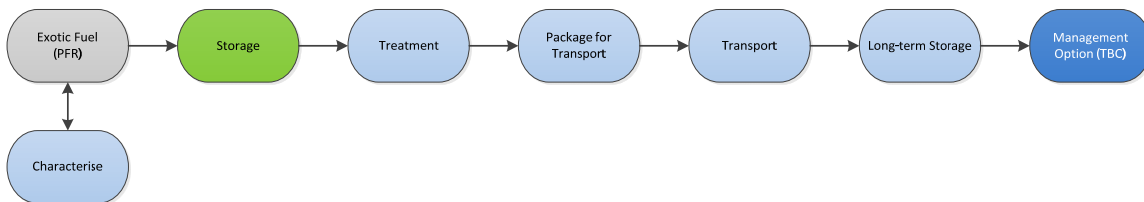


Figure 16: PWD for PFR fuel

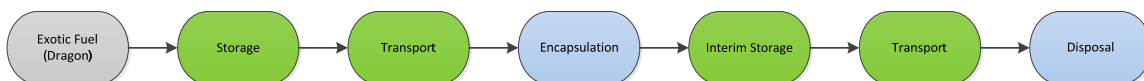
- Dragon Reactor Fuel** – The Dragon reactor was a 20 MW high-temperature helium-cooled experimental reactor located at Winfrith, and was operated from June 1965 to September 1975. The properties of the Dragon reactor spent fuel vary significantly from other commercial and experimental fuels. The fuel was heavily irradiated, has a high fissile inventory and its design makes it difficult to reprocess. It was originally placed into mild steel Full Length Containers and stored in the Dragon Fuel Store at Winfrith. The fuel was repackaged into high integrity stainless steel Third Length Containers (TLCs) before it was transferred from Winfrith to Harwell between 2002 and

<sup>10</sup> 'Dounreay fuel arrives safely at Sellafield', Sellafield Ltd website, 2015

2004, where it is currently stored dry. The planned approach for this fuel is to transport the TLCs to Sellafield, entomb them in concrete within 500l drums (Magnox Encapsulation Plant (MEP)) and interim store in the Encapsulated Product Stores (EPS) awaiting disposal to the GDF.



**Figure 17:** Dragon reactor at Winfrith undergoing decommissioning



**Figure 18:** PWD for Dragon reactor fuel

**Relevant Organisations**

- DSRL: Management of specific exotic fuels typically through transfer to Sellafield.
- MxL: Management of specific exotic fuels typically through transfer to Sellafield.
- NDA: Strategic decisions regarding the most appropriate management option for specific types of exotic of fuels.
- RWM: Disposal of exotic fuels where appropriate.



SL: Management of specific exotic fuels typically through combination of reprocessing, storage and/or treatment for disposal.

### Technology Opportunities

All of our exotic fuels are being safely and securely stored while plans for their final disposition are implemented or developed, as appropriate. Development of these plans will be supported by research in the following areas:

- Improved technical options for long-term storage of specific exotic fuels.
- Improving our understanding of potential long-term behaviours of additive materials and exotic fuel claddings under wet or dry storage conditions.
- Identifying functional requirements and treatment technologies to facilitate storage and final disposition (e.g. disposal) of exotic fuels.

Technologies associated with monitoring, storage, treatment and disposal of spent exotic fuels are therefore of interest.

## 3 Nuclear Materials

### 3.1 Plutonium

On completion of spent fuel reprocessing operations there will be around 140 tonnes of civil separated plutonium stored safely and securely in the UK. The vast majority of this material is held at Sellafield, with a relatively small amount currently held at Dounreay arising from historic activities at this site.

In 2011 the UK government proposed a preliminary policy view to pursue reuse of UK civil separated plutonium as Mixed Oxide fuel (MOX). This would see the vast majority of UK plutonium converted into fuel for use in civil nuclear reactors. The remaining plutonium that was unsuitable for conversion into MOX would be immobilised and treated as waste for disposal. In addition, the UK government decided that overseas owned plutonium in the UK, which remains the responsibility of the owners, could be managed alongside UK plutonium or transferred to UK ownership subject to acceptable commercial terms.

Whilst reuse of plutonium is the preferred policy position there is currently an insufficient understanding of the options to confidently move into implementation and NDA is continuing to work with technology suppliers, utilities and UK government to underpin reuse options. Three reuse options are currently being evaluated: 1) MOX in light water reactors; 2) CANDU MOX (CANMOX) fuel in Enhanced CANDU 6 reactors (EC6) and 3) sodium bonded U/Pu/Zr metal fuel in 2 C-PRISM type reactors [8]. Research on treatment technologies to extend the amount of plutonium that may be reused may also be beneficial.

The NDA continues to fund technology development for the immobilisation of plutonium for the small amount of plutonium that is not suitable for reuse and as an alternative strategy in the event that reuse cannot be successfully implemented in line with UK government requirements. The technology being investigated is Hot Isostatic Pressing (HIP) which uses the simultaneous application of pressure and temperature to produce a ceramic waste form of high quality and durability inside a steel can. RWM are researching the criticality safety of plutonium disposal as well as specific studies on wastefrom evolution.

In the meantime, the plutonium stocks will continue to be safely and securely stored on NDA sites in suitable facilities in line with regulatory requirements. The plutonium stocks currently held at Dounreay will be consolidated at Sellafield. This will require treatment at Dounreay followed by transport to Sellafield. Ultimately this means that all significant stocks of civil plutonium will be stored at Sellafield (e.g. Sellafield Product and Residue Store (SPRS) – a passive-cooled, high security storage facility on the Sellafield site). The biggest technical challenges to extended storage at Sellafield have been identified as pressurisation and corrosion of some types of storage cans. Corrosion in some stores may also be an issue. To address the storage can issue it is planned to heat treat and/or re-can the material at Sellafield in the SPRS Retreatment Plant (SRP). A programme for monitoring for signs of corrosion in cans and buildings is also underway.





**Figure 19:** Safe storage of plutonium at Sellafield

#### **Technology Opportunities (0 – 10 yrs)**

With regard to storage of plutonium, Sellafield Ltd is developing and validating thermal models for its stores; furthering its knowledge of can pressurisation mechanisms and developing technologies to characterise cans and their contents *in situ* or in a laboratory. This information will be used to underpin the schedule and timing of re-treatment. Sellafield Ltd is also monitoring its stores for signs of corrosion and furthering its understanding of the impact of corrosion on store performance. This information will be used to determine whether any modifications to store operating conditions are required and underpin any design modifications to the planned extensions to SPRS. Technologies for monitoring waste packages and stores that improve upon existing approaches are therefore of interest.

With regard to treatment of plutonium for extended storage, Sellafield Ltd plans, where possible, to base the process on existing technologies. Sellafield Ltd is planning development work to underpin the treatment process operating conditions for the full range of materials that must be treated.

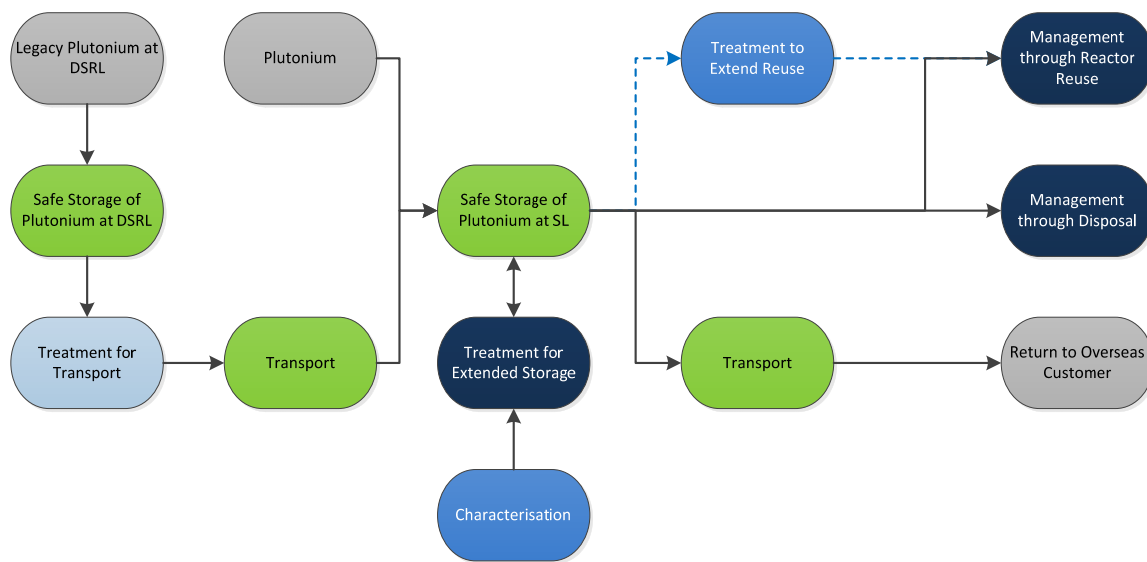
NDA is continuing to research management options for plutonium, focusing on the three reuse options as well as disposal. Our research will underpin strategic decisions and will involve furthering our understanding of the technologies associated with fuel manufacture, reactor design and operation and disposal of the resultant spent fuel and any plutonium unsuitable for reuse. There may also be some research into technologies to extend the amount of plutonium that is suitable for reuse.

DSRL is completing its existing work and there are therefore limited new technology opportunities.

**Relevant Organisations**

- DSRL: Storage, treatment and transport of plutonium.
- NDA: Strategic decisions regarding plutonium management options.
- RWM: Disposal of plutonium.
- SL: Treatment and extended storage of plutonium

**Process Wiring Diagrams**



**Figure 20:** PWD for plutonium

**3.2 Uranics**

Uranics are materials containing uranium which have been produced from fuel cycle operations such as enrichment, fuel fabrication and reprocessing since the 1950s.

We manage significant stocks of uranics which are held safely and securely at several locations. We own the majority of the uranic materials on our sites, while the remainder is owned by others including Ministry of Defence (MOD), EDF Energy (EDFE) and overseas utilities. We manage our customer-owned uranic materials in accordance with the terms of those contracts.

The NDA-owned inventory comprises the following groups:

- Magnox Depleted Uranium (MDU), a product of spent Magnox fuel reprocessing;
- Uranium Hexafluoride tails (UF<sub>6</sub> tails, also known as “Hex” tails), a by-product of legacy uranium enrichment;
- THORP Product Uranium (TPU) in the form of UO<sub>3</sub>, a product of spent oxide fuel reprocessing;
- High Enriched Uranium (HEU) from research reactor fuel development and production; and
- Low-enriched, natural and depleted unused uranium in a variety of forms as recovered materials from fuel manufacturing processes.

Our uranics inventory will change as we continue to reprocess spent fuels, sell our uranic materials, where possible, and return it to customers according to their requirements. Owing to the diverse nature of our uranics inventory there is no single preferred management option for the whole inventory with the preferred option determined on a group-by-group basis. Continued storage does not provide an end point for our uranics. Where our uranics have commercial value we will return them to the fuel cycle through sale to a third party. For a significant part of our inventory (e.g. depleted uranium arising from enrichment and reprocessing) there is currently very limited opportunity to sell this material due to the current cost of freshly mined uranium. Work is underway to define how uranic material with no foreseeable resale value could be disposed of in a GDF or by using an alternative disposal approach. RWM are evaluating potential approaches to the disposal of uranic materials in a GDF. This work will inform whether NDA should develop alternative disposal approaches.

To optimise the management of uranics the storage of our uranics inventory (other than TPU and HEU) is being consolidated at Capenhurst alongside MDU and the oxide from converted Hex. TPU is stored in purpose-built facilities at Sellafield. HEU is being consolidated at Sellafield although a large part of this material may be suitable for reuse (e.g. in the production of medical isotopes). Where it is economic to do so, we will seek to transfer our HEU to a third party to enable such reuse in line with regulatory requirements. We are utilising existing infrastructure to recover uranium from residues at Springfields and materials from Harwell and Winfrith to make it more manageable or saleable. Materials not sold are being transferred to Capenhurst for storage.

Our Hex at Capenhurst forms part of the highest hazard on the site. We are therefore committed to converting our stored Hex into uranium oxide, which is much less hazardous and more suitable for long-term management. To complete this, our Hex must be removed from its existing containers which are ageing and obsolete, treated to remove impurities, re-packaged into new containers and then deconverted alongside URENCO owned tails in a future Tails Management Facility (TMF).



**Figure 21:** Aerial view of Capenhurst site

### **Technology Opportunities**

We are interested in technologies that would make our uranics inventory more saleable. This may be new uses for our uranics or new treatments that allow our uranics to be used.

