UK Civil Nuclear Decommissioning, a Blueprint for Korea’s Nuclear Decommissioning Future?: Part II – UK’s Progress and Implications for Korea

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The nuclear legacy that remains in the United Kingdom (UK) is complex and diverse. Consisting of legacy ponds and silos, redundant reprocessing plants, research facilities, and non-standard or one-off reactor designs, the clean-up of this legacy is under the stewardship of the Nuclear Decommissioning Authority (NDA). Through a mix of prompt and delayed decommissioning strategies, the NDA has made great strides in dealing with the UK’s nuclear legacy. Fuel debris and sludge removal from the legacy ponds and silos situated at Sellafield, as part of a prompt decommissioning strategy for the site, has enabled intolerable risks to be brought under control. Reactor defueling and waste retrievals across the Magnox fleet is enabling their transition to a period of care and maintenance; accelerated through the adopted ‘Lead and Learn’ approach. Bespoke decommissioning methods implemented by the NDA have also enabled the relevant site licence companies to tackle non-standard reactor designs and one-off wastes. Such approaches have potential to influence and shape nuclear decommissioning decision making activities globally, including in Korea.

Keywords: Nuclear decommissioning, Nuclear decommissioning authority, Sellafield, Magnox reactors, United Kingdom, Korea

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<td>AGR</td>
<td>Advanced Gas-Cooled Reactor</td>
<td>NDPB</td>
<td>Non-Departmental Public Bodies</td>
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<td>AtG</td>
<td>German Atomic Energy Act</td>
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<td>C&amp;M</td>
<td>Care and Maintenance</td>
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<td>CDT</td>
<td>Centre for Doctorial Training</td>
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<td>Office for Nuclear Regulation</td>
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<td>Centre for Innovative Nuclear Decommissioning</td>
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<td>BEIS</td>
<td>Department for Business, Energy, and Industrial Strategy</td>
<td>PFR</td>
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<td>Dounreay Fast Reactor</td>
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<td>D.S.E.</td>
<td>Dismantling after Safe Enclosure</td>
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<td>Pressurised Heavy Water Reactor</td>
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<td>DSRL</td>
<td>Dounreay Site Restoration Limited</td>
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<td>Post Operational Clean Out</td>
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<td>DTC</td>
<td>Doctorial Training Centre</td>
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<td>EARP</td>
<td>Enhanced Actinide Removal Plant</td>
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<td>Research and Development</td>
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<td>EPSRC</td>
<td>Engineering and Physical Sciences Research Council</td>
<td>RAP</td>
<td>Retrievals Access Penetration</td>
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<td>FGMSP</td>
<td>First Generation Magnox Storage Pond</td>
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<td>GCR</td>
<td>Gas Cooled Reactor</td>
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<td>Submarine Dismantling Project</td>
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<td>Geological Disposal Facility</td>
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<td>HAW</td>
<td>Higher Activity Waste</td>
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<td>High-Level Radioactive Waste</td>
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<td>Steam Generating Heavy Water Reactor</td>
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<td>Immediate Dismantling</td>
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<td>Korea Electronic Power Corporation Nuclear Fuel</td>
<td>SMR</td>
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<td>Local Effluent Treatment Plant</td>
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<td>Sludge Packing Plant</td>
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<td>LLW</td>
<td>Low-Level Waste</td>
<td>SPRS</td>
<td>Sellafeld Product and Residue Store</td>
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<td>LLWR</td>
<td>Low-Level Waste Repository</td>
<td>SRP</td>
<td>Sludge Retrievals Pump</td>
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<td>LPS</td>
<td>Legacy Ponds and Silos</td>
<td>Thorp</td>
<td>THermal Oxide Reprocessing Plant</td>
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<td>Magnox</td>
<td>MAGnesium None OXidizing</td>
<td>TRL</td>
<td>Technology Readiness Level</td>
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<td>MoD</td>
<td>Ministry of Defence</td>
<td>UK</td>
<td>United Kingdom</td>
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<td>MODP</td>
<td>Magnox Optimised Decommissioning Plan</td>
<td>UKAEA</td>
<td>United Kingdom Atomic Energy Authority</td>
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<td>MSSS</td>
<td>Magnox Swarf Storage Silo</td>
<td>UKRWI</td>
<td>UK Radioactive Waste Inventory</td>
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<td>NDA</td>
<td>Nuclear Decommissioning Authority</td>
<td>VLLW</td>
<td>Very Low-Level Waste</td>
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<td>WAGR</td>
<td>Windscale Advanced Gas Cooled Reactor</td>
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1. Introduction

In the United Kingdom (UK), the term ‘Nuclear Legacy’ is used to describe those facilities that remain from early nuclear programmes. Major decommissioning challenges include: Sellafield Legacy Ponds and Silos (LPS; E.g. Pile Fuel Storage Pond (PFSP), Magnox Swarf Storage Silo (MSSS)); Sellafield Magnox & Thorp plants decontamination & dismantling; Sellafield Windscale Piles; research facilities (Dounreay & Harwell etc); non-standard and one-off reactor designs (E.g. Winfrith); Magnox reactor power plant Graphite; managing non-standard fuels, commonly referred to as ‘exotics’; and currently no Geological Disposal Facility (GDF) for Intermediate or High Level Waste (ILW/HLW). The challenges facing the UK’s nuclear industry regarding its nuclear legacy have required innovative, unique and high-tech engineering solutions. As a result, the UK has become a world-leader in decommissioning, exporting its expertise around the world.

Since the introduction of the Republic of Korea (hereafter ‘Korea’) Government’s Energy Transition Policy in 2017 [1, 2], Korea has begun to transition from being a major nuclear power producing nation to a decommissioning centric one. As the Korean nuclear industry readies itself for decommissioning it is important to establish an understanding of the challenges faced and methods available to overcome them [3-5]. While different challenges await Korea than those faced by the UK, the approaches taken by the UK offer a way forward to deal with and overcome these challenges.

In this, the second of a two-part review, we aim to provide an overview of the advances taken to solve the UK’s nuclear legacy, the future of decommissioning in the UK, and implications for the Korean decommissioning challenge. It is hoped the reader will come to appreciate the complexity of the problems regarding nuclear decommissioning but also gain an insight into some possible decommissioning strategies applicable to the Korean case.

2. Sellafield Decommissioning

Sellafield is the key site of the Nuclear Decommissioning Authority’s (NDA) estate and includes some of the most significant decommissioning challenges facing the UK. The NDA established Sellafield Ltd. (SL), a Site Licence Company (SLC), set up to specifically deal with the nuclear legacy and decommissioning operations at Sellafield. The NDA and SL have over seen the Sellafield site transition from fuel reprocessing operations to decommissioning over the past 10+ years. The major decommissioning problems facing SL and the NDA relate to a historical legacy of nuclear research and weapons programmes of the 1950s and 1960s. Sellafield alone houses...
8 of the 10 most hazardous facilities on the entire NDA estate [6]. Significant problems arise with the fuel storage ponds in which nuclear materials were simply dumped without much regard for their future recovery. Many of these legacy problems are further complicated by a lack of records and poor management practices of the time. While more recent operations such as Thorp and Magnox still pose significant challenges for decommissioning, some of these are mitigated by more modern infrastructure and better management practices of recent years.

The NDA’s overarching strategy for Sellafield largely revolves around prompt decommissioning practices, with particular focus on those risks that are deemed intolerable [7-9]. This approach has enabled the NDA to identify and prioritise treating the most hazardous areas of the site to dramatically reduce the level of remaining hazards as quickly as possible. Sellafield’s LPS are considered the most intolerable risks, requiring urgent action. The goal of decommissioning at the Sellafield site is to achieve green field status, although status as a brown field site would still be seen as a great achievement. In order to achieve this, the NDA and SL have identified a number of key long-term milestones (Fig. 1).

2.1 Current Decommissioning Progress

The focus for the LPS has been on developing the required infrastructure and capabilities to enable waste retrieval to commence. To date equipment has been installed allowing sludge removal to begin. In the MSSS waste removal machinery is being installed in preparation for the availability of facilities to receive the retrieved wastes. Active commissioning of the Sellafield Product and Residue Store (SPRS) was completed to safely and securely store nuclear materials on site [10]. Completion of the SPRS enabled materials from older stores, which either reached their end of life or were deemed no longer suitable, to be relocated. Defueling and fuel transfers were completed in 2019, with Wylfa and Calder Hall being the final two Magnox reactors to be defueled. Sellafield continues to receive fuel from the Gen II AGR (Advanced Gas-Cooled Reactor) stations for safe storage (planned closure mid-2030s). Reprocessing operations at Sellafield will be completed by the end of 2022 (COVID-19 restrictions permitting). Following the completion of fuel reprocessing operations, decommissioning of the rest of the site will become a new focal point.

2.1.1 Legacy Storage Ponds

The Pile Fuel Storage Pond (PFSP) is a 100 metre long open air pond that was built as a storage and cooling facility for irradiated fuel and isotopes from the two Windscale reactors [11]. It is the oldest pool on the site and operated successfully until 1962. It was then used for storage of miscellaneous ILW and fuel until the mid-1970s after which it, along with the contained inventory, was placed into a passive Care and Maintenance (C&M).

The First Generation Magnox Storage Pond (FGMSP) was built (1959) for the receipt, storage and decanning of irradiated Magnox fuel [12]. The pond also took over fuel handling operations from the PFSP processing a total of 27,000 tonnes of fuel (almost 2.5 million fuel rods between 1960 until 1986). The pond is 20 metre wide, 150 metre long and 6 metre deep. Decanning operations ceased in 1988 when a new fuel handling plant became operational.

