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UK Civil Nuclear Decommissioning, a Blueprint for Korea's Nuclear Decommissioning Future?: Part I - Nuclear Legacy, Strategies, and the NDA

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The challenges facing companies and institutions surrounding civil nuclear decommissioning are diverse and many, none more so than those faced in the United Kingdom. The UK's Generation I nuclear power plants and early research facilities have left a 'Nuclear Legacy' which is in urgent need of management and clean-up. Sellafield is quite possibly the most ill-famed nuclear site in the UK. This complex and challenging site houses much of what is left from the early days of nuclear research in the UK, including early nuclear reactors (Windscale Piles, Calder Hall, and the Windscale Advanced Gas Cooled Reactor) and the UK's early nuclear weapons programme. Such a legacy now requires careful management and planning to safely deal with it. This task falls on the shoulders of the Nuclear Decommissioning Authority (NDA). Through a mix of prompt and delayed decommissioning strategies, key developments in R&D, and the implementation of site licenced companies to enact decommissioning activities, the NDA aims to safety, and in a timely manner, deal with the UK's nuclear legacy. Such approaches have the potential to influence and shape other such approaches to nuclear decommissioning activities globally, including in Korea.

Keywords: Nuclear Decommissioning, Nuclear Decommissioning Authority, Sellafield, Nuclear legacy, United Kingdom, Korea

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Abbreviation List:

Abbreviation	Meaning
AERE	Atomic Energy Research Establishment
AGR	Advanced Gas-Cooled Reactor
ALARP	As Low As Reasonably Practicable
BEIS	Department for Business, Energy and Industrial Strategy
C&M	Care and Maintenance
DFR	Dounreay Fast Reactor
DSRL	Dounreay Site Restoration Limited
EARP	Enhanced Actinide Removal Plant
EDF Energy	Électricité de France Energy
FBR	Fast Breeder Reactors
FDP	Final Decommissioning Plan
FGMSP	First Generation Magnox Storage Pond
FGRP	First Generation Reprocessing Plant
GCR	Gas Cooled Reactors
GDF	Geological Disposal Facility
HALES	Highly Active Liquor Evaporation and Storage Plant
HAW	Higher Activity Waste
HLW	High-Level Radioactive Waste
HM Tresury	Her Majesty's Treasury
HSE	Health and Safety Executive
HSSSEQ	Health, Safety, Security, Safeguards, Environment and Quality
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
IWM	Integrated Waste Management
KAERI	Korea Atomic Energy Research Institute
KHNP	Korea Hydro & Nuclear Power Co., Ltd.
LLW	Low Level Waste
LLWR	Low Level Waste Repository
LPS	Legacy Ponds and Silos

Abbreviation	Meaning
Magnox	MAGnesium None OXidizing
MoD	Ministry of Defence
MOX	Mixed Oxide Fuel
MRP	Magnox Reprocessing Plant
MSSS	Magnox Swarf Storage Silo
NDA	Nuclear Decommissioning Authority
NNL	National Nuclear Laboratory
NPP	Nuclear Power Plant
NSA	Nuclear Safety Act
ONR	Office for Nuclear Regulation
PFCS	Pile Fuel Cladding Silo
PFR	Prototype Fast Reactor
PFSP	Pile Fuel Storage Pond
PHWR	Pressurised Heavy Water Reactor
POCO	Post Operational Clean Out
PUREX	Plutonium URanium EXtraction
PWR	Pressurised Water Reactor
R&D	Research and Development
RSRL	Research Sites Restoration Ltd
RWM	Radioactive Waste Management Ltd
SGHWR	Steam Generating Heavy Water Reactor
SIXEP	Site Ion Exchange Plant
SLC	Site Licence Companies
SNUPPS	Standardised Nuclear Unit Power Plant System
Thorp	THermal Oxide Reprocessing Plant
UK	United Kingdom
UKAEA	United Kingdom Atomic Energy Authority
VLLW	Very Low Level Waste
WAGR	Windscale Advanced Gas Cooled Reactor
WML	Waste Management Lifecycle
WVP	Waste Vitrification Plant

Table 1. Overview of leading decommissioning strategies by country [44]