### **Relevant Organisations**

- DSRL: Storage, treatment and transport of uranics.
- MxL: Storage, treatment and transport of uranics
- NDA: Strategic decisions regarding uranics management options.
- RWM: Disposal of uranics.
- SL: Storage of uranics, principally TPU

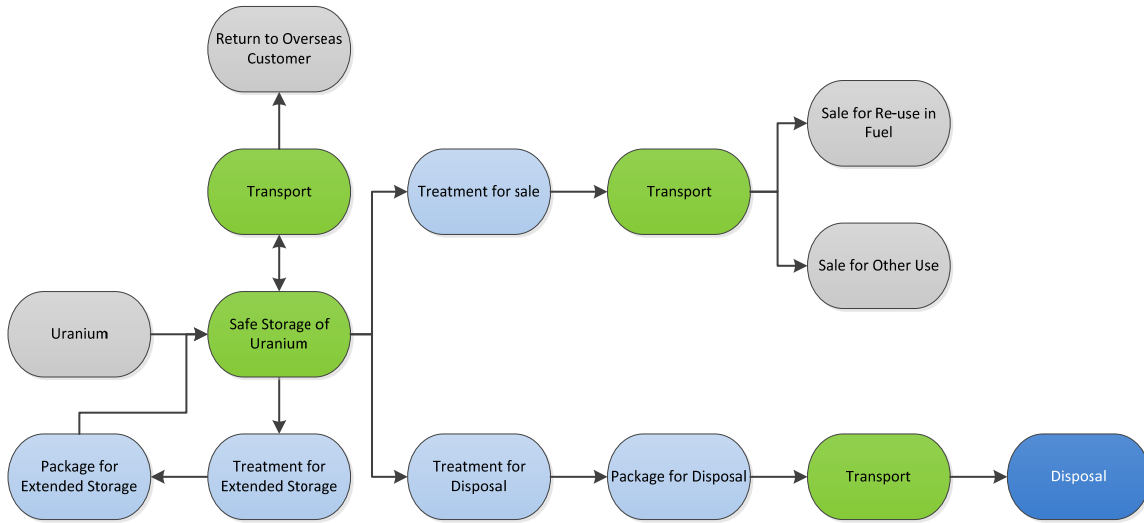


Figure 22: PWD for uranium

## 4 Integrated Waste Management

### 4.1 Classification of Radioactive Wastes

In the UK, radioactive wastes are classified according to the type and quantity of radioactivity they contain and how much heat that this radioactivity produces.

**High level wastes (HLW)** are those wastes where the temperature may rise significantly as a result of their radioactivity, so this factor has to be taken into account in the design of waste storage or disposal facilities. HLW arises as a liquid from the reprocessing of spent nuclear fuel. These liquids are subsequently treated to form solid glass blocks.

**Intermediate level wastes (ILW)** are those exceeding the upper boundaries for LLW that do not generate sufficient heat for this to be taken into account in the design of waste storage or disposal facilities. ILW comes in a wide range of forms with the majority of the volume being made up of metals, sludges, organic materials, plutonium contaminated materials, cement and graphite. The radiological, chemical and physical forms of ILW are highly varied, ranging from large solid waste items that are relatively inert to wet sludges, which can be chemically reactive and heavily contaminated.

**Low level wastes (LLW)** are those which contain relatively low levels of radioactivity. More specifically, wastes where the radioactive content does not exceed 4 GBq (gigabecquerels) per tonne of alpha, or 12 GBq per tonne of beta/gamma activity. Most LLW comes from the operation and decommissioning of nuclear facilities, and is mainly scrap metal items, paper and plastics. Some smaller amounts of LLW also come from hospitals and universities.

**Very low level waste (VLLW)** is a sub-category of LLW with specific activity limits. VLLW includes small volumes of waste, principally from hospitals and universities that can be safely disposed of with household, commercial or industrial waste (either directly or after incineration), and larger volumes of waste from nuclear sites that can be disposed to appropriately permitted landfill facilities. The major components of VLLW from nuclear sites will be building rubble, soil and steel items arising from the future dismantling and demolition of nuclear reactors and other nuclear facilities.

When developing strategies for the management of radioactive wastes, two additional categories of radioactive waste are typically used:

**Higher Activity Waste (HAW)** comprises HLW, ILW and a small fraction of LLW with a concentration of specific radionuclides that is not suitable for near-surface disposal in current facilities. A detailed overview of Higher Activity Wastes can be found in [9] along with the current NDA Higher Activity Waste Strategy in [10].

**Lower Activity Waste (LAW)** comprises the remaining LLW and VLLW.

Further information on the UK Radioactive Waste Inventory (UKRWI) and the activities that produce radioactive waste in the UK [11] can be found on the UKRWI website ([ukinventory.nda.gov.uk](http://ukinventory.nda.gov.uk)).



## 4.2 Disposal of Radioactive Wastes

Waste management is not a straightforward process of retrieval and disposal. It includes a series of steps: pursuing opportunities for waste minimisation, reuse and recycling (i.e. Waste Hierarchy [12]), waste processing, packaging, storage, records management, transport and then final disposal where required. If radioactive waste cannot be safely and cost-effectively reused or recycled, it will be disposed of. Disposal of wastes involves the emplacement of wastes in an appropriate facility without the intention of retrieval.

### 4.2.1 Disposal of Higher Activity Wastes

Currently, there are no long-term disposal facilities available for higher activity wastes in the UK. At the moment, HAW is typically treated to turn it into a stable form, packaged and then kept in robust interim storage facilities until a long-term management solution is developed. In some cases it may be necessary once HAW is retrieved to store it for an interim period pending conditioning into a stable form. Management of radioactive wastes is a matter for the devolved Governments, and there are different policies for managing higher activity wastes in the countries of the UK.

The UK Government's policy for managing higher activity wastes is 'geological disposal'. This involves placing waste deep underground in a Geological Disposal Facility (GDF) with no intention to retrieve the waste once the facility is closed. It is proposed that spent fuel that has also been declared as waste would also be disposed at such a facility.

A GDF is a highly-engineered facility capable of isolating radioactive waste within multiple protective barriers, deep underground, to ensure no harmful quantities of radioactivity ever reach the surface environment. The combination of the engineered barriers and the host rock will safely isolate the waste from people for many hundreds of thousands of years.

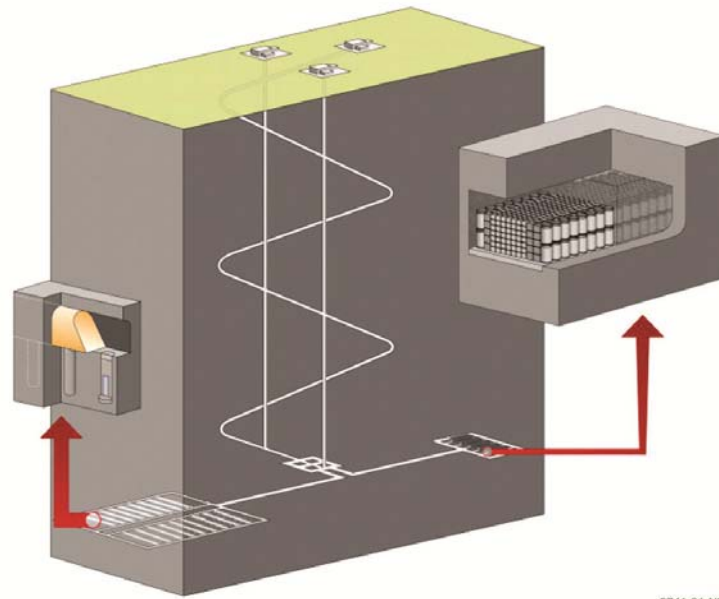
There is no GDF yet operating in the UK but UK Government identified a process for identifying a suitable host site within its 2014 White Paper on Implementing Geological Disposal. The White Paper named RWM as the developer, and UK Government and RWM are progressing the initial actions in order to prepare for the dialogue with interested communities, expected to start in 2017. Alongside the output of the ongoing geological screening work, community expressions of interest are necessary in order for RWM to progress to site specific research that will inform a choice of host site for the GDF. The geological characteristics of the site are important for the long term safety of the facility. Most importantly, it should provide a stable environment for the multiple engineered barriers and have the properties required of the geosphere to isolate and contain the waste.

The Welsh Government has also decided to adopt a policy of geological disposal for the long term management of higher activity waste and continues to support the policy of voluntary engagement.

There are no major radioactive waste producers in Northern Ireland. The Northern Ireland Government has also decided to adopt a policy of geological disposal for the long term management of higher activity waste and continues to support the policy of voluntary engagement.

The Scottish Government's policy is that the long-term management of higher activity radioactive waste should be in near-surface facilities. Facilities should be located as near to

the site where the waste is produced as possible. Developers will need to demonstrate how the facilities will be monitored and how waste packages, or waste, could be retrieved. This policy does not cover HLW because there is none in Scotland. It also does not cover spent fuels or radioactive materials that are not presently classified as waste (see sections 5.1 and 5.2).



**Figure 23:** Possible design for a Geological Disposal Facility (GDF)

#### 4.2.2 Disposal of Lower Activity Wastes

LLW is typically disposed in purpose built facilities. The biggest of these in the UK is the LLWR, which is located south of Sellafield, in Cumbria. This has several old, legacy disposal trenches that are now closed. Current disposals are made in a specially engineered facility with concrete-lined disposal ‘vaults’.





**Figure 24:** Low Level Waste storage containers at the Low Level Waste Repository near Drigg, Cumbria, UK

At the LLWR, waste is grouted with cement in metal containers to make a robust solid. The grouted metal containers containing the waste are placed within the engineered vaults until the repository can be covered with an engineered cap and closed. Most of the radioactivity in the waste will decay within a few hundred years.

The Dounreay site, in the north of Scotland, has also constructed an LLW repository for its own waste.<sup>11</sup>

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<sup>11</sup> 'Dounreay low level waste vaults begin to accept waste', DSRL website, 2015



**Figure 25:** LLW facility whilst under construction at Dounreay

LLWR and DSRL have developed Environmental Safety Cases (ESC) to support their LLW disposal sites.

Some LLW and VLLW waste streams can be disposed of at suitably authorised and permitted landfill sites alongside household, commercial and industrial wastes. For all of these disposal sites there are controls on the amount and type of radioactive waste that can be disposed of at the different sites.

### 4.3 Structure of Technical Baseline for IWM

Whilst radioactive waste itself can be classified as HLW, ILW or LLW, this report also splits it into three sections based upon its source:

- Radioactive waste from reprocessing – This covers the waste generated directly by reprocessing of spent fuel.
- Legacy radioactive waste – This covers dealing with radioactive waste stored in legacy facilities.
- Operational and decommissioning waste – This covers the waste, both radioactive and non-radioactive, generated by both the operation and decommissioning of our facilities.

In many cases the same process and associated technology is used in each section to manage the waste. Depending upon the individual circumstances (e.g. location / timing / scale of production), the same facility may also be used. This adds complexity to the overall process (e.g. scheduling) but reduces duplication and avoids increasing the number of facilities. Similarly some facilities can be modified once they have completed their initial programme of waste management to manage a new waste. Again this avoids increasing the number of facilities.

There are some wastes across the NDA estate that are referred to as 'problematic wastes', 'orphan wastes' or 'wastes requiring additional treatment' (WRATs). These are wastes which are not suitable for treatment in existing processing plants (or those currently planned at a detailed level). NDA is currently developing a strategy for the improved management of problematic radioactive waste [13]. Development and implementation of this strategy may require R&D. Examples regarding the Technical Baseline for 'problematic wastes' will be included in future issues of this report.

#### 4.4 Radioactive Wastes from Reprocessing

Reprocessing spent fuel is a complex process that first involves separating the spent fuel from the metal components of the fuel assemblies and then extracting the nuclear materials using a chemical separation process. Each of the stages within the reprocessing process generates radioactive waste. Each of these wastes needs treating to produce a wasteform suitable for disposal or discharge. The treatment can range from simply packaging in a robust container, through encapsulation in concrete, to complex chemical and physical processes involving multiple steps. Treatment is typically followed by interim storage of the treated and packaged wasteform on the Sellafield site whilst awaiting transport to a suitable disposal facility (e.g. GDF). A large proportion of the Sellafield site is dedicated to these activities of treatment and interim storage. The main reprocessing wastes and their waste classification, associated treatment process and interim storage facility are:

- **Spent fuel pond purges** – The water purged from ponds used to store spent fuel typically needs to be treated before it is discharged. The treatment usually involves both filtration and ion-exchange to remove the radioactivity. At Sellafield, the Site Ion Exchange Effluent Plant (SIXEP) uses sand bed filters and ion-exchange columns containing clinoptilolite, a naturally occurring zeolite, to treat the purged pond water from FHP prior to discharge to sea. Periodically the sand and clinoptilolite must be changed. At the moment these ILW wastes are transferred to the SIXEP Bulk Storage Tanks (BST) where they are being stored. The current approach is to package this material in the Box Encapsulation Plant (BEP) or Unconditioned Waste Transfer (UWT) facility and interim store it in the Box Encapsulation Plant Product Store (BEPPS) on the Sellafield site before finally treating the waste / waste package for disposal.
- **Graphite and stainless steel waste from dismantling of AGR fuel elements** – These ILW materials are packaged without encapsulation in 500l drums (FHP) and interim stored in the AGR Dismantler Store on the Sellafield site. It is planned to treat this waste prior to future disposal in the GDF.
- **Hulls and end pieces from dismantling of AGR fuel elements** – These ILW materials are encapsulated in concrete within 500l drums (Waste Encapsulation Plant (WEP)) and interim stored in the Encapsulated Product Stores (EPS) on the Sellafield site prior to future disposal in the GDF.