Both ponds have deteriorated over time and have become an ‘intolerable risk’. They contain an inventory of historic radioactive sludge, Low- and Intermediate-Level Waste (LLW) solids. In the case of the FGMSP, it also contained large amounts of spent fuel. The sludge (formed from decaying nuclear fuel, metallic corrosion, windblown debris, natural growing algae and other debris) has accumulated in the water and settled to the bottom of the ponds over time [13]. Of the two ponds, the contents of the PFSP are significantly more varied due to it being used as a dump for miscellaneous radioactive waste over the years. This makes decommissioning more complex due to the varied nature of the ponds contents.
Example contents of the PFSP [13]:

- Fuel cladding (Magnox, aluminium and zircaloy)
- Isotope cartridges, irradiated within the piles and Magnox reactors
- Reactor components, from Calder Hall, Chapelcross and the Windscale piles
- Residual items of sludge, larger than the sludge recovered during sludge retrieval operations
- Original process equipment, such as fuel skips, flasks, decanners, guide rails and trolleys
- Debris that has fallen into the pond over time
- Scrap items that have been stored in the pond as no other waste route was available at the time
- Ion exchange media

The sludge, approximately 300 m$^3$ and 2,000 m$^3$ in the PFSP and FGMSP ponds [11, 14], respectively, along with the remaining fuel debris and other wastes must be removed so the facilities can be safely decommissioned. In the PFSP the sludge accounts for one-third of the pond’s remaining radioactive content, after 70% of the total radioactivity was removed in 2016 with the completion of fuel exports [15]. The FGMSP held some 14,000 m$^3$ of contaminated waste in addition to the sludge. The sludge has a similar consistency to sand and is a mobile wasteform. This increases hazards associated with loss of containment. The sludge must be removed with care to ensure the water level remains in place to act as a radiation shield. The sludge also prevents effective characterization and retrieval of the other waste forms, in part due to the reduction in visibility the sludge causes if disturbed. By removing the sludge, the remaining radioactive inventory can be progressively removed safely, thus reducing the hazard/risk posed by the ponds in their current state, enabling subsequent dismantling of the structures. To achieve the planned end state, pond decommissioning is broken into six stages [11]:

- Pond preparation
- Canned fuel retrieval
- Sludge retrieval
- Metal fuel retrieval
- Solid waste retrieval
- Pond dewatering and dismantling

Pond preparation involves transforming a pond from a passive store to a plant capable of complex retrieval operations. This involves plant and equipment upgrades, removal of redundant structures and in the case of the PFSP the provision of the Local Effluent Treatment Plant (LETP) for removing particulates and dissolved activity from the pond water [16]. The LETP combines a sand bed filter (for particle removal) and ion exchange media for the removal of radionuclides, predominately caesium and strontium [13, 16]. Combined, they account for more than 99% of the soluble radioactivity of the PFSP liquor. The LETP unit can process up to 125 m$^3$ of pond water per day, of which approximately 100 m$^3$ is returned to the pond. The remaining water is discharged to a low active drain.

Canned fuels, including oxide and carbide fuels, represented the most significant inventory in the ponds. The canned fuels were removed from the pond and sent to existing site facilities to allow the fuel to be reprocessed and/or conditioned for long term storage. The bulk stocks of fuel have now been removed from the PFSP [15], leaving the sludge as the biggest remaining radioactive hazard. Substantial quantities of fuel remain in the FGMSP and are actively being removed.

Sludge retrieval involves providing the equipment necessary to retrieve the bulk of the sludge. In the case of the PFSP initial sludge removal involves pumping the material into a purpose-built treatment plant next to the pond, before being transferred to the drum filling plant where it is grouted, rendering the waste passively safe, and prepared for long term storage ready for final disposal in a GDF. Early 2017 saw the first 500-litre drum containing the mud-like radioactive sludge being moved to the encapsulation plant [17]. The sludge in the FGMSP is less dense and easier to remove. Removal is performed via a centrifugal slurry
suction pump (Sludge Retrieval Pump, SRP) mounted upon a floating remote-controlled platform which is controlled from the sides of the FGMSP fuel pond (Fig. 2, Fig. 3) [18, 19]. This maintains operator safety at all times owing to the levels of radiation present in the pond due to the remaining spent fuel. The sludge is then pumped through a flexible suction hose and sent to the new £200 million Sludge Packing Plant (SPP) [19]. The slurry is sent to the SPP in batches of 80 m³ (including flushing of the slurry line with pond water) where it is stored in tanks and allowed to settle. After settling, the top layer of water is sent back to the FGMSP pond. The settled sludge is then grouted and stored before long term disposal. The first of the sludge was removed in 2015 [19].

Metal fuel retrieval provides the fuel handling, conditioning, sentencing and export equipment required to remove metal fuel from the ponds for export to on-site facilities for interim storage and disposal. A final retrieval project will provide methods for handling, retrieval, packaging and export of the remaining solid ILW within the pond. This includes residual metal fuel pieces, fuel cladding (Magnox, aluminium and zircaloy), isotope cartridges, reactor components, and miscellaneous activated and contaminated items. Conditioning of these wastes is then performed via one of the sites treatment plants prior to disposal. One significant challenge to the removal of the sludge from the FGMSP is the presence of old metal fuel storage boxes which lie at the bottom of the pond. Their presence limits the movement of the suction hose and prevents all the sludge being removed. Removal of these boxes began in mid-2018 with the first 100 of over 1,200 being removed. Robotic laser cutting will be employed to cut up the retrieved boxes to allow them to be flat packed and stored more effectively [20]. This marks a significant step in de-cluttering the pond, giving operators enough room to manoeuvre and suck up the remaining sludge.
Removal of the solids and sludge will represent a significant reduction in radiological inventory. Subsequently pond dewatering and dismantling of the structures can occur with strategies currently being developed to enable this to happen. A ten-year project to dewater the pond was started during 2019, while sludge is still being removed. Due to the challenges faced in cleaning the inventory from the FGMSP pond, the programme is expected to last several decades before the pond structure can be decontaminated and finally dismantled.

Fig. 4. PFCS waste retrievals methodology using the RAP rig.

Fig. 5. Silo containment doors (PFCS). Photograph courtesy of Sellafield Ltd.

2.1.2 Legacy Storage Silos

The Pile Fuel Cladding Silo (PFCS) was commissioned along with the Windscale Piles and associated equipment in the early 1950s for use as a dry ILW storage facility for waste (outer fuel casings) resulting from the de-canning of pile fuel and later Magnox fuels [16]. The silo is a concrete structure 29 metres long 10 metres wide and 18 metres high and is divided into six compartments, each containing ILW. Each of the six compartments is split into two bays (a north and south bay) separated by a dividing wall. When tipping operations stopped in the 1960s the silo was filled with argon gas to prevent the magnesium alloy from igniting and was sealed with the intention of never being opened again.

The Magnox Swarf Storage Silo (MSSS) was built to store waste from the UK’s fleet of Magnox reactors. Before being reprocessed, Magnox fuel is stripped of its outer magnesium cladding, a procedure known as decanning. This removed cladding, termed swarf and mixed with UO$_2$, was stored underwater. The first facility of six silos, each silo 16 metre deep, began operations in 1964. By 1983 a total of 22 silos had been built [21]. From the 1990s wet storage of Magnox swarf was superseded by dry storage options.

As time has passed the silos have begun to show significant signs of degradation and are no longer a tolerable
risk. Removal, treatment and appropriate long-term storage of the waste as well as decontamination and dismantling of the silos are a high priority.

To gain access to the waste within the PFCS silo, rectangular shaped holes have been cut at the top of each of the facility’s six compartments. Cutting and accessing inside the silo was performed by a specially designed rig, capable of safely cutting the hole whilst maintaining airtight containment, known as the Retrievals Access Penetration (RAP) rig (Fig. 4) [22]. In tandem with the hole cutting, six deflector plates positioned at the top of the silo had to be removed to allow for clean and easy access of the waste below [23]. Due to the potential risk of fire and high radiation levels owing to the ILW below, remote water jet cutting techniques were used. Such a technique is incapable of generating sparks and does not require site workers to enter the silo. Specially fitted doors (Silo containment doors – 124 tonne each) were pre-installed on all compartments and lowered over the apertures temporarily sealing each silo (Fig. 5). These giant steel doors will provide radiological shielding and maintain the inert argon atmosphere inside the silo until waste retrievals begin (currently scheduled for 2020–21). The current anticipated completion of retrievals is 2027. To retrieve the waste, a crane arm suspended through the cut holes will be extended while carrying a grabber that will drop down to scoop the waste up (Fig. 4). The collected waste will then be lifted out of the container and into a specially-designed metal box, and taken for conditioning, transport and be safely stored, prior to final disposal.

The MSSS closed in 2000 and is now being decommissioned. Before the building can be decontaminated and demolished the remaining waste, including the water in which it is submerged, must be retrieved. The agreed strategy for waste retrieval involves mechanical retrieval of the bulk solid wastes; loading the waste into shielded transfer packages; processed and encapsulated for long-term storage; and safe storage on the Sellafield site until a permanent GDF is constructed. To achieve this a 360 tonne Silo Emptying Plant (SEP) machine has been developed which will sit above the silos and will reach into the silos to remove the waste with a hydraulic grab (Fig. 6, Fig. 7) [16]. The waste will then be placed into a 50-tonne waste transfer package which is suitable for shielding and transferring of the waste. The package will be used to transfer nuclear waste between the silo facility and Silo Direct-Encapsulation Plant (SDEP) [24]. The drums will remain at Sellafield in
interim storage until a permanent GDF is available. The SEP machines have begun removing magnesium swarf waste from the building’s 22 silo compartments since 2019. Although accessing within the ageing nuclear silos presents a slight increase in near-term risk, the work is essential to the longer-term mission of overall risk and hazard reduction. The greatest risk increase is during the retrievals work. Dramatic reductions in the apparent risk will drop with both residuals removal and the emptying of the silos.

2.1.3 Windscale Piles

Decommissioning work began during the 1980s. This involved sealing off the bioshield, installing ventilation and monitoring utilities, removal of loose fuel elements outside the core, and draining the water duct. As of 2004, Pile 1 still contained about 15 tonnes of uranium fuel.