Country	Current activities	Strategy
Belgium	Small: Eurochemic reprocessing plant and BR3 reactor	BRD3: early dismantling to greenfield
Bulgaria	Moderate: four units shutdown	Deferred dismantling with safe enclosure
Czech Republic	No decommissioning activities	Deferred dismantling with safe enclosure
France	Moderate to large: several NPPs and research reactors	Early dismantling of shut-down first-generation reactors
Germany	Large: many NPPs, research reactors and fuel-cycle facilities	Mainly early dismantling to greenfield. Some deferred with safe enclosure
Hungary	No decommissioning activities	Deferred dismantling with safe enclosure
Italy	Moderate: four NPPs and fuel cycle facilities	Early dismantling
Latvia	Small: one research reactor	Immediate dismantling
Lithuania	Moderate: two NPP units shutdown	Immediate dismantling
Netherlands	Small: one NPP	Deferred dismantling with safe enclosure
Poland	Small: one research reactor	Immediate dismantling
Romania	Small: one research reactor	Immediate dismantling (Research reactor)
Slovakia	Moderate: NPP A1 under decommissioning. NPP V1 shutdown	Under evaluation (as of 2012)
Slovenia	No decommissioning activities	Immediate dismantling
Spain	Small: one NPP	Deferred dismantling with safe enclosure
Sweden	Small: two NPP reactors at same site	Early decommissioning
United Kingdom	Large: many NPP, research reactors and fuel cycle facilities	Deferred dismantling with safe enclosure

1. Introduction

With an aging nuclear fleet and changing geo-political climate, nuclear decommissioning in the Republic of Korea (here after 'Korea') has been thrust to the forefront of the minds of those in the industry (Decommissioning trends [1, 2]; Decommissioning planning [3]; Cost analysis and forecasts [4, 5]; Risk assessment [6-8]; Environmental impact analysis [9, 10]; Decontamination and dismantling methodologies [11-16]; Waste handling, management, and treatment [17-19]; Wasteforms [20-23]; Waste disposal, reactive barriers and geological waste repository [24-28]; Radionuclide migration and groundwater analysis [29, 30]; and Site remediation [31, 32]). 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 [1]. Gaining such an understanding is imperative for the implementation of a successful decommissioning program. Looking to those nations who are already employing effective programmes for nuclear decommissioning offers a chance to learn, adapt and implement a workable model for the Korean nuclear industry [33-38].

Ever since the dawn of the atomic age there has been a potential for the application of nuclear energy as a source of clean civil power. However, civil applications have often struggled to shake off the shackles of negative public opinion due to nuclear being synonymous to some with severe accidents, military applications, the cold war and mishandled radioactive wastes [39, 40]. Despite these negative connotations, the United Kingdom (UK) has often found itself at the forefront of civil nuclear applications, most notably connecting the first nuclear reactor to a national power grid at Calder Hall in 1956 [41]. Over the subsequent decades the UK came to embrace nuclear power with mixed results. From successfully deploying its first fleet of Magnox reactors throughout the 1960s and the development of fuel reprocessing facilities at Sellafield, to the economic difficulties of the UK Advanced Gas-Cooled Reactor (AGR) and Pressurised Water Reactor (PWR) programmes of the 80's and 90's [42, 43]. The UK now faces the prospects of an ever-growing energy demand with an aging nuclear fleet, an uncertainty over future new build, and mounting obligations to decommission historical facilities.

1.1 Nuclear Decommissioning

As defined by the International Atomic Energy Agency (IAEA) in 2007, "Decommissioning is the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility" [33]. Decommissioning activities can vary from simply closing the facility, following minimum removal of radioactive material along with continual surveillance permitting only restricted use of the facility, to the full removal of radioactive and other toxic materials such that the site can be used for new uses with no nuclear related restrictions in place [33]. The IAEA have identified three options for nuclear decommissioning. These definitions have been internationally embraced (Table 1) [44]:

- Immediate Dismantling (or Early Site Release)
- Safe Enclosure ('Safstor') or deferred dismantling
- Entombment (or 'Entomb')

As of 2020, there have been over 180 commercial, experimental or prototype reactors, and over 500 research reactors that have been retired internationally, along with a number of fuel cycle facilities [45, 46]. After operation, large parts of Nuclear Power Plants (NPPs) and facilities remain free of radioactive contamination but the small volumes that do, require appropriate management to ensure public health and environmental safety [33-34]. The future of nuclear decommissioning relies on the continued and successful development of tools, technologies and methodologies in order to overcome many of the decommissioning challenges faced by companies, institutions and governments alike. Solving such problems requires innovation and initiative from a wide range of experts both within and exterior to the nuclear industry [1].

1.2 Purpose of Review

In this, the first of a two-part review, we aim to provide an overview of the UK's approach to nuclear decommissioning, including the relevant historical context. We wish to disseminate key topics including the history of the UK nuclear industry, the current decommissioning challenges faced, and approaches taken to solve these issues. In addition, several supplementary but equally important topics focusing on decommissioning hierarchy, relevant authorities etc. are intended to be discussed. It is hoped the reader will come to appreciate the complexity of the problems regarding nuclear decommissioning in the UK, but also gain an insight into some possible decommissioning strategies applicable to the Korean case.