- **Cladding waste from decanning Magnox fuel elements** – This ILW waste is encapsulated in concrete within 500l drums (MEP) and interim stored in the Encapsulated Product Stores (EPS) prior to future disposal in the GDF.
- **Fission products from the solvent extraction process step of reprocessing spent fuel** – This HLW aqueous waste is concentrated by evaporation and stored in cooled tanks (Highly Active Storage Tanks (HASTs) within Highly Active Liquor Evaporation and Storage (HALES) facility). The evaporation stage reduces the volume of liquor that must be stored and also allows some nitric acid to be recycled back into the solvent extraction process. The evaporators used have a limited lifetime due to the corrosive nature of the material they are evaporating. A new evaporator, Evaporator D, is being added to the system to provide continued evaporative capacity. After tank storage, the Highly Active Liquor (HAL) is converted to mixed oxides and reacted at high temperature with glass-forming materials to form a vitreous product.<sup>12</sup> The molten vitreous product is poured into stainless steel containers and allowed to solidify. This treatment process is called vitrification and results in a significant reduction in waste volume. It takes place in the Waste Vitrification Plant (WVP). The vitrification process itself generates a number of wastes (e.g. NO<sub>x</sub> gas) and a complicated off-gas system is required (e.g. dust scrubber, condenser, NO<sub>x</sub> absorber, high efficiency filters). The filled stainless steel containers are interim stored in the Vitrified Product Store (VPS) on the Sellafield site prior to future disposal in the GDF. This store uses natural convection to remove the heat generated by the fission products decaying. Some of the vitrified waste is from the reprocessing of foreign spent fuel and is returned to overseas customers via the Residue Export Facility.<sup>13</sup>

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<sup>12</sup> 'Great progress on waste stock reduction', Sellafield website, 2014

<sup>13</sup> 'Highly active waste transport to Japan departs UK', Sellafield Ltd website, 2014





**Figure 26:** Vitrified Product Store (VPS) at Sellafield

- Medium active liquid wastes from the purification of uranium and plutonium –** These aqueous wastes are concentrated by evaporation and, depending upon their level of radioactivity, treated with HLW aqueous waste (i.e. vitrification) or treated as ILW. The evaporation process allows some nitric acid to be recycled back into the solvent extraction process. The ILW route uses a flocculation and ultrafiltration process in the Enhanced Actinide Removal Plant (EARP) to produce a solid waste suitable for encapsulation in concrete within 500l drums in the Waste Packaging and Encapsulation Plant (WPEP) and aqueous waste that can be discharged to sea. The resulting 500l drums are interim stored in the WPEP store prior to future disposal in the GDF.



**Figure 27:** Encapsulation line at Sellafield Waste Packaging and Encapsulation Plant (WPEP)

- **Low active liquid wastes (e.g. spent dust scrubber liquid)** – These low active wastes contain low but measurable amounts of activity. They are typically routed to the Segregated Effluent Treatment Plant (SETP) where they are neutralised and held for confirmation of its composition prior to discharge within agreed limits.
- **Spent solvent from the solvent extraction process step of reprocessing spent fuel** – Whilst the majority of solvent is recycled in the solvent extraction process, some waste solvent is produced. This ILW waste is treated in the Solvent Treatment Plant (STP). For the most significantly contaminated solvents this starts with washing with various aqueous liquids (e.g. water, sodium carbonate solution) to remove the vast majority of the radioactivity and produce an aqueous ILW waste that can be treated in EARP and a lightly contaminated solvent. The lightly contaminated solvents are heated with sodium hydroxide which results in the production of three wastes that can be separated and treated by incineration (kerosene), in EARP (aqueous) or in SETP (Sodium dibutyl phosphate).

Once UK reprocessing of spent fuels comes to an end, the operational life of many of the facilities that treat the reprocessing waste may also start to come to an end. Waste from Post Operational Clean Out (POCO) of the reprocessing facilities will need to be managed. Some treatment facilities will continue but with reduced scope; treating legacy, operational and /or decommissioning waste. Some treatment facilities will be modified to manage new wastes. Some treatment facilities will start decommissioning. Planning and managing the implications of the end of reprocessing is a key activity for Sellafield Ltd.

### Relevant organisations

- MxL: Management of wastes from reactor pond storage of spent fuel.  
 RWM: Disposal of Higher Activity Wastes.  
 SL: Management of radioactive wastes from reprocessing.

### Technology Opportunities

The management of radioactive waste from both Magnox and THORP reprocessing of spent fuel is an established operation. Given that reprocessing is nearing completion, there is limited opportunity to improve the existing technology for management of the main wastes. Understanding, maintaining and extending the lifetime of existing infrastructure is ongoing. Some key areas of research include:

- Improved lifetime assessment through new inspection approaches and technologies for vessels (e.g. HASTs) and pipework.
- Approaches and technologies for extending the life of existing infrastructure (e.g. Evaporator C).

There is however a need to understand how the existing facilities will treat wastes from POCO of the reprocessing facilities and how existing treatment facilities could be modified to manage new wastes. Some of the key areas of research include:

- Understanding the benefits of co-processing reprocessing wastes with POCO wastes.
- Understanding the impact of solids (formation, transport and treatment) on POCO of HAL treatment process.
- Wasteform development (e.g. glass formulation) for vitrification of POCO HAL feeds.
- Options for treating effluents that allow decommissioning of existing facilities (e.g. SETP) to take place.

The interim storage of treated radioactive waste from reprocessing will continue on the Sellafield site for a number of years and there are opportunities to improve the storage of waste packages. Many of the stores are already constructed and partially filled and this constraint must be taken into consideration when proposing new approaches and / or technologies. There are also synergies with the interim storage of other packaged wastes (e.g. decommissioning waste). Some of the key areas of research include:

- Remote monitoring of waste packages (e.g. corrosion)
- Remote monitoring of stores (e.g. humidity)

Research into the disposal of HAW is on-going and being led by RWM [14]. Key areas of research include:

- Role and evolution of barriers (package evolution; engineered barrier system; geosphere)
- Release and movement of contaminants through the multi-barrier system (radionuclide behaviour; gas generation and migration; biosphere)
- Control of low probability events and their outcome (criticality safety; waste package accident performance)

RWM also has projects investigating specific technical topics:

- Disposal of wastes containing carbon-14.
- Disposal of high-heat-generating wastes.
- Disposal of uranium (depleted, natural and low enriched).
- Maintaining and developing the range of geological disposal concepts.

These disposal R&D requirements are common across radioactive wastes from reprocessing, legacy facilities and operational and decommissioning wastes.

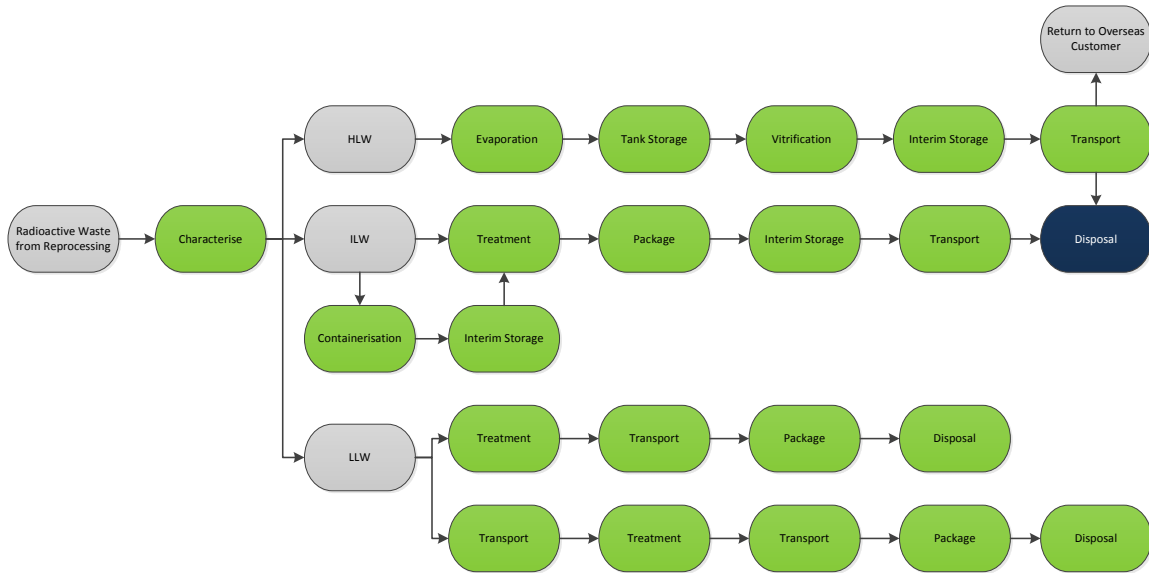


Figure 28: PWD for radioactive wastes from reprocessing



#### 4.5 Radioactive Wastes from Legacy Facilities

There are a number of facilities across the NDA estate where radioactive waste has been stored or allowed to accumulate in less than ideal conditions. Many of these facilities contain Higher Activity Wastes and are quite old and / or not built to modern standards i.e. legacy facilities. Reducing the risk and hazard associated with these facilities is one of the NDA's highest priorities. In general this involves improving the facility, retrieving the radioactive waste and managing it to modern standards. This allows the empty facility to be decommissioned. There are many common challenges associated with the management of radioactive wastes from legacy facilities:

- Records associated with the radioactive waste inventory are often incomplete.
- Records associated with the operation of the facility are often incomplete.
- The current state of the waste is often uncertain and has usually changed significantly from when it was placed in the facility (e.g. corrosion has occurred).
- The facility was often not designed or operated with waste retrieval and / or decommissioning as a consideration.
- The condition of the facility is often still deteriorating.
- The condition of the facility often precludes certain retrieval options.
- The realisation of both technical opportunities (e.g. new treatment technologies or routes becoming available) and risks (e.g. changes to inventory based upon improved characterisation information) results in frequent changes to the Technical Baseline for the management of the wastes from these legacy facilities.

The main legacy facilities across the NDA estate that contain radioactive waste that requires retrieval are:

- **Floc Storage Tanks (FST) at Sellafield** – A series of ten concrete storage tanks were built in the 1950s to store liquid effluents from reprocessing operations. The overlying liquid was discharged leaving floc, a sludge like substance containing the majority of the radioactivity, in the tanks. The tanks operated until the mid-1990s when the Low Active Effluent Treatment plants came online. In the 1990s a project was completed to install an overbuilding above the storage tanks and to refurbish the tanks themselves. Floc from the storage tanks is currently being re-suspended and transferred to EARP for treatment.
- **Pile Fuel Storage Pond (PFSP) at Sellafield** – Constructed between 1948 and 1952, the pond initially stored, cooled and decanned Windscale Pile Fuel for reprocessing. It was modified in the 1950s so that it could accept fuel from Calder Hall. When operations in the pond came to an end, it continued to be used for fuel, contaminated items and operational waste. The facility consists of a subdivided outdoor storage pond and an adjoining decanning building containing a series of sub-ponds, otherwise known as bays, connected underwater to the main pond. The challenge is to safely retrieve the radiological inventory taking into consideration the congested location of the facility on the Sellafield site, the high levels of radiation in the facility and potential for contamination.



**Figure 29:** Pile Fuel Storage Pond (PFSP) at Sellafield

The approach for the fuel was to retrieve it using refurbished PFSP lifting equipment supported with underwater Remotely Operated Vehicles (ROVs). For oxide fuel, it was then transferred to the Active Handling Facility (AHF) for repackaging and subsequent management alongside other oxide fuels. For metal fuel, it was transferred to FHP for interim storage. It will be subsequently treated, provisionally by encapsulation in cement. Removal of bulk fuel from the pond was completed in February 2016<sup>14</sup>.

The current approach for the sludge is to initially transfer it to a corral within the pond using a variety of technologies (e.g. suction hoods, water lances, skip washing) and subsequently transfer it to WEP for encapsulation in concrete within 500l drums.

The current approach for the remaining ILW is to retrieve the waste in fuel skips and transfer it to BEP where the skip will be flood grouted with concrete, transferred into a 3m<sup>3</sup> stainless steel box and interim stored in BEPPS on the Sellafield site prior to future disposal in the GDF.

Effluent from the pond is routed through a Local Effluent Treatment Plant (LETP) (combination of sand bed filters and ion exchange cartridges) to SETP.