More recently work has focused on carrying out intrusive survey work of the Pile 1 core and developing approaches to remove the final fuel elements and isotopes from the damaged reactor. However, as the rapid decommissioning of the Windscale Piles are not deemed critical (compared to the significantly greater hazards posed by the LPS) continued decommissioning operations have been greatly reduced. Current plans aim for Windscale Pile 1 and 2 to enter C&M with fuel and isotopes removed by 2030. In contrast, the Pile 1 chimney was seen as a significant hazard and therefore was prioritised for decommissioning (See below). Final site clearance is expected by 2050.

Although not an ideal situation, it is a good example of how carefully planned delays in decommissioning at one site allows for accelerated activities at another, thus reducing the overall site risk much quicker.

2.1.4 Windscale Chimney (Pile 1)

The Windscale fire of 1957 released significant quantities of radioactive dust and material from the core of the reactor. However, most of the radionuclides (estimated at 95%) were caught by the filters placed at the top of the 125-metre-tall Pile-1 chimney [25]. Following the fire, the contaminated filters were removed with the remaining chimney being sealed, allowing for the radiation to decay, and awaiting a suitable course of action to be decided.

Decommissioning of the remaining chimney first started in the 1980s with the removal of some of the brick and ancillary facilities [25]. The structure was reopened in 2014 which allowed for the removal of the filter galleries from the top of the stack by conventional demolition techniques (e.g. drilling and pneumatic hammers) and to enable preparation of the remaining stack (square “diffuser” filter holding structure and stack column) for demolition. Conventional demolition techniques (e.g. wrecking balls) could not be used to bring down the contaminated chimneys due to the proximity of surrounding structures and associated radiological risks, so they had to be demolished systematically from the top down. Special diamond wire saws are being used to cut the tower into blocks. The diamond saws allow for precision cutting and generate minimal dust which is potentially radioactive. To facilitate removal of the chimney, a three-stage approach was prepared (Fig. 8) [26]:

1) Cut the structure into large blocks.
2) Use a tower crane built alongside the chimney to lift and move the large block sections to the ground.
3) Use available licensed landfill facilities for debris

![Image](image_url)
disposal to avoid the need for unnecessary decontamination of the concrete.

By mid-2018 preparations to dismantle the chimney were complete, including construction of the 152 m crane needed to lower the cut block sections (6 tonnes each) (Fig. 9). Work is currently underway to demolish the chimney’s diffuser structure which will disappear before the end of 2022. The remaining chimney will then be taken down to a height of 35 metres before being capped. This will mark the end state of the current project. The remaining 35 metres will be removed once decommissioning of the remaining reactor housing is started.

Approximately 500 tonnes of structural materials (bricks, masonry and steel work) comprised the filter section of the chimney alone. To date 66 tonnes of brickwork have already been removed from the external walls. Demolishing a chimney, the size of the Windscale Pile-1, is expected to generate approximately 5,000 tonnes of waste with varying degrees of radiological contamination. Most debris free of contamination or Very Low-Level Waste (VLLW) will be disposed of at licensed landfill facilities throughout the UK. The adjacent chimney (Pile-2), which was unaffected by the fire in Pile-1, was reduced in height in 2001 and was significantly easier to achieve.

2.1.5 Calder Hall Cooling Towers

The four cooling towers of the Calder Hall power plant, which closed in 2003, posed significant engineering hazards due to structural decay and high winds around the Sellafield site. The towers were 88 metres in height and used the natural draught hyperboloid design. Concerns of un-controlled collapse meant the towers were judged to be too hazardous to remain on site and were prioritised for demolition.
Demolition of similar structures is typically done by a wrecking ball owing to the techniques low cost and ease of use as well as being a relatively low-tech solution. However, the technique is slow with high dust generation therefore the impact upon the safety and continued operation of the Sellafield site would have been significant. To minimise site disruption, it was decided the towers would be demolished via a controlled explosion.

Controlled explosions hold the advantage of being significantly quicker therefore reducing the long-term disruption upon the rest of the site. However, due to the density of the buildings around the site and the potential for significant radiological hazards to be released should any of these buildings be damaged several precautions were in place for the demolition. A major preventative measure was the installation of fabric and netting around the base of the towers which was designed to catch any flying debris as the towers collapsed. An additional measure was to time-delay the explosion so that the towers would implode both into each other and away from all other buildings.

The four cooling towers of the shutdown Calder Hall plant at Sellafield were demolished using explosives in 2007. Following thorough safety inspections of the exclusion zone and surrounding plants, the demolition was declared a success [27]. Over 20,000 tonnes of rubble required disposed. The steel components were recycled, while the concrete was recovered, ground up, processed and used to fill the voids of the cooling ponds beneath the towers.

2.1.6 Windscale Advanced Gas Cooled Reactor (WAGR)

In 2011 the WAGR became the first nuclear power reactor to be decommissioned in the UK following a twenty-year project. The final stage of the reactor decommissioning was completed in the May of 2011 when the Outer Ventilation Membrane was removed from the reactor’s concrete bioshield [28]. The remaining bioshield and outer reactor building is in passive C&M. The dismantling of the reactor building is being deferred until about 2040 to take advantage of radioactive decay.

2.2 Sellafield Decommissioning Prospects

2.2.1 Magnox, Thorp & Waste Reprocessing Facilities

Currently, much of the focus of decommissioning operations at Sellafield centre around the legacy reactors and fuel storage facilities. But as fuel reprocessing ends at the Thorp and Magnox reprocessing plants, attention will soon turn to decommissioning Sellafield’s, now legacy, reprocessing facilities.

Thorp closed in 2018 with Magnox expected to close in 2022. What follows is a year of shutdown to allow the most severe and short-lived radiation to decay before beginning an intense period of Post Operational Clean Out (POCO). POCO is the actions taken by the plant operators at the end of the plant’s operational life to allow the structured and recorded removal of residual plant process inventory or stored wastes, utilising existing plant facilities and processes, in order to facilitate decommissioning of a nuclear facility [29]. Thorp was expected to enter a 5-year POCO cycle during 2019 with the Magnox reprocessing plant entering a similar 5 POCO cycle from 2021/2022.

Since closing in 2018, preliminary POCO operations have begun at Thorp. Inside the Head End Shear Cave (HESC), where the nuclear fuel rods were extracted from their casings and cut into pieces before being dissolved in heated nitric acid, the radiation level is 280 Sv·h⁻¹ [30]. To begin conducting POCO a mechanical arm will be carefully guided through the HESC. Cell washing will be performed repeatedly using a combination of water and acids to bring down the level of radioactivity. Ultimately, the plan is for humans to be able to enter the contaminated cave.

Although POCO operations at Thorp are only expected to last three-five years, the entire decommissioning programme will take many decades to complete. Final demolition is expected to take place between 2075 and 2095. The total bill for decommissioning Thorp is estimated
at £4bn as of 2020 [30]. Despite reprocessing at Thorp ending, it leaves behind thousands of steel canisters of vitrified high-level wastes. Further, there will be wastes produced in the decommissioning process itself. Ultimately, the government’s policy is for intermediate and high-level wastes to be disposed of in a GDF.

As decommissioning of the Sellafield site continues, many of the waste processing plants such as the Enhanced Actinide Removal Plant (EARP), Site Ion Exchange Plant (SIXEP), and others will be used to support decommissioning process by treating arising wastes where possible. As and when each of the waste processing plants are considered no longer necessary, they will enter a period of POCO (similar to Thorp and Magnox) before being dismantled and decommissioned. As these are scheduled to happen sometime in the future, plans are yet to be finalised, although it is envisioned the entire site will reach its end state by 2120.

3. Magnox Reactor Decommissioning

Wylfa’s closure in 2015 marked the end of an era and the end of Magnox power generation in the UK. Through carefully planned waste retrieval, decontamination, dismantling and environmental remediation programs, decommissioning of the fleet will be conducted to manage the legacy in a safe and secure manner. However, many challenges have and will continue to be faced, with final site clearance of Wylfa, the final reactor to be fully decommissioned, not expected to be completed until 2105. Most of the Magnox reactors will not have their nuclear licenses terminated before around the year 2100 (Table 1) [31].

The overarching decommissioning approach is deferred reactor dismantling after 85 years from reactor shutdown. The deferred approach takes advantage of the process of natural radioactive decay to reduce the levels of radioactivity and hence lower the risk to people and the environment. After final shutdown of the reactors each site begins the transition to a state of C&M to ensure the safety of the reactor, public and the environment until the time comes for final reactor dismantling. This will involve reducing hazards on site by:

- Transferring of all spent fuel to off-site facilities for treatment and storage
- Transferring of nuclear materials to offsite facilities for management
- Dismantling reactors or preparing reactor buildings for safe storage
- Decommissioning redundant facilities
- Retrieving, treating, packaging and disposal/storage of waste
- Managing contaminated land

To achieve C&M the NDA and Magnox Ltd (Associated SLC) focus on nine work programs;

- Defuelling – focuses on the removal of remaining fuel from the reactors and transfer to Sellafield for reprocessing (Complete as of 2020) [8]. The strategy is to reprocess all Magnox spent fuel by 2022.
- Ponds – responsible for the removal of waste and redundant furniture from fuel storage ponds, draining pond water and stabilising pond surfaces, decommissioning existing effluent treatment plants and delivery of new, fit-for-purpose effluent treatment plants.
- Plant and Structures – responsible for asbestos removal, deplanting, demolition and preparation of the safestores for C&M. Implementation will be through the use of conventional waste removal and demolition techniques.
- Site Restoration – responsible for land quality, remediation and groundwater monitoring.
- Reactors – responsible for the dismantling of reactors (including the Winfrith SGHWR and Dragon reactors; and Harwell BEPO, DIDO and PLUTO reactors, See below).
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Table 1. Key milestones for the Magnox reactor fleet [31]