2. UK's Nuclear Legacy

For a time, the UK was at the forefront of civil nuclear power research and technology. This brought about many advances in nuclear technology and applications which, to this day, effect how nuclear power is harnessed for civil applications. However, being at the forefront of such a technological advance was not without its costs. The UK's Generation I NPPs (Gen I) and early research facilities have left a Nuclear Legacy which is in urgent need of management and clean-up. As a result, the UK has a varied portfolio of facilities to decommission [47].

In the UK, the term 'Nuclear Legacy' is used to describe those facilities that remain from early nuclear programmes. Some of these sites were established during the very earliest days of the nuclear industry which emerged in post-war Britain of the mid-late 1940's. The UK's Nuclear Legacy includes:

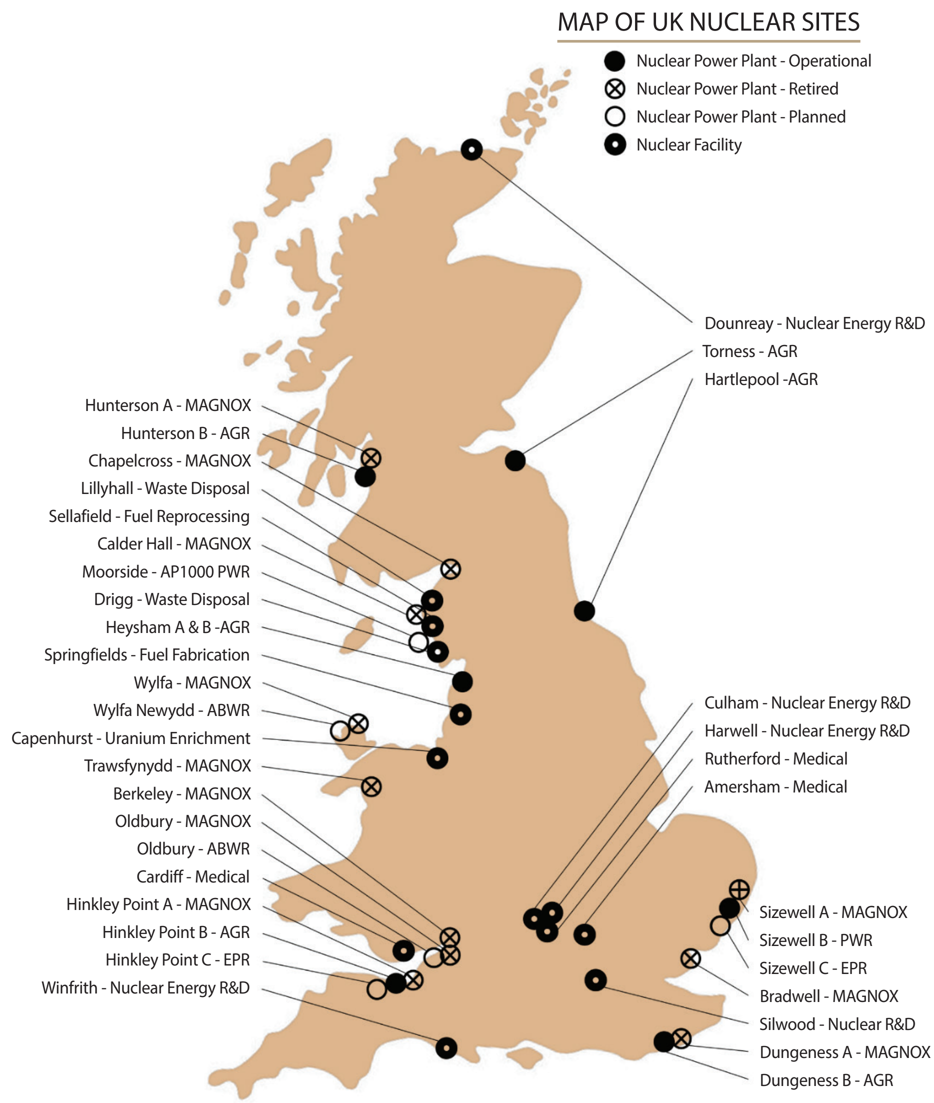

Fig. 1. Map of UK NPPs and nuclear facilities (excluding military installations).