- **Magnox Swarf Storage Silo (MSSS) at Sellafield** – The silo was constructed in the 1960s to underwater store the fuel cladding from Magnox spent fuel (i.e. Magnox swarf). Its storage capacity was increased on a number of occasions by the

<sup>14</sup> 'Nuclear clean-up milestone makes Sellafield safer', Sellafield Ltd website, 2016

construction of additional compartments. The silo was also used by a number of other Sellafield plants for storage of their ILW. The overall result is that whilst the majority of the waste within the silo is Magnox swarf, its total inventory is quite diverse and subject to some uncertainty. The underwater nature of the storage is also likely to have changed the nature of the waste (e.g. Magnox swarf can corrode in water releasing hydrogen to give a sludge). The challenge is to safely retrieve the radiological inventory, including swarf, sludge and remaining waste, taking into consideration the congested location of the facility on the Sellafield site, the condition of the ageing facility, the presence of hydrogen, the high levels of radiation in the facility and potential for contamination.



**Figure 30:** Aerial view of the Magnox Swarf Storage Silo at Sellafield

The current approach for retrieving the waste is to construct three rail-mounted Silo Emptying Plants (SEPs) on the top of MSSS.<sup>15</sup> These SEP machines will retrieve waste from the top of the individual silo compartments within MSSS using mechanical grabber technology, load it into a skip and package it into a transport container for transport to either BEP or the Package to Box Transfer Facility (PBTF) facility. The

<sup>15</sup> 'Sellafield special delivery marks nuclear clean-up milestone', Sellafield Ltd website, 2015

SEP machines will periodically need to redistribute the waste within each compartment to avoid an unstable 'crater' being formed. They will also need to move compartments to ensure the compartments are emptied at similar rates in order to allow liquor levels within the silo to be reduced.

In BEP the skip will be either transferred to a modified 3m<sup>3</sup> stainless steel box for interim storage in BEPPS on the Sellafield site or, in the unlikely event it contains items that need to be opened or reduced in size, its contents emptied out, relevant items disrupted using remotely operated robots and then returned to a skip for transfer to a modified 3m<sup>3</sup> stainless steel box for interim storage in BEPPS. It is currently planned for PBTF to transfer skips to boxes when BEP is required for managing waste from other legacy facilities. It is also initially planned to use the refurbished Encapsulated Product Store Import/Export Facility (EPS I/EF), to be known as EPS Waste Transfer Facility (EPS WTF), as a route to transfer skips to modified 3m<sup>3</sup> stainless steel boxes whilst BEP is completed. These boxes would be interim stored in the EPS.<sup>16</sup>

Prior to future disposal in the GDF, the 3m<sup>3</sup> stainless steel boxes will require additional treatment to make a disposable package. At the moment this is planned to be filling the annulus and cap of the box with grout in a simple ILW Finishing Plant on the Sellafield site.

The water in the silo has become radioactive through reaction with the waste in the silo. In order to reduce the hazard, a process known as Liquor Activity Reduction (LAR) is carried out<sup>17</sup>. This involves regularly removing liquor from the silo, transferring it via the Effluent Distribution Tank (EDT) to SIXEP for treatment and adding fresh water back to the silo to dilute the remaining radioactivity. A similar process, without the re-addition of clean water, will be used to remove liquor from the silos once the waste has been retrieved.

- **Pile Fuel Cladding Silo (PFCS) at Sellafield** – Built between 1950 and 1951 the Pile Fuel Cladding Silo houses six extremely tall waste containers or 'silos'. The facility's primary role was to receive and safely store radioactive fuel cladding from the military project at Windscale. As Magnox power stations started to generate electricity for domestic use, it also received fuel cladding from the Calder Hall and Chapelcross power stations and other miscellaneous waste items. Routine addition of waste was stopped in 1964 and PFCS has been in Care and Maintenance (C&M) since then. A number of upgrades to the building have been completed. This included the installation of an argon inerting system to reduce the risk of fire within the facility. The challenge is to safely retrieve the diverse radiological inventory taking into consideration the congested location of the facility on the Sellafield site, the condition of the ageing facility, the presence of argon necessary for inerting the waste, the high levels of radiation in the facility and potential for contamination.

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<sup>16</sup> 'New world class waste store at Sellafield', Sellafield Ltd website, 2014

<sup>17</sup> 'Radiation risk reduced as two million litres of liquid nuclear waste safely pumped from old store', Sellafield Ltd website, 2015





**Figure 31: Pile Fuel Cladding Silo (PFCS) at Sellafield**

The current approach is to construct special silo doors<sup>18</sup> to allow remotely operated vehicles to enter the silo and transfer the waste to 3m<sup>3</sup> stainless steel boxes whilst maintaining containment and argon inerting<sup>19</sup>. Once filled and sealed the boxes will be transferred for interim storage to BEPPS on the Sellafield site. Operating experience from retrieving waste from the first of the six silos will be used to inform the approach used to retrieve waste from the subsequent silos. During retrievals, information regarding the waste will be recorded to allow an optimised waste treatment facility to be designed and constructed. This waste treatment facility will condition the waste to allow disposal in the GDF.

- **First Generation Magnox Storage Pond (FGMSP) at Sellafield** – Built during the 1950s and 1960s as part of the UK's expanding nuclear programme, FGMSP is an open air pond designed to receive and store irradiated fuel from Magnox reactors and to remove the fuel cladding prior to the fuel being processed.

In 1974, a long reprocessing shutdown at Sellafield caused fuel to be stored underwater in the storage pond for longer periods than normal. This resulted in the Magnox fuel corroding in the pond, which in turn gave rise to increased radiation levels and poor underwater viewing. This slowed the rate of decanning leading to increased

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<sup>18</sup> 'Engineering feat opens door to Sellafield clean-up progress', Sellafield Ltd website, 2016

<sup>19</sup> 'Goliath crane built for retrievals', Sellafield Ltd website, 2013

residence times and further fuel corrosion. The plant continued to operate until its replacement, FHP at Sellafield, was commissioned in 1986. The final fuel was received into FGMSF in 1992.



**Figure 32:** First Generation Magnox Storage Pond (FGMSF) at Sellafield

Over the years the pond has accumulated significant quantities of waste materials including sludges, from corrosion of fuel cladding, fuel fragments and other wind-blown debris, as well as skips of fuel. The challenge is to safely retrieve and treat the wide-ranging radiological inventory, taking into consideration the congested location of the facility on the Sellafield site, the condition of the ageing facility, the high levels of radiation in the facility and potential for contamination.

The wide-ranging waste and fuel within FGMSF means that a single approach to managing the material is not appropriate. The current approach for sludge within the pond is to mobilise it and then pump it to the Sludge Packaging Plant 1 (SPP1) for buffer storage in large stainless steel vessels followed by encapsulation in concrete in 3m<sup>3</sup> boxes and interim storage in BEPPS on the Sellafield site.<sup>20</sup> For the remaining material, both waste and fuel skips, the current approach is to sort, segregate, condition and consolidate the material within the pond using a range of technologies including underwater ROVs<sup>21</sup>, existing Skip Handling Machine (SHM) and a variety of skips / baskets. The consolidated material will then be retrieved from the pond and

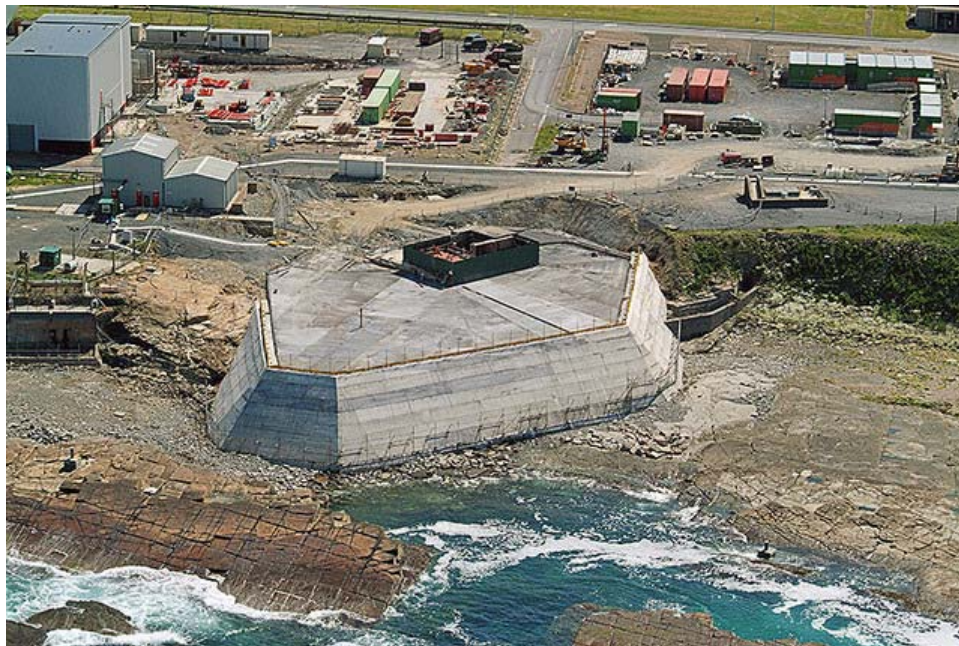
<sup>20</sup> 'Sludge removal marks significant step in Sellafield clean-up', Sellafield Ltd website, 2015

<sup>21</sup> 'Mini submarines recover historical medical kit', Sellafield Ltd website, 2015



either transferred for direct treatment (e.g. encapsulation in concrete in a 3m<sup>3</sup> stainless steel box using BEP and interim storage (e.g. BEPPS), transferred to FHP for interim storage or containerised for interim storage (e.g. placed in a Self-Shielded Box (SSB) for interim storage in SSB Store) whilst an appropriate treatment route is developed or becomes available (e.g. schedule gap in BEP). As well as managing the material within the pond, the pond water itself and additional effluent from pond operations (e.g. skip washing) must be managed. The current approach is to transfer any effluent via the Effluent Distribution Plant (EDP) to SIXEP for treatment prior to discharge.

- Shaft and Silo at Dounreay** – Highly radioactive waste generated during the operation of the Dounreay fast reactor research site was originally sentenced to two underground facilities: the shaft, a 65-metre deep column that formed part of the site construction in the 1950s, was used for disposals until 1977 and the silo, a shallow concrete bunker, was used as a store until 1998. Both the shaft and silo do not meet modern standards for acceptable disposal and the waste must therefore be retrieved. Challenges include safely retrieving and treating the wide-ranging radiological inventory, the depth of the shaft, the high levels of radiation and potential for contamination.



**Figure 33:** Aerial view of the shaft on the Dounreay site

The shaft has been isolated from the surrounding groundwater by drilling approximately 400 boreholes in the rock around the shaft and injecting very fine grout under pressure to seal up any fissures. By diverting much of the groundwater around the shaft instead of through, the volume of liquid waste generated during retrieval is



greatly reduced. For waste retrieval both petal and clam shell grabs will be deployed to retrieve waste from the full depth of the shaft using a crane having X-Y traverse capability to ensure complete coverage of the cross section of the shaft. A deployment platform, Shaft Intervention Platform (SIP), will be used to transport a ROV down the shaft to remove any obstructions on the side walls. A high-pressure water jet deployed by the SIP will be used to recover materials from a side tunnel of the shaft.<sup>22</sup>

Waste retrieved from the shaft will be sorted using ROVs with power manipulators and an assortment of tools for sizing and handling waste items. The waste will also be segregated into solid and effluent waste streams, using equipment including a shredder and size reducing tooling to shred and screen the debris and cut large items. The waste will be characterised by gamma and fissile monitoring systems to ensure that it can be processed and a package suitable for disposal can be produced. Sludge waste will be de-watered using a vibrating screen and then encapsulated in concrete. Solid waste will be compacted and encapsulated in concrete. The encapsulated waste will be interim stored in an unshielded ILW store on the Dounreay site for subsequent near-site, near surface storage or disposal. Effluent from sludge dewatering will be filtered, treated by ion-exchange, analysed and then discharged to sea.

For the silo, part of the roof will need to be removed using diamond wire cutting to facilitate retrieval. To retrieve solid waste an electric overhead travelling crane with appropriate grabs will be installed whilst a system of pumps will be installed to retrieve sludge. The waste will be sorted using ROVs similar to those used on the shaft before being transferred to treatment through the shaft waste treatment facility.

- **Management of Fuel Element Debris (FED) at Magnox sites** – Prior to being sent for reprocessing, some Magnox reactor sites removed and stored parts of the magnesium alloy cladding that surrounds the nuclear fuel – Fuel Element Debris (FED). Some FED remains at some Magnox sites and needs to be safely retrieved from the vaults where it is currently stored, treated and then interim stored prior to future disposal in the GDF. The waste is retrieved from the vaults using remotely operated equipment (e.g. 'grab & bucket') with the exact design dependent upon the design of the vault. Once retrieved, the treatment option for the FED is determined by a number of factors including the level of contamination of the FED, the location of the reactor and the type of material that the FED has been stored with.