<table>
<thead>
<tr>
<th>Magnox Reactor</th>
<th>Lifetime Output (TWh)</th>
<th>Site Enters C&amp;M</th>
<th>Final Site Clearance Begins</th>
<th>Final Site Clearance Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berkeley</td>
<td>43</td>
<td>2023</td>
<td>2070</td>
<td>2079</td>
</tr>
<tr>
<td>Bradwell</td>
<td>60</td>
<td>- *</td>
<td>2083</td>
<td>2092</td>
</tr>
<tr>
<td>Chapelcross</td>
<td>60</td>
<td>2025</td>
<td>2085</td>
<td>2095</td>
</tr>
<tr>
<td>Dungeness A</td>
<td>115</td>
<td>2025</td>
<td>2087</td>
<td>2097</td>
</tr>
<tr>
<td>Hinkley Point A</td>
<td>130</td>
<td>2027</td>
<td>2081</td>
<td>2090</td>
</tr>
<tr>
<td>Hunterston A</td>
<td>73</td>
<td>2024</td>
<td>2071</td>
<td>2080</td>
</tr>
<tr>
<td>Oldbury</td>
<td>137</td>
<td>2027</td>
<td>2092</td>
<td>2103</td>
</tr>
<tr>
<td>Sizewell A</td>
<td>110</td>
<td>2027</td>
<td>2088</td>
<td>2097</td>
</tr>
<tr>
<td>Trawsfynydd</td>
<td>69</td>
<td>2029</td>
<td>2074</td>
<td>2083</td>
</tr>
<tr>
<td>Wylfra</td>
<td>232</td>
<td>2026</td>
<td>2097</td>
<td>2105</td>
</tr>
</tbody>
</table>

*Bradwell has already entered care and maintenance

- Waste Strategy, Permissioning and Projects – responsible for the development and integration of the decommissioning and waste management strategy; preparation of ILW and LLW disposability cases; and assurance. responsible for the design, procurement, installation and commissioning of plant, equipment and systems required to deliver the waste management strategy.
- Waste Operations – responsible for the implementation of the waste management strategy; operation of waste plants, including ILW stores; disposition of all LLW, hazardous and conventional waste off the site.
- Asset Management – responsible for managing the physical assets across the 12 sites.
- Care and Maintenance – responsible for establishing the arrangements to accept and manage sites as each achieves its defined interim state entry configuration.

These nine programs have been established to create a one-stop decommissioning service for the sites. Approaching the work in this manner allows the use of innovative techniques and methods as well as providing a sequenced approach to work using the ‘Lead and Learn’ approach [7]. By controlling and overseeing work at every site, lessons and approaches learned at one site can be directly applied to another site ‘in-house’; thus, reducing risks and/or accelerating decommissioning without the need for tedious or time-consuming negotiations between otherwise separate plant operators.

Unlike Sellafield, many of the risks and hazards associated with the Magnox fleet are reasonably well understood. This level of understanding is reflected in the strategy with a long-term strategical plan in place. This holds the added benefit of being able to apply a common decommissioning approach to the whole fleet; only deviating for site specific problems.

### 3.1 Waste Inventory & Waste Management

The Magnox radioactive waste strategy, in general, is to send LLW off-site while ILW will be packaged for ILW disposal at a suitable disposal facility when it becomes available. For the Magnox sites in England and Wales current assumptions are that ILW packages will be sent to the UK’s GDF for final disposal. Currently expected to become available from 2040 [32]. In contrast, at the Scottish sites ILW packages will be stored on-site and above ground for up to 300 years.
3.1.1 Magnox Graphite

Decommissioning the UK’s Gen I reactors will generate significant amounts of Higher Activity Wastes (HAW) (Table 2). In the UK, the definition of HAW includes HLW, ILW and some LLW that is unsuitable for disposal in the Low-Level Waste Repository (LLWR). HAW arises from activities such as, reactor operation, reprocessing of spent nuclear fuel, and decommissioning. A considerable proportion of this HAW will be radioactive graphite. The principal source of radioactive graphite from the Magnox reactor sites is the reactor core graphite, typically in the form of irradiated graphite core bricks, which served the function of a neutron moderator and reflector. The current baseline strategy for disposal of the Magnox graphite is packaging in cement and direct geological disposal. Graphite wastes amount to approximately 27% of the total UK ILW inventory [33]. However, this would only account for less than 2% of the planned GDF footprint [34]. This is because the planned GDF footprint will be dominated by the disposal of HLW, which must be suitably spaced to allow for heat dissipation.

Under current plans, final decommissioning of both the Magnox and the AGR reactors will not happen until sometime after the planned GDF has begun receiving wastes (expected 2040). Flexibility within the Magnox fleet (and AGRs) baseline decommissioning plans (Table 3) provides time for the maturity and Technical Readiness Level (TRL) of alternative graphite management options.

<table>
<thead>
<tr>
<th>Current Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decommissioning Assumed to take place 2074–2101</td>
</tr>
<tr>
<td>Reactor buildings dismantled and sites cleared for next use De-licensing of the sites is assumed</td>
</tr>
<tr>
<td>Waste Form Moderator and reflector graphite bricks (ILW &amp; LLW)</td>
</tr>
<tr>
<td>Waste Retrieval Assumed to be in air, top entry, graphite bricks retrieved intact</td>
</tr>
<tr>
<td>Waste Packaging RWMD 4 m stainless steel package (no internal shielding assumed)</td>
</tr>
<tr>
<td>Waste Conditioning Encapsulation to RWMD specifications in a cementitious grout assumed using the final site clearance waste management facility</td>
</tr>
<tr>
<td>Waste Transport and Disposal Transport for disposal in the GDF (in Scotland, waste will be consigned to an appropriate near surface facility)</td>
</tr>
</tbody>
</table>

*Packaged Volume Assuming Packaging Plans from UKRWI 2010*
to improve, before there is a need to finalise disposal plans. In the meantime, advances in technology may result in better treatment options or enhanced volume reduction procedures for graphite wastes which would lead to less associated wastes requiring disposal [36]. Alternatively, beneficial re-use may become a candidate for implementation.

3.2 Decommissioning Progress: Site Case Studies

Across the Magnox fleet a range of challenges have and continue to be faced along the road to complete decommissioning. For example: At Berkeley a trial decontamination program of the 22 metre high boilers led to 85% being removed from the site as scrap [37]; Early decommissioning at Hunterston A saw the use of remotely operated vehicles to remotely access waste bunkers and retrieve more than 650 tonnes of radioactive graphite and metallic wastes, before being packaged into specially engineered stainless-steel boxes; while at the Oldbury site the introduction of a mobile demineralisation plant to supply the sites 26 m³·day⁻¹ water needs allowing for the pre-existing, and now redundant, demineralisation plant (that supplied some 910 m³·day⁻¹) to be decommissioned [38]. While many of these challenges are the same across each site, some are more unique and in some cases are site specific. Where possible, approaches applied at one site have been adapted for other sites, thus streamlining the entire decommissioning process using the ‘Lead and Learn’ approach. What follows is a series of case studies highlighting individual aspects of selected sites.

3.2.1 Bradwell – First to Enter C&M

In late 2018 Magnox Ltd announced that the Bradwell Site had entered a state of C&M. This was the first Magnox Nuclear Power Plant (NPP) in the UK to enter C&M. To secure C&M, and gain regulatory approval, both reactor buildings were defueled, decommissioned and covered in weatherproof cladding. This created ‘safestores’. All ILWs were packaged and remain safely stored on site. Bradwell has been referred to as a pathfinder site, by delivering hazard reductions safer and sooner and making many first-of-a-kind innovations and developing innovative approaches for decommissioning [39, 40]. The equipment and procedures developed to retrieve, condition and package ILW at Bradwell are now being utilised across the remaining Magnox fleet to progress decommissioning and hazard reduction operations. The lessons learned from reaching C&M at Bradwell are directly informing the NDA and allowing for changes to the decommissioning strategy where improvements can be identified. This has become known as the ‘Lead and Learn’ approach, experiences from one decommissioning site are being directly implemented into the next.

Bradwell decommissioning key facts:

- In excess of 10 million hours worked.
- In excess of 980 people on site at peak decommissioning.
- Total waste disposed of: 90,000 tonnes.
- Over 95% of waste disposed of as non-radioactive.
- Of the conventional waste: 66% recycled; 24% reused on site; 10% disposed.

Today the site continues to receive ILW packages from Dungeness A and Sizewell A. These will be stored in the site’s interim storage facility along with Bradwell’s waste packages. During C&M inspection and maintenance will initially occur once a year before being reduced to every five years. Final site clearance is expected by 2092.

3.2.2 Chapelcross – Preserving a Socioeconomic Legacy

Due to the size and complexity of most nuclear installations they have a large and often positive impact on the local areas in terms of job security and socioeconomic stability. As most facilities have a substantial lifetime of 25–50 years the surrounding areas can often be hit hard and take time to adjust after a sites closure. Mitigating such a negative
Chapelcross was one of the world’s earliest NPPs, a sister site of Calder Hall, and the first built in Scotland. When Chapelcross permanently closed in 2004, 80% of the workforce lived within 15 miles of the site contributing a majority share of their £30 million annual payroll into the local economy each year. The closure of the site and the loss of this income is potentially damaging to the local community with rising unemployment and job insecurity. To reduce the negative socioeconomic impact of the plant closing the local council (local government) along with partners such as the NDA launched a large economic investment and development project – ‘Chapelcross Project’ (www.cxproject.co.uk).

Over a 5-year period until 2017 the Chapelcross Project generated almost £4 million which was used to directly aid almost 300 people and 194 separate businesses in the local area. The fund also funded functional skills courses in Mathematics and English for ex-Chapelcross staff with the aim to qualify them for prospective jobs. In addition, over £1 million has been invested by the council in the Gretna Central Avenue Park and other public projects. Similar schemes are under consideration for the remaining Magnox fleet.