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<sup>22</sup> 'Dounreay contractor's innovation awarded', DSRL website, 2015

Current Proposed Treatment Approach		Site
Compaction of segregated Magnox FED, disposed as LLW		Oldbury
		Sizewell A
		Bradwell (part)
Acid dissolution	Nitric acid	Bradwell (part)
	Carbonic acid	Dungeness A*
Encapsulation in cement within stainless steel boxes		Hunterston A
		Trawsfynydd
Placed in drums (un-encapsulated) which are then cement encapsulated (entombment)		Berkeley (part)
		Hinkley Point A
Containerised in a thick walled container that provides both shielding and physical containment		Berkeley (part)

\* Completed

Acid dissolution of FED involves sorting the waste and using an acid, typically either carbonic acid (Dungeness A) or nitric acid (Bradwell<sup>23</sup>), to dissolve the FED, which is mostly non-radioactive magnesium, leaving any insoluble items to be dealt with as ILW and a liquid effluent stream. At Bradwell the liquid effluent stream is treated by neutralisation, precipitation, filtration and ion-exchange in the Aqueous Discharge Abatement Plant (ADAP) and monitored to confirm to suitability for discharge prior to actual discharge.

<sup>23</sup> 'Fuel Element Debris (FED) treatment - Frequently asked questions', Magnox Ltd website, 2015



**Figure 34:** Video feeds from inside the Fuel Element Debris (FED) vault at Berkeley

**Relevant organisations**

- DSRL: Management of radioactive wastes from legacy facilities.
- LLWR: Management of radioactive wastes from legacy facilities and disposal of Lower Activity Wastes.
- MxL: Management of radioactive wastes from legacy facilities.
- RWM: Disposal of Higher Activity Wastes.
- SL: Management of radioactive wastes from legacy facilities.

**Technology Opportunities**

Significant progress has been made on developing and implementing the Technical Baseline for radioactive wastes from legacy facilities. Changes to the Technical Baseline can be made where there is a clear benefit (e.g. acceleration of risk reduction).

The interim storage of treated radioactive waste from legacy facilities will continue on different sites for a number of years and there are opportunities to improve the storage of waste packages. Some of the stores are already constructed and partially filled and this constraint must be taken into consideration when proposing new approaches and / or technologies for these stores. There are also synergies with the interim storage of other packaged wastes (e.g. decommissioning waste). For approaches that involve containerisation of waste, there may be opportunities to optimise future treatment of these packages through better understanding of the evolution of the waste and waste package or the development of new treatment technologies (e.g. thermal). Some of the key areas of research include:

- Reduced cost waste packages.
- Remote monitoring of waste packages (e.g. corrosion, hydrogen evolution).
- Remote monitoring of stores (e.g. humidity, temperature).

Research into the disposal of HAW is on-going and being led by RWM [14]. Key areas of research include:

- Role and evolution of barriers (package evolution; engineered barrier system; geosphere).
- Release and movement of contaminants through the multi-barrier system (radionuclide behaviour; gas generation and migration; biosphere).
- Control of low probability events and their outcome (criticality safety; waste package accident performance).

RWM also has projects investigating specific technical topics:

- Disposal of wastes containing carbon-14.
- Disposal of high-heat-generating wastes.
- Disposal of uranium (depleted, natural and low enriched).
- Maintaining and developing the range of geological disposal concepts.

These disposal R&D requirements are common across radioactive wastes from reprocessing, legacy facilities and operational and decommissioning wastes.

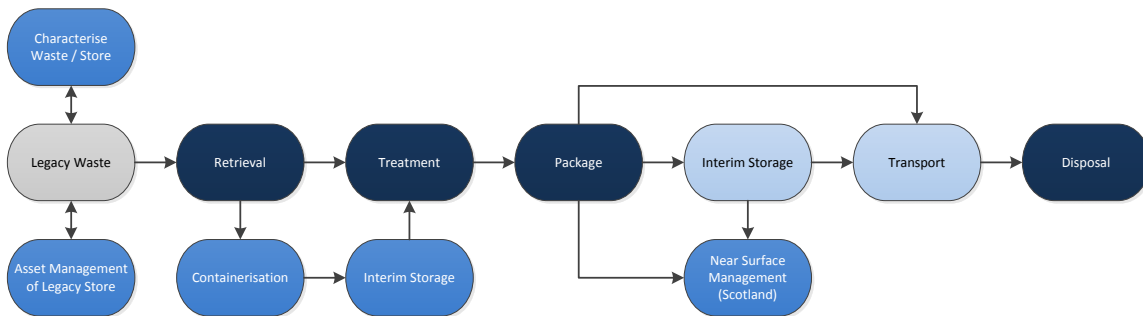


Figure 35: PWD for radioactive wastes from legacy facilities

#### 4.6 Operational and Decommissioning Wastes

This covers the waste both radioactive and non-radioactive generated by both the operation and decommissioning of our facilities. Operational waste covers waste generated by virtue of delivering other activities (e.g. contaminated materials from plant maintenance activities, spent ion-exchange filters from spent fuel pond treatment plants). Decommissioning waste covers waste generated during any stage of the decommissioning and remediation process (e.g. building rubble from the demolition of a building). In both cases the waste may be radioactive by virtue of it becoming contaminated through contact with other radioactive materials (e.g. tanks that have had radioactive liquor within them) or becoming activated by coming into contact with (or close to) a strong source of neutron radiation (e.g. graphite from the core of a nuclear power reactor).

Operational radioactive waste typically has a clear and underpinned waste management route in place. Decommissioning radioactive waste is typically, large volume solid ILW and graphite wastes associated with decommissioning including Sellafield active plant and equipment and Magnox reactors. Many of these waste streams may not arise for many decades and their form and volume will depend on the decommissioning approach implemented. Key principles of our approach to managing these operational and decommissioning wastes include:

- supporting key risk and hazard reduction initiatives by enabling a flexible approach to long-term waste management. For some wastes it may be necessary to adopt a multi-stage process to achieve a final disposable product; this could include the separate management of bulk retrievals and residual material to support hazard reduction programmes;
- taking into consideration the entire waste management lifecycle;
- applying the Waste Hierarchy [12];
- promoting timely characterisation and segregation of waste;
- seeking opportunities to share waste management capabilities and learning across the NDA estate and beyond;
- supporting and promoting the use of robust decision-making processes to identify the most advantageous options for waste management; and
- enabling the availability of sustainable, robust infrastructure for continued operations, hazard reduction and decommissioning.

Based upon these principles, site and waste specific strategies have been developed to manage the operational and decommissioning wastes. Key examples of how ILW is being managed across the NDA estate include:

- **Plutonium Contaminated Material (PCM) at Sellafield** – PCM at Sellafield includes a wide range of items including filters, small plant items, redundant glove boxes and soft wastes produced during the operation, maintenance, refurbishment and decommissioning of plutonium process facilities associated with final stages of spent fuel reprocessing. It also includes wastes transferred from legacy stores at the LLWR. Raw PCM wastes are interim stored in 200l drums in the Engineered Drum Stores (EDS) prior to being treated in the Waste Treatment Complex (WTC). Approved 200l drums are fed to the WTC where drums are supercompacted. The compacted drums

are loaded into a product container and annulus grouted with cement, before being returned to EDS for interim storage prior to future disposal in the GDF. Sellafield Ltd has also designed and installed a remote system for exporting PCM from a decommissioning facility. Size-reduced PCM (produced by a ROV) is delivered to a posting station via a conveyor system. The posting station contains a manipulator that an operator controls remotely to sort, post and compact waste into a PVC bag and subsequently a waste drum. The posting station fully contains any contamination, allowing the operators to work in a free-breathing environment. This removes the risk of injury due to manual handling of the PCM and eliminates the need for air-fed suit operations.

- Conditioning in thick-walled self-shielding containers** – Thick-walled waste containers can be used to provide both radiation shielding and physical containment. This approach is being used at a number of Magnox sites through the use of Ductile Cast Iron Containers (DCIC). The waste will be retrieved and dewatered or dried in the container before being interim stored in a lightly shielded ILW Store prior to future disposal; radiological shielding is provided primarily by the containers.



**Figure 36:** Ductile Cast Iron Containers (DCIC) at Dungeness A

- Encapsulation in self-shielding containers** – At Dounreay and a number of Magnox sites some waste will be retrieved and immobilised using grout in containers suitable for final disposal. Container choice is dependent upon shielding requirements (e.g. A 500l drum for wastes with a low shielding requirement; 6m<sup>3</sup> concrete boxes or 3m<sup>3</sup> boxes or TRUShield containers for those requiring more shielding). The waste



packages will be interim stored prior to disposal in the GDF or long-term near surface management for Scotland in lightly shielded ILW stores or existing buildings.

- **Encapsulation in stainless steel containers** – At Dounreay and a few Magnox sites some wastes are retrieved and immobilised by cement encapsulation within stainless-steel containers suitable for final disposal.<sup>24</sup> The waste packages will be interim stored prior to disposal in the GDF or long-term near surface management for Scotland in ILW stores incorporating radiological shielding (where required) or the waste packages will be over-packed to ensure adequate shielding is provided.

Key examples of how LLW is being managed across the NDA estate include:

- **Disposal in a LLW Repository** – Most LLW from across the UK has been disposed at the LLWR in Cumbria. A former Royal Ordnance Factory (ROF), the first disposals of radioactive waste took place in 1959. The radioactive waste is typically contaminated paper, cardboard, plastic, protective clothing, soil, rubble and metal. Waste was initially placed into landfill-style trenches but is now grouted in metal containers before being stacked in concrete lined, highly engineered vaults. A cap will cover the containers when the vaults are full. The Dounreay site also has a new LLW repository. This repository will only accept solid waste from Dounreay site operations and the nearby Ministry of Defence's Vulcan Naval Reactor Test Establishment. Both LLWR and DSRL have developed ESCs to support their LLW disposal sites.
- **Disposal not in a LLW Repository** – Some LLW is not suitable for near-surface disposal in current facilities (e.g. core graphite from the decommissioning of NDA's Magnox reactors). The baseline strategy for reactor core graphite is to dismantle reactor cores following a period of quiescence (typically 85 years) and package the graphite for disposal. Disposal in a GDF is the planned end point for the packaged waste in England and Wales. The Scottish Government Policy is that the long-term management of HAW, such as reactor core graphite, should be in near-surface facilities and that those facilities should be located as near to the site where the waste is produced as possible / practicable.
- **Disposal of large structures as bulk waste items** – The deconstruction of the concrete structure of the Dounreay Materials Test Reactor Post Irradiation Examination (PIE) Cave was carried out using diamond wire / diamond saw cutting to size reduce the structure into large blocks that were placed in interim storage pending disposal at LLW repository at Dounreay.<sup>25</sup>
- **Metals Recycling** – Metals with low levels of surface radioactivity can be recycled. The waste is cut into pieces before being placed into large containers, similar to shipping containers. The metals are then taken to a recycling facility, where the surface of the metal is removed by shot blasting, leaving clean metal beneath. The clean metal is then rigorously checked for any leftover contamination before it can be approved for recycling alongside other metals. Metals with slightly higher levels of

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<sup>24</sup> 'Shifting radioactive waste at Hunterston A'. Magnox Ltd website, 2016

<sup>25</sup> 'Reactor decommissioning demonstrates new approach to bulk waste disposal', DSRL website, 2013

radioactivity can also be recycled. This metal is melted, the radioactive contaminants removed and the clean, molten metal separated out for recycling. A very small volume of radioactive waste remains for direct disposal in an authorised LLW facility.

- **Supercompaction** – Some waste is subject to high force compaction to reduce the overall volume that requires disposal. Supercompaction facilities are available at Sellafield (Waste Monitoring and Compaction Facility (WAMAC)) and Dounreay (Waste Receipt Assay Characterisation Supercompaction (WRACS)).



**Figure 37:** The supercompactor at Dounreay

- **Incineration** – Some LLW, such as plastic, textiles and oils, can be incinerated. This burns the waste at high temperatures in a controlled chamber and reduces the volume of waste for disposal by around 90% or more. After incineration, only ash and filter dust remains, which is subsequently disposed of in an authorised LLW disposal facility.
- **Alternative Disposal** – Some LLW and VLLW can be disposed of at permitted landfill sites alongside non-radioactive wastes. There are strict controls on the amount of radioactive waste that can be disposed of at regular landfill sites. This is in addition to controls associated with the non-radioactive hazards associated with the waste.

Application of the waste hierarchy has encouraged these new approaches for managing LLW in a more sustainable way. Sites divert waste away from the LLW repositories by using characterisation and segregation to identify different waste treatment and disposal options, helping to extend the operational life of the LLW repositories.

NDA sites generate non-radioactive waste including demolition rubble, packaging, paper and food waste. Some non-radioactive waste is hazardous, such as asbestos, process chemicals, oil and other general waste. The nuclear industry's contribution to total UK waste volumes is very small compared to that of UK households and non-nuclear industry, (approximately 0.2% of hazardous waste and 0.04% of other Directive waste). Our approach to managing these

wastes is to use the well-established technologies and capability that exists in the wider waste industry and within our sites.

Key examples of how non-radioactive waste is being managed across the NDA estate include:

- **Recycling of concrete aggregates** – The reuse of recycled concrete aggregates in new constructions is an established waste management approach. For example, Sellafield Ltd have used this approach to manage some of the excavated concrete aggregate from the Calder Hall cooling tower basins for use as road bases for the land rover tracks associated with the Outer Perimeter Security Zone (OPSZ) project.<sup>26</sup>
- **Disposal of asbestos** – Asbestos was historically installed on plant and buildings as insulation. On the Magnox reactor sites the asbestos is typically non-radioactive and can be found on the heat exchangers, gas circuit and in the turbine hall. The strategy for the management of asbestos is removal of all bulk asbestos and disposal to a suitable licensed disposal facility. All asbestos removal is carried out by licensed asbestos contractors.<sup>27</sup>

### Relevant organisations

DSRL:	Management of operational and decommissioning wastes including disposal of LLW.
LLWR:	Management of operational and decommissioning wastes including treatment routes for LLW and disposal of LLW.
MxL:	Management of operational and decommissioning wastes.
RWM:	Disposal of HAW.
SL:	Management of operational and decommissioning wastes.

### Technology Opportunities

Significant progress has been made on developing and implementing the Technical Baseline for operational and decommissioning wastes. Changes to the Technical Baseline can be made where there is a clear benefit (e.g. reduction in cost). Some of the key areas of research include:

- Improved encapsulants (e.g. reduced cost, higher waste incorporation, increased security of supply, easier processability, increased compatibility with wastes); and
- Improved treatment technologies (e.g. thermal).

Some of the stores are already constructed and partially filled and this constraint must be taken into consideration when proposing new approaches and / or technologies for these

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<sup>26</sup> 'Recycling collaboration realises major cost savings', Sellafield Ltd website, 2012

<sup>27</sup> 'Europe's largest asbestos removal project completed at Chapelcross Site', Magnox Ltd website, 2015

stores. There are also synergies with the interim storage of other packaged wastes (e.g. waste from legacy facilities). Some of the key areas of research include:

- Reduced cost waste packages;
- Remote monitoring of waste packages (e.g. corrosion); and
- Remote monitoring of stores (e.g. humidity, temperature).

Research into the disposal of HAW is on-going and being led by RWM [14]. Key areas of research include:

- Role and evolution of barriers (package evolution; engineered barrier system; geosphere);
- Release and movement of contaminants through the multi-barrier system (radionuclide behaviour; gas generation and migration; biosphere); and
- Control of low probability events and their outcome (criticality safety; waste package accident performance).

RWM also has projects investigating specific technical topics:

- Disposal of wastes containing carbon-14;
- Disposal of high-heat-generating wastes;
- Disposal of uranium (depleted, natural and low enriched); and
- Maintaining and developing the range of geological disposal concepts.

These disposal R&D requirements are common across radioactive wastes from reprocessing, legacy facilities and operational and decommissioning wastes.



**Figure 38:** PWD for operational and decommissioning wastes

For operational and decommissioning wastes the treatment step can sometimes result in the re-classification of some or all of the waste. For example, the incineration of LLW results in both ash / filter dust that requires management as LLW and aerial discharge of the gases from combustion of the waste. The generic PWD does not highlight these secondary waste routes.

### 4.6.1 Liquid and Gaseous Discharges

Liquid and gaseous discharges are generated by SLCs during operations and decommissioning. Whilst discharges are generated at all stages of the nuclear fuel cycle, discharges are primarily associated with operations, decommissioning and most significantly spent fuel reprocessing. Our SLCs are required to implement the UK Strategy for Radioactive Discharges [15] and comply with relevant UK legal requirements. These are driven by the following general principles:

- unnecessary introduction of radioactivity into the environment is undesirable;
- sustainable development;
- use of Best Available Technology (BAT) in England and Wales and Best Practicable Means (BPM) in Scotland;
- the 'precautionary principle' which allows for decisions to be made in situations where there is evidence of potential harm in the absence of complete scientific proof;
- the 'polluter pays' principle where those responsible for producing the waste bear the costs of prevention, control and reduction measures; and
- the preferred use of 'concentrate and contain' in the management of radioactive waste over 'dilute and disperse' in cases where there would be a definite benefit in reducing environmental pollution.

The process used to treat liquid effluent typically includes a combination of technologies selected and ordered on the basis of the characteristics of the effluent. The technologies include:

- Settling tanks;
- Neutralisation vessels;
- Precipitation tanks;
- Flocculation tanks;
- Ion-exchange vessels;
- Filtration plants (e.g. sandbed filters, ultrafiltration using membranes); and
- Bulking tanks.

The process used to treat gaseous discharges typically includes a combination of technologies selected and ordered on the basis of the characteristics of the discharge. The technologies include:

- Filtration (e.g. High-efficiency particulate air (HEPA) filters);
- Wet scrubbing (e.g. Caustic scrubbers);
- Electrostatic precipitators (ESPs); and
- Absorbents (e.g. activated charcoal).



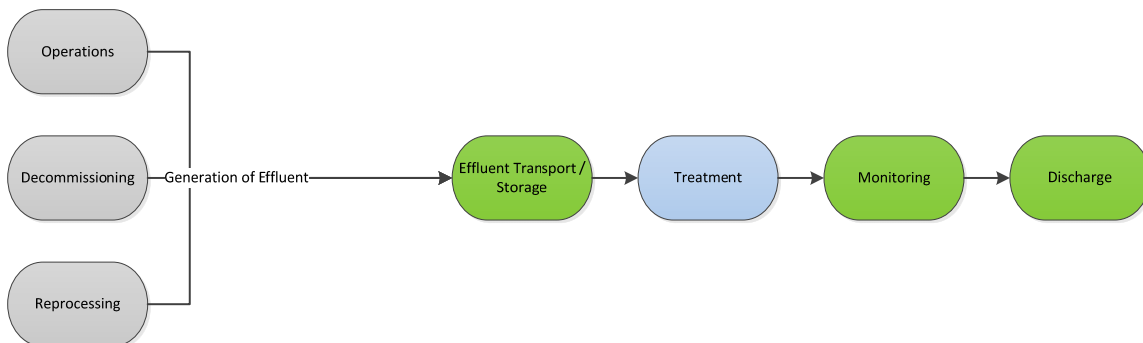
**Relevant organisations**

- DSRL: Management of site specific liquid and gaseous discharges.
- LLWR: Management of site specific liquid and gaseous discharges.
- MxL: Management of site specific liquid and gaseous discharges.
- SL: Management of site specific liquid and gaseous discharges.

**Technology Opportunities (0 – 10 yrs)**

The technical baseline for operational and reprocessing liquid and gaseous discharges is established. The liquid and gaseous discharges for decommissioning activities are more varied. Particularly at Sellafield, the variety can be challenging from a scheduling and compatibility viewpoint. Key areas of research include:

- Modular and mobile effluent treatment facilities to allow the decommissioning of existing effluent facilities or to manage short-term effluent requirements; and
- In-line monitoring technologies to avoid the transport of samples and increase sampling interval.



**Figure 39:** PWD for liquid and gaseous discharges

## 5 Site Decommissioning & Remediation

Site Decommissioning & Remediation defines our approach to decommissioning redundant facilities and managing land quality in order that each site can be released for its next planned use. Redundant facilities are facilities that have completed their operations and no further use for them has been identified. The operational life of a facility may be extended by identifying a new decommissioning use for the facility (e.g. fuel cooling ponds as temporary storage facilities). This may require some partial decommissioning and remediation.

On completing operations a facility transitions to a decommissioning state. This transition phase comprises activities such as organisational transition and Post Operational Clean Out (POCO). POCO typically involves the removal of bulk radioactive material and redundant equipment from the facility in a manner that makes use of the operational systems and personnel such that the subsequent decommissioning mission is as straightforward as possible.

For redundant reactors, POCO involves the removal of the irradiated fuel. For other facilities, it typically means operating the facility with washout reagents. The washout reagents are initially the original process reagents but can include later strong acids, strong alkalines or even complexing agents. A key consideration is that the washout reagents must remove radioactivity from the system whilst being compatible with existing downstream waste facilities. As such POCO involves using knowledge of how the facility has become contaminated over its operating lifetime and information gained from characterising the facility to plan the washouts (e.g. order, quantity, operating conditions, chemistry). Many of the facilities across the NDA estate are unique and facility specific POCO process flowsheets are used.

During transition redundant equipment is often removed. This can include safety mechanisms associated with the operating facility when they are no longer required. The choice of whether to remove redundant equipment during transition or during the decommissioning phase is dependent upon a number of factors including how easy it is to access the equipment, whether it will require modification to allow removal (e.g. size reduction) and whether it will enable other decommissioning activities (e.g. releases space, enables access). Where human access is possible standard mechanical handling (e.g. portable cranes) and size reduction technologies (e.g. mechanical saw, diamond wire, plasma torch) are typically used.

The transition phase ends with a clear handover to the decommissioning phase, which is termed as an 'Interim State'. The facility will then be either prepared for a period of C&M / Deferral or move directly to full-scale decommissioning (Deferred vs Continuous Decommissioning). The choice is dependent upon a number of factors both technical (e.g. deferral may allow short-lived radionuclides to decay) and non-technical (e.g. available funding). The Magnox reactors at the Berkeley site were the first in the UK to enter C&M in December 2010 with decommissioning not planned to start until 2074. As part of preparation for deferral, parts of the facility may be sealed to prevent external access or control the facility environment (e.g. humidity). Remote surveillance equipment may also be installed. Systems may be shut down in specific ways to protect them during the long period of inactivity. A key aspect of deferred decommissioning is the collection and retention of records (e.g. surveillance reports, waste quantities, equipment operating instructions) and knowledge. Certain small, non-active auxiliary facilities (e.g. change rooms) may be fully decommissioned

at this stage as it is more economical to replace them when final decommissioning starts than to maintain them during C&M / Deferral.

Activities on site are typically kept to minimum during C&M / Deferral. They involve surveillance through direct and/or remote inspections, planned maintenance of the facility and its equipment and updating of records.

Preparation for Decommissioning involves establishing the facilities and equipment necessary for final decommissioning. If a period of C&M / Deferral has preceded then some basic facilities may need to be re-established (e.g. change rooms). Depending upon the facility being decommissioned additional ventilation systems or environmentally controlled areas may need to be constructed as final decommissioning can raise the amount of airborne contamination and/or demolish existing containment structures. New waste handling facilities may also be required in order to handle the increased waste volumes, to handle new waste streams or simply to transfer waste to existing remote facilities.

Decommissioning typically involves a cycle of decontamination and deconstruction (e.g. deplant, dismantle, size reduce) supported by characterisation to monitor progress to leave a facility suitable for demolition by standard non-active methods. The challenges are usually more difficult than for POCO as the working environment is usually more extreme (e.g. higher dose, more airborne activity), the equipment more difficult to size reduce (e.g. heavier, thicker metalwork), the contamination less susceptible to simple decontamination approaches (e.g. concrete contaminated to variable depth) and overall scale of the problem greater. Across the NDA estate many decommissioning projects have been successfully completed although we are only now starting to make progress on the most challenging projects. Whilst Sellafield Ltd has many of the most well-known decommissioning challenges (e.g. HALES), there are significant and unique decommissioning challenges across the whole of the NDA estate, many of which are linked to the UK's early research on nuclear power. To decommission these facilities new technologies and new approaches will be required.

All stages of Site Decommissioning & Remediation are supported by characterisation. Characterisation can be typically split into *in situ* and *ex situ* characterisation. Currently the majority of characterisation is carried out *ex situ* in analytical laboratories using standard analytical technologies (e.g. gamma spectroscopy) on samples taken from the facility being decommissioned. Compared with routine reactor operations or fuel reprocessing, the characterisation needs of decommissioning are less regular in occurrence and more diverse in nature. At the same time progress in decommissioning is often determined by characterisation results. Together these factors highlight the need for a flexible, speedy approach to characterisation. One approach to address this need is the use of more *in situ* characterisation where the operator carries out their own analysis within the facility being decommissioned reducing the analysis timescale by eliminating transport of samples and results back and forth.

Land Quality Management involves managing risks to people and the environment from radioactive and non-radioactive contamination in ground and groundwater. Across the NDA estate, all of our sites have some radioactive and non-radioactive contamination either as a result of nuclear operations or from previous non-nuclear use. Using results from characterisation programmes, routine monitoring and environmental modelling studies (e.g. geochemical), site plans for managing land quality are being used to ensure that remedial action is proportionate to risk, now and in the future. Approaches and technologies for Land Quality Management used in the re-development and contaminated land industry are used

extensively. *In situ* remediation is typically preferred to *ex situ* remediation. Across the NDA estate, the greatest challenge with respect to Land Quality Management is at Sellafield. Techniques that have been investigated range from monitored natural attenuation, bioremediation, pump-and-treat to full scale excavation.