More recently preparations have been made for a new investment project, the ‘Chapelcross Development Framework’, which is aimed more centrally at the existing site post-decommissioning. It is hoped that new businesses and research facilities will occupy the former nuclear site, which maintains good road and rail links as well as utilities, and provide significant job growth in various areas of science and business, including a new environmentally friendly energy solution.

3.2.3 Dungeness A – Divers Decommission

Most spent fuel ponds contain LLWs and ILWs in addition to the spent fuel they are primarily designed to hold. Pond clean-out conventionally takes place using remotely operated equipment to lift the whole skips clear of the water. However, this process is slow and possess a number of hazards, most notably increased radiation exposure to workers and the generation of hazardous dusts and particulate debris. To overcome this, highly trained underwater scuba divers operated underwater to cut up the remaining radioactive wastes to the required sizes before being hauled to the surface [41].

The divers conducting underwater work in the former cooling ponds at the Dungeness A nuclear power plant were a first for UK nuclear decommissioning. The divers cut up the pond skips that were once used to store used nuclear fuel at the site and packaged them for disposal. The water that is still in the ponds acts as added radiation shielding for the divers thus reducing dose rate. Meanwhile, cutting the skips while they remain in the ponds avoids the potential for airborne contamination. The cut-up skips, which are classed as ILW, will be stored in approved waste containers in a shielded storage area on site before they are packaged for interim storage.

Using this innovative underwater decommissioning technique, radiation levels for workers were around 20 times less than with conventional techniques. As well as reducing the overall radiation dose for workers, the diving technique has a lower environmental impact, is quicker and more efficient. The work in Dungeness A’s ponds was deemed so successful that similar approaches have since been used at other sites.

3.2.4 Trawsfynydd – Old Site, New Life?

The Trawsfynydd Site is located in the Snowdonia National Park, North Wales (Fig. 10). It drew cooling water from Llyn Trawsfynydd, an artificial lake formed in 1928 to retain water for Maentwrog hydroelectric power station. This makes Trawsfynydd the first and only inland nuclear power station in the UK. Trawsfynydd generated 69 terawatt hours of electricity during 26 years of operation and shutdown in 1993 [42]. Decommissioning of the site includes removal and storage of all solid ILW,
resins and liquid in the interim storage facility; upgrades to site infrastructure in preparation for C&M, redundant buildings have been demolished and the reactor safestores are being reconfigured in preparation for a major project to reduce their height by around two thirds due to safety concerns regarding the integrity of the outer reactor buildings (Fig. 11) [43].

The Magnox Optimised Decommissioning Plan (MODP) was implemented in 2010 with the goal of accelerating the transition to C&M [43]. The MODP forms part of Magnox Ltd ‘Lead and Learn’ approach. Trawsfynydd was identified as one of two sites, for which several of the key decommissioning objectives have been brought forward. This enabled Magnox Ltd and the NDA to learn from their experiences of decommissioning the site and pass on these learnings to the remaining Magnox fleet and subsequent decommissioning projects. Remaining structures on the site will be cleared by 2083.

The re-use of existing nuclear sites is of great interest as there is potential to make good on assets such as land and local infrastructure. However, finding suitable re-use schemes and projects can be difficult depending on the end-state criteria of a site, previous usage and local socioeconomic environment. As a front runner in site re-use and re-purposing, Trawsfynydd has been identified as a potential Small Modular Reactor (SMR) site under a new £40 million scheme to build ‘mini’ atomic power plants in the UK [44].

There are currently no sites in the UK approved for building a power station based on SMR technology. The lake at Trawsfynydd is sufficiently large to provide
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adequate cooling to a 700 MW capacity reactor. Further, the site retains its existing national grid connection and is government owned. This would make Trawsfynydd, and the surrounding area, technically suitable and relatively easy to designate as a new nuclear site. Moreover, there are other geographical advantages: with nearby ports and a local bypass scheme already implemented within the area, the site has the necessary transport infrastructure to bring large components to the site. The site is also close to nuclear centres of excellence on Deeside, Manchester and Sheffield, along with Sellafield. At the time of writing no plans are yet approved with preliminary discussion still on-going.

4. Other Facilities

The UK has a long history of nuclear research & development as well as the establishment of multiple nuclear fuel cycle support facilities as part of a complete and independent nuclear fuel cycle; with the exception of raw uranium mining and uranium ore purification. These, facilities, although less hazardous, still pose significant decommissioning challenges and require appropriate decontamination, dismantling and site-remediation. The sites often house bespoke one-offs or unique wastes (e.g. Dounreay, fast breeder fuels) or are large-scale plants such as Capenhurst and Springfields requiring significant man-hours to dismantle. Major sites (excluding Sellafield and Magnox power reactors) currently undergoing some form of decommissioning are:

- Fuel Fabrication & Uranium Enrichment
  - Capenhurst
  - Springfields
- Nuclear Energy R&D
  - Culham
  - Dounreay
  - Harwell
  - Silwood Park
  - Winfrith
- Waste Disposal Facility
- Drigg
- Other
  - Ministry of Defence (MOD) Sites (e.g. Vulcan)

4.1 Strategy End State

While each site poses its own set of unique challenges, the end state for each is broadly similar. The target end states for sites, as defined by the NDA, broadly cover [8]:

- Radioactive and non-radioactive contamination will be reduced to meet the requirements of the relevant regulatory regime for the next planned use of the site and the current use of adjacent land.
- Where the next planned use no longer requires a nuclear site licence, radioactive contamination will be reduced to meet the criteria for delicensing, with any remaining radioactive substances being subject to the relevant environmental permitting regime.
- The physical state of designated land will be made suitable for the next planned use of the site; structures and infrastructure will be made safe or removed where necessary, having first explored opportunities for their re-use.

4.2 Fuel Fabrication & Uranium Enrichment Facilities

4.2.1 Capenhurst (Urenco)

The Capenhurst site (SLC: Urenco UK Ltd) located near Ellesmere Port in Cheshire has been home to the UK’s uranium enrichment facilities since 1971. Today the site serves as both a uranium enrichment plant as well as a waste storage site for uranic materials (Depleted Uranium etc.); In addition, site decommissioning of redundant facilities is on-going.

URENCO are responsible for the removal, decontamination and disposal of all uranic contaminated plants and
facilities such that buildings are left clean and in a state suitable for general use. The tails disposal provision is to deconvert uranium hexafluoride (UF₆) to triuranium octoxide (U₃O₈).

The site is expected to remain operational for the near future and a nuclear licensed site for a 100+ years. Decommissioning of the centrifuge plants covers two distinct areas of work.

• The removal, decontamination and disposal of contaminated plant and equipment, including centrifuges, to comply with appropriate licensing authority requirements.
• The removal and disposal of non-contaminated plant and equipment and the requirement to leave the building structure to meet Urenco’s future needs.

Similar to the former operational plants at Sellafield (e.g. Thorp), those at Capenhurst will undergo POCO shortly after final shutdown. POCO will degas the plant to remove all remaining uranium hexafluoride gas. All UF₆ cylinders are also to be removed as well as all uranium bearing chemicals e.g. charcoal. POCO will also involve the removal of non-uranium bearing chemicals and process fluids such as compressor oil, circulating water etc.

After successful completion of POCO operations, but prior to further plant dismantling, the plant will undergo radiological characterisation. For in-situ dismantling of the contaminated plant, Urenco possess proven working methods. This enables contaminated plants to be dismantled in situ while maintaining containment of any radioactive contamination. The centrifuge machines themselves will be removed from the plant intact. Removed components will undergo decontamination at a designated decontamination plant. Those items deemed not to be contaminated will be dismantled in situ using conventional dismantling/construction techniques (e.g. circular saws, wrecking balls etc.) as they do not pose a radiological hazard and the Capenhurst site, unlike Sellafield, can accommodate such techniques due to a lower risk posed by the surrounding infrastructure.

Decommissioning wastes will either be sent to scrap companies (recycled) or to waste disposal companies for land burial. All consignments leaving the site will be subjected to a radiological monitoring regime, with certification being required prior to the consignment being moved.

The long-term future use of the site has not yet been defined. In the short term it will remain as a storage site for deconverted tails as well as a variety of other radioactive wastes. As part of the short-term reuse plans for the site, in 2016 Capenhurst was chosen to store radioactive waste from decommissioned Royal Navy nuclear submarines as part of the MoD Submarine Dismantling Project (SDP) [45].

4.2.2 Springfields (NDA)

Springfields is a nuclear fuel manufacturing site located near Preston in Lancashire with manufacturing operations beginning since the 1940’s. Site operations are the responsibility of the SLC Springfields Fuels Limited (SFL). The site has historically manufactured a variety of fuel products for UK and international customers, in more recent years decommissioning of historic uranic residues and redundant facilities has become more prevalent. Today, the main Springfields activities include:

• Oxide fuels for AGRs and Light Water Reactors, as well as intermediate fuel products, such as powders, granules and pellets
• Manufacture of Uranium Hexafluoride (now in C&M)
• Processing and recovery of Uranium residues
• Decommissioning and demolition of redundant plants and buildings

Springfields remains an operational fuel production facility, and as such, decommissioning is required to be carried out in a manner that provides for the protection of the health and safety of the workforce, the public and the environment. The Springfields Decommissioning Policy
and Strategy is to commence the initial stages of POCO and decommissioning as soon as reasonably practicable after the end of a plant’s useful life. Fuel production plants, especially those handling uranium, gain nothing from radioactive decay. In addition, the cost benefit of eliminating surveillance and maintenance activities, after production activities have ceased, leads to early decommissioning being the preferred strategy.

Over the last twenty years a significant phase of decommissioning at Springfields has been successfully completed. Between 1996 and 2020 over 120 plant buildings and support facilities have been successfully decommissioned and/or demolished. These range from 1940s buildings, which were utilised for nuclear fuel manufacturing operations, to formerly sealed chemical agent manufacture and storage facilities. The now redundant Magnox fuel manufacturing facilities are being decommissioning at Springfields.

A key factor in the success of the Springfields decommissioning programme to date has been strategic early decommissioning immediately following the end of a plant’s operational life. This allows the utilisation of existing site knowledge and experience both from past decommissioning projects, plus operational knowledge from former plant operators, management and support functions. Early decommissioning also means existing waste disposal routes/authorisations can be fully utilised and any future C&M costs are minimised.

4.3 Nuclear Energy R&D Facilities

4.3.1 Dounreay (NDA)

Dounreay (SLC: Dounreay Site Restoration Ltd., DSRL) is located in Caithness on the north coast of Scotland. It was established as a research site in the mid-1950s, for pursuing fast breeder reactor technology, with fuel production and processing facilities. There were three reactors, the last of which ceased operation in 1994. Historically much of Dounreay’s nuclear waste management was poor. In 1998, following a report damning the site and some of its practices it was decided to accelerate site decommissioning from an original 100 years to just 60 years with initial cost estimates of £4.3 billion (Equal to £7.4 billion in today’s money) [46, 47]. Both the timeframe and cost estimates have since been heavily revised.

The over-riding decommissioning strategy being implemented at Dounreay is prompt decommissioning to an interim end state before final site clearance. Under the oversight of DSRL, initial plans are to transition the Dounreay site to an interim care and surveillance state by 2036, complete waste removal by 2070, before final transition to a brownfield site by 2336. Apart from decommissioning the reactors, reprocessing plant, and associated facilities, there are five main environmental issues to be dealt with [48]:

- A 65 metre deep shaft used for intermediate level nuclear waste disposal is contaminating groundwater, and is threatened by coastal erosion in about 300 years’ time.
- Irradiated nuclear fuel particles on the seabed near the plant, estimated to be about several hundreds of thousands in number. Over the years many have washed ashore onto the local beaches including in 2012 when a two million becquerel particle was found at Sandside beach [49, 50]. This poses a significant environmental and public health hazard.
- 18,000 m$^3$ of radiologically contaminated land, and 28,000 m$^3$ of chemically contaminated land.
- 1,350 m$^3$ of high and medium active liquors and 2,550 m$^3$ of unconditioned intermediate level nuclear waste in storage.
- 1,500 tonnes of sodium, of which 900 tonnes are radioactively contaminated from the Prototype Fast Reactor (PFR).

Significant hazard reduction has been achieved through the transfer of all spent nuclear fuels to Sellafield. Remaining exotic fuels are being consolidated at Dounreay.
throughout the early 2020s. Site decommissioning and remediation work is well underway with more than 100 buildings already demolished. At the Dounreay site a dedicated LLW repository for solid wastes is receiving operational and demolition wastes. Emptying the Dounreay Shaft and immobilising the highly radioactive liquid raffinate from PFR/DFR (Dounreay Fast Reactor) fuel reprocessing operations are considered the highest risks on the Dounreay site. Shaft emptying will be complete in 2025 with final remediation of the shaft and silo area by 2028.

To take the site to an interim end state by 2029 current key milestones are [48]:

- 2019 – All DFR breeder fuel removed.
- 2023 – Shaft will be back-filled and capped.
- 2024 – All liquid raffinates immobilised.
- 2025 – All fuel in long-term storage or shipped off site.
- 2025 – DFR dismantled.
- 2026 – PFR dismantled.
- 2028 – Shaft and Silo encapsulation complete.
- 2030 – Site clearance and environmental restoration phase 3 complete.
- 2030–33 – Interim End State achieved.

One area of significant concern at the Dounreay site is the environmental impact of historic operations. Nuclear fuel was reprocessed at Dounreay for almost 40 years. The process generated metallic fragments, some of which entered the site’s effluent system and were discharged to the sea [50]. Routine monitoring of the coastline around Dounreay began to detect particles of this material in the early 1980s, when practices at the site were changed to prevent any more discharges of this material. The particles behave like grains of sand and are transported by the action of the sea. Particles vary in size and radioactivity. Generally, smaller and less active particles are found on beaches used by the public while larger particles have been found only on the foreshore at Dounreay. This area is not used by the public. Beaches on either side of Dounreay are monitored routinely using radiation detection instruments and any particles found are removed (Fig. 12). Between 2008 and 2012, a remotely-operated submersible scoured the seabed and retrieved a number of fragments. Continuous monitoring of nearby beaches provides important information.

Fig. 12. Aerial view of Dounreay and surrounding area. Surveyed beaches highlighted.
about the effectiveness of the particle recovery programme. This programme is agreed and regulated by the independent Scottish Environment Protection Agency (SEPA) and funded by the NDA. Although decommissioning of the site is expected to be completed, it is likely the surrounding area will forever remain contaminated, at least until the radioactivity has decayed naturally.

4.3.2 Harwell (NDA)

Harwell was established by the UK Atomic Energy Authority (UKAEA) in 1946 in Oxfordshire and was home to research scale nuclear reactors and radiochemical support facilities. During the early 1990s most research operations at the site ceased with decommissioning taking over leading to more than 100 buildings and facilities being removed. Today, Harwell is a multi-occupancy and multi-ownership site. Some areas of the site remain in the decommissioning phase with a view to redevelopment and remains a nuclear licensed site. Other parts of the site make up the Harwell Science and Innovation Campus. As part of site re-use, it is home to the Diamond Light Source (commonly known simply as Diamond) which is the UK’s national synchrotron light source science facility, as well as a number of other companies and organisations. The end state for the Harwell site is for a fully delicensed site.

Two of the reactors have been completely removed while fuel from the remaining three has been removed allowing them to undergo decommissioning. Historic wastes are being retrieved from their existing storage locations to allow them to be repackaged in safer wasteforms for the purpose of longer-term storage before final disposal. It is expected that decommissioning will be completed by 2025 with final site clearance by 2064 [9].

Harwell is further advanced with delicensing than any of the other NDA sites. Decommissioning works are being achieved in two key phases: interim state (2008–2031) and site closure (2032 to 2064) [8, 9]. The end-state of the site will be achieved when all redundant buildings on the site have been demolished (inc. base slabs removal), all contaminated land remediated, and all areas of the site fully delicensed.

As decommissioning at Harwell approaches the end, and enters the interim state, there will be a storage area for radioactive waste and three small buildings containing the remains of the redundant reactors (DIDO and PLUTO) which will be kept under long-term safe enclosure. This allows radioactive decay to occur making final site clearance easier. The rest of the Harwell site will be available for new non-radiological development after licence termination.

In the UK, nuclear installations with plants such as nuclear reactors, fuel reprocessing facilities, or research facilities are licensed under the Nuclear Installations Act. Once the land has been licensed strict guidelines must be met in order to terminate a site licence (in whole or part), it is not simply a case of demonstrating that the licensable activity has ceased. But the benefit of delicensing in this way, other than acknowledging that all hazards have now been removed, is that the process can be used to support a redevelopment proposal because delicensing requires an in-depth validation of the land quality. A nuclear site licence restricts the reuse of the land by landowners, licence termination is therefore a step on the path to commercial redevelopment. The main steps reported by the licensee in the Harwell case are [51]:

- Historical survey of records and maps/drawings
- Planning of a staged investigation
- Radiological (and chemical) surveys/sampling of the land
- Building/drains/surveys/sampling
- Investigation/remediation of anomalies
- Preparing a Delicensing Safety Case
- Formal submission to Office for Nuclear Regulation (ONR)
- ONR verification surveys
- Clarifications/discussions
- ONR Approval
• Mark the new boundary
• Issue of Licence Variation

As of 2013 four main zones had been delicensed with others currently going through the delicensing process [51]. The zones delicensed as of 2013 are:

• ETSU Area, 5 hectares, delicensed 1992
• Pilot Area, 7 hectares, delicensed 2006
• Eastern Area Facilities, 5 hectares, delicensed 2010
• North Gate/B146 Area, 5 hectares, delicensed 2012

A major learning curve from delicensing the Harwell site has been the importance of good record keeping. During delicensing approaches to technical issues and record keeping were developed. A good records management system is essential to provide accurate and reliable records thus making delicensing easier. This allowed the operators of the site to reassure the NDA and the community that it could delicense the land, and thus gave confidence that the desired end state could in time be delivered. Further, as delicensing may take place years after decommissioning works, is it impractical to rely on memories and thus ensuring comprehensive post decommissioning reports are produced is vital. Finally, by involving the delicensing team in decommissioning and demolition planning, a smooth transition from one operation to the other could be maintained.

4.3.3 Winfrith (NDA)

Winfrith was a R&D site set up by the UKAEA in 1957 for experimental reactor designs. Research at the site helped support the efforts made at Harwell. At its peak over 2,000 people worked at Winfrith. A total of nine R&D reactors were operated at Winfrith until the sites closure in 1990.

Since its closure, seven reactors - Zenith, Nero, Juno, Hector, Nestor, Dimple and Zebra - have been removed [9, 52]. Other support structures such as cooling towers and auxiliary buildings have also been demolished. All the nuclear fuel and the majority of hazards have now been removed from the site. However, two reactors remain, both requiring dismantle, and are considered to be some of the most complex decommissioning challenges of the Winfrith site. Both the Steam Generating Heavy Water Reactor (SGHWR), an enormous, water-cooled reactor and the only one of the nine reactors to supply nuclear power to the National Grid, and Dragon, a prototype gas-cooled reactor, remain. To date, Engineers have stripped out miles of steel pipework surrounding the SGHWR core. This has enabled new structures to be constructed around the core thus sealing it off providing a radiological barrier allowing robots to cut it in to pieces safely and with a reduced radiological hazard. Due to the severity of the radiation within the core, no humans will be able to access the reactor once the robots begin dismantling it. As part of the planning stage for dismantling the SGHWR core a full-scale model was built to plan how the techniques would work. In the case of the Dragon reactor a bespoke robotic “laser snake” has been implemented capable of cutting into the structure. The active plant around the reactor core has already been stripped out and removal of the core is due to begin in 2020 achieving an interim end state by 2023. Current plans would see the site’s final closure taking place in 2048. Further optimisation of the decommissioning program could see that date brought forward “significantly” [53].