Examples of current Site Decommissioning and Remediation projects include:

- **Research Reactors at Dounreay** – There are three civil research reactors on the Dounreay site undergoing decommissioning:
  1. Dounreay Materials Test Reactor (DMTR) – It was built to test the effects of irradiation on metals and in 1958 was the first operational reactor to achieve criticality in Scotland. Operations ended in 1969. Much of the DMTR and its ancillary buildings have been decommissioned (e.g. fuel pond cleared out, decommissioning of the Remote Handled Intermediate Level Waste (RHILW) store and PIE caves completed). For the reactor internals the current approach is to immobilise the internals and size reduce the cured matrix into bulk LLW/ILW blocks using diamond wire/saw cutting technologies;



**Figure 40:** Decommissioning of Dounreay Material Test Reactor (DMTR)

2. Dounreay Fast Reactor (DFR) – It was built to test the breeder reactor concept and in 1962 became the first fast reactor in the world to provide electricity to a national grid. Operations ended in 1977; and
3. Prototype Fast Reactor (PFR) – It was the second and last fast reactor to be built in the UK and went critical in 1974. Operations ended in 1994.

Both fast reactors used liquid metal, sodium/potassium for DFR and sodium for PFR, as the coolant. Managing the liquid metal is one of the main challenges associated

with decommissioning these reactors. The approach to decommissioning these fast reactors is as follows:

- Remove bulk liquid metal coolant and destroy it in purpose built plants. This is now complete for both reactors;
  - Remove fuel from the reactors. PFR fuel is removed and a portion of DFR breeder elements remain in the reactor;
  - React the remaining residue liquid metal coolant that coats the reactor internal components by injecting nitrogen mixed with water vapour (Water Vapour Nitrogen (WVN) process);
  - Remove highly radioactive internal components with remotely operated tools<sup>28</sup> and package them in waste containers in purpose built facilities. Store the higher activity waste containers on the DSRL site;
  - Cut up the remaining reactor vessel components and shell and dispose as low level radioactive waste on the DSRL site;
  - Remove other systems and components from the plant buildings; and
  - Demolish the plant buildings.
- **Berkeley Reactors into Care & Maintenance (C&M)**<sup>29</sup> - The baseline strategy for our Magnox reactor sites is to defer reactor dismantling for around 85 years following shutdown. The drivers for this deferred reactor dismantling strategy are:
    - benefitting from radioactive decay in terms of dose rate reductions that enable dismantling to be undertaken with significant worker access, and changes in the categorisation of radioactive wastes;
    - avoiding the need for interim storage of reactor waste pending consignment to the GDF; and
    - the substantial reduction with increasing deferral time of lifecycle costs on a discounted or Net Present Value (NPV) basis.

The two Magnox reactors at the Berkeley site went into C&M (known as Safestore) in 2010, the first Magnox reactors to enter this phase. This involved defueling the reactors, characterisation of the facilities, initial deplanting (e.g. removal and recycling of redundant equipment), building works to ensure structural integrity and the installation of appropriate environmental monitoring (e.g. temperature and humidity), security and management systems. At Berkeley, the building works included the decommissioning of both reactors' eight primary gas circuits, removal of asbestos, boilers being lowered and laid down in a horizontal position, reactor roof lowered and the building clad to give robust buildings with lower visual impact. The boilers have

<sup>28</sup> 'Robots to rip out reactor core', DSRL website, 2015

<sup>29</sup> 'Reactor closure marks a first for the UK nuclear sector', Magnox Ltd website, 2010

subsequently been recycled<sup>30</sup> by smelting at Studsvik in Sweden via LLWR's metallic waste treatment framework contract. Once in C&M access will normally only be required every five years for basic monitoring and maintenance checks until Final Site Clearance (FSC).

- **Steam Generating Heavy Water Reactor (SGHWR) at Winfrith** – The SGHWR was built as a prototype power-producing water-cooled reactor. Construction started in 1963 and was completed in 1967. Operations ended in 1990. Much of SGHWR has been decommissioned (e.g. defueling complete, emptying and decontaminating of the fuel ponds complete, cooling towers demolished, redundant equipment removed including refueling machine and ventilation stack). The current stage is to decommission the primary containment, the reactor core and, finally, demolish the building and all remaining facilities. The current approach<sup>31</sup> for the reactor core involves a combination of a main segmentation cell above the reactor core into which core components will be raised and segmented before being transferred onto a floor mounted rail and trolley system to an auxiliary segmentation area for further size reduction and packing into waste baskets for grout encapsulation. Subsequent decommissioning and demolition will use conventional manual and machine operated technologies.
- **Fuel Storage Ponds at Magnox sites** – Concrete ponds were used at most of the Magnox sites to store fuel prior to the fuel being sent to Sellafield for reprocessing. The ponds can be decommissioned when all the used fuel has been removed from a site. The main decommissioning challenges are the metal skips that held the fuel, accumulated sludge at the bottom of the pond from corrosion of the magnesium fuel cladding, and caesium and strontium contamination in the water, the sludge and the walls. Whilst each pond facility is subtly different a common approach has been adopted so that lessons learnt from decommissioning the first ponds can be applied to subsequent ponds. The common six-stage approach is as follows:
  1. Furniture removal – Various techniques including long-reach tooling, existing cranes and divers are used to *in situ* size reduce and remove pond furniture;
  2. Sludge removal – Various techniques including portable dredgers, vacuum systems, filter baskets and ROVs are used to remove the sludge. Trials are being undertaken using divers to remove residual sludge;
  3. Drain and stabilise – Pond water typically needs to be treated either using an existing or purpose built effluent treatment plant. A modular floating 'pontoon' system (as used in marinas) was used as a working platform on the pond surface at Hunterston A. These are particularly effective as they move with the pond surface as the ponds are drained. The Hinkley Point A reactor pond one has recently been drained and stabilised;<sup>32</sup>

<sup>30</sup> 'End of an era as the final boiler leaves Berkeley', Magnox Ltd website, 2013

<sup>31</sup> 'Reactor decommissioning contract awarded at Winfrith', Magnox Ltd website, 2016

<sup>32</sup> 'Hinkley pond drained', Magnox Ltd website, 2015



4. Contaminated concrete removal – Level of contamination varies between ponds and, if required, a decontamination technique is selected (e.g. high pressure water jetting, concrete scabbling or shaving) based upon the depth and location of the contamination;
5. Ancillary plant removal; and
6. Entry into C&M – Surfaces of the pond may be further treated (e.g. coated with a sealant) to protect them during C&M.



**Figure 41:** Scabbling of the pond walls at Trawsfynydd

- **PCM Magazines at LLWR<sup>33</sup>** – When the LLWR site was a ROF, concrete bunkers (magazines) were constructed to store munitions e.g. TNT. During the 1950s and 1960s PCM was stored in some of the magazines. During the 1990s modern facilities were constructed to facilitate the removal, repackaging and transport of the waste for safe storage in modern purpose built facilities at the Sellafield site. A programme to decommission these magazines was launched in 2008, with the objective to demolish them and to remove all legacy drums and generated PCM waste drums from the LLWR site, in a safe, cost-effective and timely manner. Bulk PCM material has been repackaged in drums and returned to Sellafield for long term storage. Decommissioning is now underway and involves removing contamination from the face of the concrete structures (e.g. concrete scabbling) and removal of the ventilation systems in preparation for demolition using traditional techniques.
- **First Generation Reprocessing Plant at Sellafield** – The First Generation Reprocessing Plant (FGRP) was constructed in the early 1950s to carry out the first

<sup>33</sup> 'PCM teamwork pays dividends', LLWR Ltd website, 2016

stage of reprocessing fuel from the Windscale Pile Reactors. It was later modified for oxide fuels following the opening of the Magnox Reprocessing Plant, before ceasing operations in the 1970s. The plant contains four highly active cells, each containing redundant radioactive material, and two medium active cells. The primary decommissioning challenge associated with FGRP is the safe removal of a 61m high ventilation stack located on the roof of the building which is itself located in a congested area within the Sellafield site. Demolition of the stack could however not be completed until a new ventilation plant, the Separation Area Ventilation (SAV) Plant, was constructed and commissioned to provide ventilation services to buildings that previously used the FGRP stack. The SAV project comprised the new two-storey ventilation plant room housing ventilation equipment, a ventilation discharge monitoring plant room and a series of new steel support structures. The project has recently been completed.<sup>34</sup> This interconnectivity is one of the challenges associated with decommissioning the Sellafield site. For the demolition of the FGRP stack, a self-climbing platform, similar to the one used to decommission the chimneys at London's Battersea Power Station, will be used to bring the stack down bit by bit in a controlled manner. Conventional demolition using explosives is not feasible because of the location of the stack.

The facilities within the FGRP, which in many ways are representative of the wider decommissioning challenges across the Sellafield site, also offer the opportunity to demonstrate new decommissioning technology. For example, a fibre laser mounted on a snake-arm robot has been used to size-reduce a redundant dissolver within FGRP as a demonstration of the technology for remotely size-reducing equipment within a radioactive environment<sup>35</sup>.

- **Windscale Pile Chimney at Sellafield** – As part of the Windscale Pile Reactors two chimneys with filters installed at the top were constructed to provide passive cooling of the reactors. In 1957, a fire occurred in Pile No. 1 causing a release of radioactivity to the environment and contaminating the associated chimney and its filters. Following the fire the chimneys were sealed at the top and the contaminated filters removed, so air inlet ducts could be isolated. The chimney associated with Pile No. 2 was reduced to the level of the adjacent reactor building in 2001, but the chimney associated with Pile No. 1 poses more of a challenge due to radioactive contamination from the fire. As well as the radiological issues, there are many conventional safety issues. It is 120m high and is located in a highly congested location within the Sellafield site. The proposed approach uses existing demolition technology. A tower crane will be installed next to the chimney and used to lower large concrete blocks that have been cut from the chimney using diamond wire and following a pre-defined cutting path.<sup>36</sup>

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<sup>34</sup> 'Build it up to knock it down – completion of ventilation stack allows demolition of predecessor', Sellafield Ltd website, 2016

<sup>35</sup> LaserSnake2 project led by OC Robotics, and including TWI, the National Nuclear Laboratory, ULO Optics and Laser Optical Engineering. Part funded by NDA, Innovate UK and Department of Energy and Climate Change (DECC)

<sup>36</sup> 'Windscale chimney decommissioning', Sellafield Ltd website, 2014

- **Ground and Groundwater Remediation at Sellafield<sup>37</sup>** – The Sellafield site is located to the west of the Lake District on the edge of the Irish Sea; it sits either side of the River Calder and surrounding land use is mainly pasture with some farm dwellings. Radioactive liquors are known to have leaked to ground from several plant buildings, waste storage vaults and burial trenches within site. These are largely associated with older process plants in the Separation Area, an area around the current and older production plants in the centre of site. Records from boreholes and other excavations undertaken during decades of site engineering and construction work have demonstrated that radioactively contaminated ground exists beneath parts of Separation Area and occasionally in the wider site. In addition there is potential for other components of spent fuel reprocessing to have contaminated ground. These include inorganic salts from neutralised acids, solvents and organic compounds as well as contaminants more typically associated with industrial activity, such as heavy metals, fuel and oils. There has also been on site disposal of waste throughout plant operations, during the 1950s trenches within Separation Area were used and later landfills were built up on the coastal fringe and northern perimeter of the site. Sellafield Ltd has a programme of work to understand, control and manage the legacy of ground contamination to ensure protection of the workforce, the public and the environment. It is an extensive programme that will last for over 100 years. The short to medium term objectives of the programme are to minimise any increase in the contaminated ground inventory and limit expansion of the volume of contaminated ground. The longer term objective is to work towards the site's end-state as stated in the NDA strategy [3].

A major programme of land quality characterisation and assessment beneath the Separation Area of the site was successfully completed in 2010. The investigation has led to a considerable improvement in the interpretation of the geology, hydrogeology and land quality of the Sellafield site which confirms much of the previous understanding and gives confidence in the current management arrangements for the historical contamination.

There is an on-going programme of groundwater monitoring at Sellafield to identify any significant changes in groundwater, both underlying and in the vicinity of the Sellafield site. The strategy for the monitoring programme is reviewed on a periodic basis and in 2010 it was aligned with the principles of the Data Quality Objective (DQO) method [16]. The programme makes extensive use of groundwater monitoring wells, some with multiple sampling points (>170 sampling points and typically >600 samples per year).

A considerable amount of data is generated by the characterisation and monitoring programmes. Industry standard software is used to enhance Sellafield Ltd's understanding of the data, using GIS (Geographical Information System) programmes to visualise spatial data and subsurface data visualisation software, to focus more specifically on borehole data analysis.

A number of conceptual and predictive computer models have been developed to aid Sellafield Ltd's understanding of the current challenge and how it could change over

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<sup>37</sup> 'Land Quality Management at Sellafield', Sellafield Ltd website

the coming years. The models have highlighted the importance of considering the site as a whole rather than individual issues.

The approach to ground and ground remediation at the site will continue to evolve as there is greater clarity on the site end state and additional characterisation data is collected as decommissioning progresses. Land contamination will be managed both through *in situ* and *ex situ* methods.

## Relevant organisations

DSRL:	Decommissioning of redundant facilities and remediation of site.
LLWR:	Decommissioning of redundant facilities and remediation of site.
MxL:	Decommissioning of redundant facilities and remediation of sites.
SL:	Decommissioning of redundant facilities and remediation of site.