UKAEA is restoring the Winfrith site to allow for unrestricted use. It is hoped that by remediating the site, Winfrith can become a major science and technology centre for the region. With redundant facilities removed, areas of the site have been restored to brownfield status, for eventual non-nuclear use.

Winfrith will be the first reactor site in the NDA estate to be “cleared” and provides an important opportunity for the NDA and Magnox Ltd to demonstrate that sites can be cleared and be available for future use. This has the potential to set a precedent for the future decommissioning
and remediation strategies of other sites in the NDA estate. Delicensing of Winfrith is expected by 2050, being the first site to be entirely delicensed.

4.4 Waste Disposal Facilities

4.4.1 Drigg LLWR

Drigg, the UK’s Low Level Waste Repository (LLWR), is expected to continue to operate over the lifetime of many decommissioning projects. Under current plans, final proposed vault construction will be completed in 2050 with final wastes being shipped to the site for disposal in 2070. The disposed waste will remain in-situ as determined by the site’s Environmental Safety Case. The repository will remain subject to institutional controls for as long as required by the relevant regulatory regime to manage risks to people and the environment.

5. UK’s Decommissioning Future – Research & Development

In the UK, most government funding into civil nuclear R&D is channelled through the Department for Business, Energy and Industrial Strategy (BEIS) via its various subsidiary agencies and Non-Departmental Public Bodies (NDPB). Total funding (public, private and overseas) for civil nuclear R&D in the UK in 2018/19 was around £331 million (₩ 530 billion) [54]. Most of this funding was public which accounted for around 59% (approx. £195 million) (Fig. 13) [54]. The majority of this public funding was from the NDA SLCs (NDA indirect), which focussed on waste management and decommissioning.

R&D funding supported by the NDA is allocated from the NDA’s annual budget. In the financial year 2017 to 2018 the NDA spent £101 million on R&D which accounted for approximately 3% of its annual expenditure [55]. The NDA allocates this funding through two routes: site-specific activities or strategic R&D investments.

The NDA and its SLCs continue to drive successful R&D across the UK’s nuclear sector. Specifically, the NDA has overseen the completion of a number of R&D projects in the areas of underwater autonomous robots for legacy storage pond characterisation; implementation of remote waste handling robotics; performance of grout and cement additives; X-ray sorting of fuel element debris; remote retrieval of contaminated water; and radiation mapping for remote characterisation of nuclear facilities [55]. In addition, Sellafield continues to work with multiple industrial and academic partners to ensure the smooth
running and constant progression across its R&D portfolio, including through continued University engagements (e.g. Centre for Innovative Nuclear Decommissioning (CINDe) led by the National Nuclear Laboratory (NNL) working in collaboration with Sellafield Ltd, University of Manchester, Lancaster University, University of Liverpool, and the University of Cumbria; Engineering and Physical Sciences Research Council (EPSRC) Nuclear Energy Futures Centre for Doctorial Training (CDT) established cross five Universities: Bangor University, University of Bristol, University of Cambridge, Imperial College London, and The Open University; EPSRC Nuclear FiRST Doctorial Training Centre (DTC) formally established between the University of Manchester & University of Sheffield), R&D programmes and centres of expertise.

Since the establishment of the NDA there have been a number of major successes such as the Dalton Cumbrian Facility, Nuclear Graduates Programme, Nuclear FiRST DTC, and multiple R&D consortia which brought together researchers from both industry and academia. The wider nuclear R&D community will also see the further development of existing, and the introduction of new programmes such as:

- Conclusion of the DISTINCTIVE programme (http://distinctiveconsortium.org/)
- Continuation of the DAWNMANTLE project
- Initiation of the TRANSCEND consortium (https://transcendconsortium.org/)
- Sellafield Game Changes (https://www.gamechangers.technology/)
- Effluents Centre of Expertise
- Sludge Centre of Expertise
- Establishment of the Henry Royce Institute (https://

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<th>Similarities</th>
<th>UK</th>
<th>Korea</th>
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<tr>
<td></td>
<td>No GDF for HAW (UK), HLW (Korea)</td>
<td>No decommissioning centric authority presently set-up</td>
</tr>
<tr>
<td></td>
<td>Aging and/or full waste storage facilities requiring decommissioning</td>
<td>PWR decommissioning</td>
</tr>
<tr>
<td></td>
<td>Fuel storage pond decontamination</td>
<td>PHWR decommissioning</td>
</tr>
<tr>
<td></td>
<td>Research reactor(s) dismantling</td>
<td>Limited storage space for spent fuels</td>
</tr>
<tr>
<td></td>
<td>R&amp;D facilities (non-reactor)</td>
<td>Aggressive decommissioning targets</td>
</tr>
<tr>
<td></td>
<td>Fuel fabrication facilities</td>
<td>Nuclear decommissioning in infancy</td>
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<tr>
<td></td>
<td>Redundant workforce/socioeconomic impacts</td>
<td>Limited decommissioning experience</td>
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<td></td>
<td>License termination</td>
<td>Prompt decommissioning strategy</td>
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<td></td>
<td>Site end-states and eventual reuse</td>
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<th>Differences</th>
<th>UK</th>
<th>Korea</th>
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<tbody>
<tr>
<td>Nuclear Decommissioning Authority Established</td>
<td>• Historic wastes/orphan wastes/bespoke wastes</td>
<td></td>
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<tr>
<td>GCR decommissioning</td>
<td>• Nuclear accident clean-up (Windscale Piles)</td>
<td></td>
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<td>Reactor Graphite</td>
<td>• Non-standard/prototype reactor designs</td>
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<tr>
<td>Legacy ponds and silos</td>
<td>• Mix of prompt &amp; deferred decommissioning strategies</td>
<td></td>
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<tr>
<td>Fuel reprocessing facilities</td>
<td></td>
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<tr>
<td>Historic nuclear weapons R&amp;D</td>
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<tr>
<td>Historic wastes/orphan wastes/bespoke wastes</td>
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<td>Nuclear accident clean-up (Windscale Piles)</td>
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<td>Mix of prompt &amp; deferred decommissioning strategies</td>
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Table 4. Comparison of similarities and differences related to nuclear decommissioning challenges facing both the UK and Korea
6. Implications for the Korean Decommissioning Challenge

Currently, nuclear power generation in Korea accounts for approximately 25% of the nation’s energy needs across a total of 24 reactors. However, with the introduction of the Energy Transition Policy, initiated in 2017, nuclear decommissioning is rapidly becoming the major focus of the nuclear industry in Korea [1, 2, 7].

At the fundamental level, harnessing nuclear power raises the same basic decommissioning challenges regardless of nation: transition from operation to decommissioning; reactor defueling; component radiometric surveying and decontamination; component dismantling; infrastructure demolition; waste management and long-term safe disposal of radioactive wastes; site remediation (ground & groundwater); and license termination activities. Differences lie in how this nuclear power was harnessed: i.e. reactor type (e.g. GCR (UK) vs PWR and PHWR (Korea) etc); extent of reactor R&D programs (i.e. research reactors); historical reactor operational factors (e.g. neutron flux and reactor lifespan); historical use of nuclear power (i.e. civil vs military); fuel cycle employed nationally, specifically open vs closed; government policy (e.g. gradual phase-out with some continued use vs complete removal); site end-state and reuse options. A comparison of key similarities and differences related to nuclear decommissioning facing both the UK and Korea are highlighted (Table 4).

6.1 Decommissioning Similarities

6.1.1 Long-term HLW Disposal

Both the UK and Korea are yet to confirm the siting of a GDF for the long-term disposal of HLW. This poses a significant issue to Korea as limited storage space remains across the nations existing NPPs fuel storage ponds. Therefore, contingences should be made for the storage of fuels prior to decommissioning. This may involve re-siting fuels from a redundant reactor to an operational one or the construction of additional temporary storage away from the NPP earmarked for decommissioning in order to allow for decommissioning activities to commence unimpeded. The UK faces a similar issue. In the short term at least, the UK can continue to utilise Sellafield as a temporary storage site for spent and reprocessed fuels from its fleet of Magnox, and later AGR, reactors. This enables reactor decommissioning to take place. However, the urgent need for a long-term solution to the UK’s spent nuclear fuel remains. Korea does however have a track record of developing and building an underground disposal facility, unlike the UK, situated at Gyeongju built to house LLW and ILW. The facility can be seen as a basic blueprint for any future HLW disposal facilities.

6.1.2 Facility Decommissioning

Aside from a nation’s core reactor fleet, facilities exist to support different aspects of a fuel cycle, for which the UK has many (e.g. Magnox & Thorp reprocessing plants, Springfields etc). Korea also has a number of support facilities such as the Korea Atomic Energy Research Institute (KAERI) and the Korea Electronic Power Corporation Nuclear Fuel (KEPCO-NF) fuel assembly facility. Once these sites reach their end-of-life POCO activities are necessary to ensure radioactive contamination is appropriately removed. Throughout its history of decommissioning the UK has built a wealth of knowledge and expertise regarding POCO best practices and technologies which could be exploited for the Korean case. In addition, secondary
waste treatment plants such as EARP and SIXEP situated at Sellafield could also form the basis for any future waste treatment plants to be situated in Korea such as those designed and being discussed for the treatment of waste concrete [56, 57], decontamination processes such as the HYBRID process [58, 59], or bespoke wastes originating from outside the industry [60]. Often many of the chemical, physical, and engineering challenges associated with treating one waste type at one site can be directly applied to a similar waste type at a different site, be those national or international.