## Technology Opportunities

Whilst the approach to Site Decommissioning is often facility specific there are however some common technical challenges:

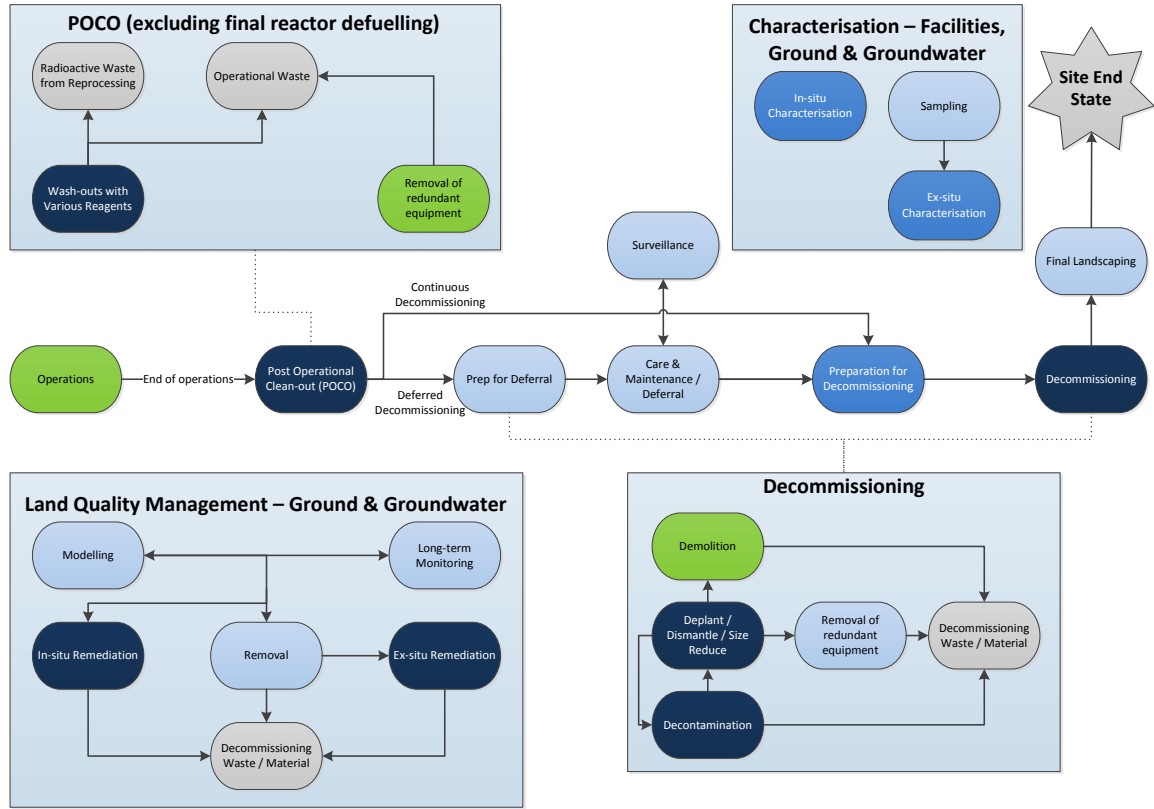
- Improved data visualisation tools to assist decision making;
- *In situ* characterisation to determine level of contamination:
  - Portable versions of existing characterisation techniques; and
  - Non-destructive evaluation technologies.
- Improved decontamination techniques:
  - Increased efficiency and effectiveness;
  - Reduction in secondary waste; and
  - Removal of heels and residues from process vessels.
- Remote or enhanced operation for extreme conditions (e.g. high dose, confined spaces):
  - Enhanced tools and techniques for air-fed suit decommissioning operations;
  - Enhanced tele-operation (e.g. virtual reality and haptics); and
  - Robotics and autonomous systems.
- Technologies and approaches for monitoring facilities and their contents over extended periods of C&M / deferral; and
- Waste treatment technologies for decommissioning wastes:
  - Sort and segregation approaches.

Similarly whilst the approach to Site Remediation is often site specific, there are however some common technical challenges:

- Improved groundwater monitoring:
  - Increased automation to increase frequency of monitoring and reduce cost;
  - Increased information (e.g. isotopic ratios, chemical speciation, improved limit of detection) to identify source of contamination;
  - Increased information (e.g. *in situ* groundwater flux measurement) to improve predictions of movement of contaminants; and
  - Improved statistical approach to monitoring programme.
- Improved data visualisation tools to assist decision making;
- Improved knowledge regarding interactions of radionuclides with the environment:
  - Refine or eliminate assumptions in conceptual and predictive models; and
- Techniques for early detection of leaks from existing facilities;
- *In situ* remediation of contaminated ground:
  - Techniques (e.g. bioremediation) that either reduce or limit the spread of contaminants and can be applied on sites with facilities still present.
- *Ex situ* remediation of contaminated ground:
  - Techniques (e.g. sort and segregation; thermal treatment) that reduce the volume of contaminated ground that requires further long-term management.

The timing and scale of these Site Decommissioning and Remediation challenges varies depending upon the site characteristics and decommissioning progress. For example, R&D needs associated with *in situ* and *ex situ* remediation of contaminated ground are mostly associated with the Sellafield site and significantly in the future (typically after 2025).

Process Wiring Diagram



**Figure 42: PWD for site decommissioning and remediation**

(Land Quality Management and Characterisation activities are carried out throughout the Site Decommissioning and Remediation lifecycle)



## 6 Summary

This document provides a high-level overview of the processes and associated technologies used or planned to be used to deliver the NDA mission (i.e. Technical Baseline) and the organisations responsible for their development and implementation. It has been constructed from a combination of the NDA's Strategy [3] and the NDA estate's Technical Baseline and underpinning R&D (TBuRD) submissions. It has been structured around NDA's four driving Strategic Themes:

- Nuclear Materials;
- Spent Fuels;
- Integrated Waste Management; and
- Site Decommissioning & Remediation

Each section provides relevant historical context, description of the current approach and associated technologies, relevant delivery organisations, technology opportunities and a high-level Process Wiring Diagram.

The information from each section is summarised in a single diagram, NDA Estate Technology Map (Figure 43). Key areas of significant future R&D include:

- Treatment, reuse and disposal of plutonium;
- Geological disposal of waste;
- Management of legacy wastes and in particular its retrieval, treatment, packaging and disposal;
- POCO and treatment associated with decommissioning;
- Characterisation of ground, groundwater, facilities and waste; and
- *Ex situ* and *in situ* treatment of ground and groundwater.

The majority of the R&D requirements are associated with the Sellafield site and the disposal of its waste. Their timing is therefore dependent upon the progress of decommissioning at Sellafield. There are however significant technical challenges across the rest of the NDA estate. R&D is therefore fundamental to ensuring the cost-effective delivery of our mission. Significant technology opportunities have also been identified across the NDA estate. The implementation time for the technology opportunities varies considerably. For example, there is a relatively short timescale for implementation of any technology opportunities for reprocessing NDA's spent fuels whereas technology opportunities associated with decommissioning the Sellafield site will exist for at least 50 years. Ideas for new approaches and technologies come from a range of sources, including NDA estate employees, our supply chain organisations, related industries (e.g. oil and gas decommissioning) and academia. This document will provide the technical community with information regarding the approaches and technologies currently being adopted. Future versions of this document will include any changes to the Technical Baseline and highlight the impact of R&D on the delivery of the NDA's mission.



Figure 43: NDA Estate Technology Map – Current R&D needs, risks and opportunities

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## 8 Abbreviations

For abbreviations that refer to a specific building or facility, the SLC is listed along with the most appropriate section within the report for further information.

ADAP	Aqueous Discharge Abatement Plant (MxL, page 45)
AGR	Advanced Gas-cooled Reactors
AHF	Active Handling Facility (SL, page 38)
ATR	Annual Technical Report
BAT	Best Available Technology
BEP	Box Encapsulation Plant (SL, page 40)
BEPPS	Box Encapsulation Plant Product Store (SL, page 40)
BPM	Best Practicable Means
BST	Bulk Storage Tanks (SL, page 31)
C&M	Care and Maintenance
CANDU	Canadian Deuterium-Uranium
DECC	Department of Energy and Climate Change
DCIC	Ductile Cast Iron Container
DFR	Dounreay Fast Reactor (DSRL, page 15)
DMTR	Dounreay Materials Test Reactor (DSRL, page 59)
DQO	Data Quality Objective
DSRL	Dounreay Site Restoration Ltd
EARP	Enhanced Actinide Removal Plant (SL, page 33)
EDFE	EDF Energy
EDP	Effluent Distribution Plant (SL, page 43)
EDS	Engineered Drum Stores (SL, page 48)
EPS	Encapsulated Product Stores (SL, page 40)
ESC	Environmental Safety Case
FED	Fuel Element Debris
FGMSP	First Generation Magnox Storage Pond (SL, page 41)
FGRP	First Generation Reprocessing Plant (SL, page 62)
FHP	Fuel Handling Plant (SL, page 10)
FSC	Final Site Clearance

FST	Floc Storage Tanks (SL, page 37)
GDF	Geological Disposal Facility
GIS	Geographical Information Systems
HAL	Highly Active Liquor
HALES	Highly Active Liquor Evaporation and Storage (SL, page 32)
HAST	Highly Active Storage Tank (SL, page 32)
HAW	Higher Activity Wastes
HEPA	High-Efficiency Particulate Air
Hex	Uranium Hexafluoride
HEU	High Enriched Uranium
HIP	Hot Isostatic Pressing
HLW	High Level Waste
I/EF	Import/Export Facility (SL, page 40)
ILW	Intermediate Level Waste
IWM	Integrated Waste Management
LAR	Liquor Activity Reduction
LAW	Lower Activity Wastes
LETP	Local Effluent Treatment Plant (SL, page 38)
LLW	Low Level Waste
LLWR	Low Level Waste Repository Ltd
LP&S	Legacy Ponds and Silos (SL, collective name for FGMSP, PFSP, MSSS and PFCS)
LWR	Light Water Reactor
MDU	Magnox Depleted Uranium
MEP	Magnox Encapsulation Plant (SL, page 32)
MOD	Ministry of Defence
MOX	Mixed Oxide Fuel
MSSS	Magnox Swarf Storage Silo (SL, page 38)
MxL	Magnox Ltd
NDA	Nuclear Decommissioning Authority
NM	Nuclear Materials
NOx	Nitrogen Oxides
NPV	Net Present Value

OPSZ	Outer Perimeter Security Zone (SL, page 52)
PBTF	Package to Box Transfer Facility (SL, page 40)
PCM	Plutonium Contaminated Material
PIE	Post Irradiation Examination
POCO	Post Operational Clean Out
PFR	Prototype Fast Reactor (DSRL, page 16)
PFCS	Pile Fuel Cladding Silo (SL, page 40)
PFSP	Pile Fuel Storage Pond (SL, page 37)
PWD	Process Wiring Diagram
R&D	Research and Development
RHILW	Remote Handled Intermediate Level Waste
ROF	Royal Ordnance Factory (LLWR, page 50)
ROV	Remotely Operated Vehicle
RWM	Radioactive Waste Management Ltd
SAV	Separation Area Ventilation (SL, page 63)
SEP	Silo Emptying Plant (SL, page 39)
SETP	Segregated Effluent Treatment Plant (SL, page 34)
SF	Spent Fuels
SGHWR	Steam Generating Heavy Water Reactor (MxL, page 61)
SHM	Skip Handling Machine (SL, page 42)
SIP	Shaft Intervention Platform (DSRL, page 44)
SIXEP	Site Ion Exchange Effluent Plant (SL, page 31)
SL	Sellafield Ltd
SLC	Site Licence Company
SME	Small and Medium-sized Enterprise
SPP1	Sludge Packaging Plant 1 (SL, page 42)
SPRS	Sellafield Product Residue Store (SL, page 20)
SRP	SPRS Retreatment Plant (SL, page 20)
SSB	Self-Shielded Box
STP	Solvent Treatment Plant (SL, page 34)
TBuRD	Technical Baseline and underpinning Research and Development
THORP	Thermal Oxide Reprocessing Plant (SL, page 12)



TLC	Third Length Container
TMF	Tails Management Facility (URENCO, page 23)
TPU	THORP Product Uranium
TRL	Technology Readiness Level
UKRWI	UK Radioactive Waste Inventory
UWT	Unconditioned Waste Transfer (SL, page 31)
VLLW	Very Low Level Waste
VPS	Vitrified Product Store (SL, page 32)
WAMAC	Waste Monitoring and Compaction Facility (SL, page 51)
WEP	Waste Encapsulation Plant (SL, page 31)
WPEP	Waste Packaging and Encapsulation Plant (SL, page 33)
WRACS	Waste Receipt Assay Characterisation Supercompaction (DSRL, page 51)
WTC	Waste Treatment Complex (SL, page 48)
WTF	Waste Transfer Facility (SL, page 40)
WVN	Water Vapour Nitrogen
WVP	Waste Vitrification Plant (SL, page 32)