The UK has gained a range of expertise during decommissioning fuel storage ponds, research reactors, and R&D facilities. To this end the UK has had to adapt and develop a multitude of bespoke technologies capable of handling many challenging wastes and environments such as the SRP, RAP and robotic laser cutting methodologies. The UK has also shown the benefits of implementing appropriate site/facility preparations prior to decommissioning, with the implementation of the LETP and SPP at Sellafield being of particular note. Korean nuclear sites also house several similar facilities. While it is unlikely Korea will face such challenging wastes, for example those found in the LPS at Sellafield, there may be instances in which unexpected wastes arise. Being able to adapt technologies that already have a proven record of deployment could considerably reduce the economic and technology burden faced by Korea, especially in instances were a one-off waste presents itself and developing a bespoke ‘Korean made’ technology would be economically unfavourable.

6.1.3 Socioeconomic Impacts

The closure and eventual decommissioning of Kori-1 will see the workforce at the site diminish. The loss of such a large and central employer has often had a negative impact on local economies. A mismatch in skill sets between former site workers and the requirements of the local area can also lead to former workers struggling to find new work, further exacerbating any stresses in a local economy. Such impacts have been felt at sites around the UK. To overcome these, initiatives such as the Chapelcross Development Framework have been developed and options for site reuse, such as housing SMRs at Trawsfynydd, have been considered. Korea would do well to begin to consider such initiatives in advance of site closures so that any plans can be put in place while decommissioning is taking place to ensure a smooth transition. New businesses or research facilities could occupy former nuclear sites, become major science and technology centres for a region, and provide significant job growth in various areas of science and business; thus, making good on assets such as land and local infrastructure.

6.1.4 License Termination

Termination is a culmination of years of planning, preparation and implementation of decommissioning activities. As license termination is the final stage it can sometimes be overlooked or side-lined in favour of more pressing matters. However, establishing a well understood procedure early can help inform decommissioning strategies. Further, as decommissioning progresses areas of a site can have their licenses gradually removed allowing for a quicker turnover of the site for new uses, such as Harwell in the UK. In delicensing the site at Harwell extensive details have been prepared [51]. Such details could benefit Korea by providing a blueprint for site license termination and begin a process that can be used to support redevelopment proposals.

6.2 Decommissioning Differences

Historical paths taken by the two nations in harnessing nuclear power has resulted in a number of differences now facing the UK and Korea in terms of decommissioning. As a nation at the forefront of nuclear power, the UK is left with a significant nuclear legacy as extensively highlighted previously [7]. Korea, on the other hand, has benefited from adapting prior technological advances eliminating the need for extensive early R&D, which has led
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6.2.1 No Decommissioning Centric Authority

As highlighted by Kim [61], it is important to establish governing stakeholders’ involvement in decommissioning projects since technical and socio-political issues are mixed. Further, it is a government’s role to set up the legal guideline for decommissioning a facility in order to maximize social and workforce safety. Given the social sensitivity toward nuclear power, it is necessary to build a consensus among stakeholders at every stage of decommissioning. Civil society’s participation should be included in the process in terms of enhancing public acceptance for decommissioning strategies [61]. This is an area in which the UK has excelled with the implementation of the state-orientated NDA [7]. Similarly, Korea is also typically state-oriented with the government as the largest stakeholder of the nuclear industry across multiple entities. Adapting a state-orientated approach to decommissioning, similar to that of the NDA, should be achievable within Korea; the benefits of which were discussed in part I of this review [7].

6.2.2 Limited Decommissioning Experience vs Aggressive Decommissioning Goals

At the time of writing the nuclear decommissioning industry in Korea remains in its infancy, relative to other nations, including the UK (Table 5) [7, 61]. Collectively, France, Germany, Japan, the UK, and the USA have gained more than two centuries of decommissioning experience, be that in the form of strategic planning or implementation of chosen strategies, since the closure of their earliest NPPs. The USA alone has almost 60 years of experience since the closure of GE Vallecitos in 1963, longer than the lifespan of Kori-1. It is necessary for Korea to rapidly, but safely, expand on this limited experience by developing and/or acquiring relevant technology, defining a decommissioning framework and training a workforce. In the meantime, issues surrounding Korea’s limited decommissioning experience may be exacerbated by aggressive decommissioning goals. At the time of Kori-1 closure in 2017 prompt decommissioning was planned to be completed over the next 15–20 years. Wolsong-1 (PHWR) was closed in late 2019.

Table 5. Comparison of decommissioning experience between nations with advanced decommissioning programs, and Korea [62]

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of facilities</th>
<th>Year of 1st Closure</th>
<th>Decommissioning Strategy</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>35&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1973 (CHINON A-1)</td>
<td>I.D.</td>
<td>[63]</td>
</tr>
<tr>
<td>Germany</td>
<td>30&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1974 (NIEDERAICHBACH)</td>
<td>I.D. or D.S.E.&lt;sup&gt;g&lt;/sup&gt;</td>
<td>[64]</td>
</tr>
<tr>
<td>Japan</td>
<td>24&lt;sup&gt;f&lt;/sup&gt;</td>
<td>1998 (TOKAI-1)</td>
<td>Mixed</td>
<td>[65]</td>
</tr>
<tr>
<td>UK</td>
<td>14&lt;sup&gt;f&lt;/sup&gt;</td>
<td>1988 (BERKELEY-2)</td>
<td>D.S.E.</td>
<td>[66]</td>
</tr>
<tr>
<td>USA</td>
<td>34</td>
<td>1963 (GE VALLECITOS)</td>
<td>Mixed</td>
<td>[67]</td>
</tr>
<tr>
<td>Korea</td>
<td>2&lt;sup&gt;i&lt;/sup&gt;</td>
<td>2017 (Kori-1)</td>
<td>I.D.</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup>As of 2020/2021.
<sup>b</sup>Facilities permanently shutdown, undergoing decommissioning, or completely dismantled.
<sup>c</sup>Year in which first commercial NPP closed.
<sup>d</sup>I.D. = Immediate Dismantling, D.S.E. = Dismantling after Safe Enclosure (Deferred Dismantling).
<sup>e</sup>Includes all basic nuclear installations (power plants, research reactors, laboratories, fuel reprocessing installations, waste treatment facilities, etc.).
<sup>f</sup>NPPs including prototype and experimental reactors.
<sup>g</sup>German Atomic Energy Act (AtG) allows for a choice of decommissioning strategies put prohibits permanent safe enclosure.

<sup>i</sup>Commercial NPP reactors.
A further five reactors are scheduled for closure between 2023–2026, bringing the total to seven. This aggressive decommissioning schedule has the potential to place great strain upon the nuclear industry within Korea [7, 61].

Unlike in the UK where radioactive graphite poses significant issues, Korea would gain little from a deferred decommissioning strategy based on radiological grounds alone. However, due to factors such as no GDF for HLW, limited maturity of decommissioning technology, and the establishment of a decommissioning workforce required, there may well be instances in which deferred decommissioning may be advantageous. Therefore, planned deferrals should not be ruled out in select cases, with flexibility built into all decommissioning strategies as a minimum. To this end the UK has developed a wealth of knowledge regarding deferred decommissioning strategies, in particular Magnox C&M. A suitable C&M framework could be adapted by Korea and employed where necessary.

**6.2.3 Kori-1 PWR Decommissioning: Adopt a ‘Lead and Learn’ Approach**

All the NPPs in Korea are of the PWR type, except for Wolsong. With the planned prompt decommissioning of Kori-1 there is a fantastic opportunity to implement a ‘Lead and Learn’ approach, as successfully utilized by Magnox Ltd. In effect Kori-1 could be seen as an equivalent to Bradwell or Trawsfynydd. The tools, techniques and approaches to decommissioning developed at the Kori-1 PWR NPP could be seen as a milestone for Korea’s decommissioning industry; an industry estimated to be in the region of 22.5 trillion won [1, 68]. Technology and skills transfer from Kori-1 across the remaining NPP fleet could significantly accelerate decommissioning throughout Korea while maintaining safety and minimising the economic burden.

**6.3 Implementation of a Strategic Nuclear Decommissioning Blueprint in Korea**

To ensure a successful decommissioning industry within Korea it is vital to understand the challenges facing Korea and develop robust plans for executing decommissioning to avoid prolonged technical delays,
economic mismanagement, or failures in safety potentially effecting both the environment and humans alike. Adopting lessons learned from overseas can greatly reduce the decommissioning burden facing Korea, for which the UK is an excellent case study. A summary of key approaches taken by the UK and discussed across this two-part review are provided in Table 6 [7].

7. Conclusions

With the closure of Wylfa, aging nuclear facilities such as Sellafield, and the beginning of the end for the AGR fleet, the UK is left with a growing legacy of decommissioning problems. Concerns over long-term nuclear waste disposal, and the uncertainty surrounding a suitable GDF, only adds to these problems. However, the NDA has made great strides in tackling this legacy. Since its inception in the early 2000s the NDA has successfully developed a detailed understanding of the legacy and produced the first-ever UK-wide strategy for tackling it; prioritised funds towards the highest hazards; reshaped the industry and introduced international delivery partners; delivered value for money by driving performance and efficiency; invested in skills to build the future capability of the UK’s nuclear workforce; and worked with communities in priority areas to help them plan for sustainable futures. In December 2018 it set out its draft business plan for coming years. Over the next 10 years the NDA aims to defuel all Magnox stations; transfer four Magnox sites into C&M; and continue making progress on the volume reduction of high hazards including dealing with the LPS at Sellafield. Soon there-after the NDA hope to have all other Magnox sites in C&M; have completed decommissioning activities at Harwell and Winfrith; Clean-out intermediate level wastes from Dounreay; and have confirmation of a suitable site to host the UK’s GDF; all within a 20-year timeframe. The challenges faced by the UK nuclear industry require innovative, unique and high-tech engineering solutions and as a result the UK has become a world-leader in decommissioning. While different challenges await Korea, the approaches taken by the UK offer a foundation upon which the Korean nuclear industry can adapt and build upon. The authors wish good luck to the Korea decommissioning industry as they embark on the path to decommissioning.

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Notes

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