- Research sites used during the development of the nuclear industry
- Facilities associated with nuclear weapons development
- The UK's 1st generation of NPPs (Magnox fleet)
- Nuclear fuel fabrication plants and reprocessing facilities (e.g. Magnox, Thorp plants etc)

Sellafield is undoubtedly the most recognisable nuclear site in the UK. This complex and challenging site houses much of what remains from the early days of nuclear research in the UK including first of a kind nuclear reactors (Windscale Piles, Calder Hall, and the Windscale Advanced Gas Cooled Reactor) and the UK's early nuclear weapons programme. Nonstandard designs were used for many of the Gen I (Magnox) and Gen II (AGRs) reactors which leads to difficulties during decommissioning as changes must be made to the decommissioning approach;

Table 2. UK NPPs – Current and retired

Name	Unit No.	Type	Model	Status	Net (MWe)	Gross (MWe)	Building Started	Operation	Closure
Calder Hall	4	GCR	MAGNOX	Shut down	196	240	1953	1956	2003
Chapelcross	4	GCR	MAGNOX	Shut down	192	240	1955	1959	2004
Berkeley	2	GCR	MAGNOX	Shut Down	276	332	1957	1962	1989
Bradwell	2	GCR	MAGNOX	Shut down	246	292	1957	1962	2002
Hunterston A	2	GCR	MAGNOX	Shut down	300	346	1957	1964	1990
Hinkley Point A	2	GCR	MAGNOX	Shut down	470	534	1957	1965	2000
Trawsfynydd	2	GCR	MAGNOX	Shut down	390	470	1959	1965	1991
Dungeness A	2	GCR	MAGNOX	Shut down	450	460	1960	1965	2006
Sizewell A	2	GCR	MAGNOX	Shut down	420	490	1961	1966	2006
Oldbury	2	GCR	MAGNOX	Shut down	434	460	1962	1967	2012
Wylfa	2	GCR	MAGNOX	Shut down	980	1,060	1963	1971	2015
Dungeness B	2	GCR	AGR	Operational	1,040	1,230	1965	1985	2028
Hinkley Point B	2	GCR	AGR	Operational	870	1,310	1967	1976	2023
Hunterston B	2	GCR	AGR	Operational	920	1,288	1967	1976	2023
Hartlepool	2	GCR	AGR	Operational	1,190	1,310	1968	1989	2024
Heysham A	2	GCR	AGR	Operational	1,170	1,250	1970	1989	2019
Torness	2	GCR	AGR	Operational	1,190	1,364	1980	1988	2023
Heysham B	2	GCR	AGR	Operational	1,220	1,360	1980	1989	2023
Sizewell B	1	PWR	SNUPPS	Operational	1,191	1,250	1988	1995	2035

thus increasing costs and time requirements. Many facilities, including very early reactors, were scientific experiments that were never used for commercial production but have left a legacy of engineering one-offs and non-standard waste types meaning there is little room for a 'one size fits all' approach to decommissioning (e.g. Winfrith site). During these early days of the nuclear industry plans for decommissioning were scarcely contemplated. This is the 'Nuclear Legacy'.

2.1 Reactors

2.1.1 Magnox – Gen I GCRs

As an island nation with limited resources energy security has always been a priority for the UK. July 1954 saw the establishment of the United Kingdom Atomic Energy Authority (UKAEA) to oversee and pioneer the development of civilian nuclear power generation. The programme started by the UKAEA expanded rapidly. Just two years later on the 27th August 1956 the world's first NPP to deliver electricity at commercial scale began operation at Calder Hall, now the location of Sellafield. Calder Hall's sister site, Chapelcross, commenced power generation in 1959.

Calder Hall and Chapelcross were Gas Cooled Reactors (GCR) of the of Magnox type (Gen I) with a combined gross capacity of 480 MWe. Natural uranium metal fuel was used with a graphite moderator and carbon dioxide coolant. Magnox (MAGnesium None OXidizing) fuel is so called because of its magnesium alloy cladding. Due to the chemical reactivity of the cladding, the fuel elements cannot be stored forever but must be reprocessed. Temporary storage requires the control of storage pond chemistry including maintaining the ponds at high pH (pH > 11.5) to minimise fuel cladding corrosion which creates long term storage problems. Any corrosion that does occur during storage leads to the formation of radioactive sludges which are highly mobile, significantly complicating any decommissioning activities. The Magnox reprocessing plant situated at Sellafield (see section; 2.2.1 Site Infrastructure) was opened to reprocess the Magnox fuel. The success of Calder Hall and Chapelcross brought a government promise that a civil nuclear power building programme would achieve 5,000 − 6,000 MW capacity by 1965 [41]. The age of safe clean nuclear power generation in the UK had begun [48].

The late 1950s and early 1960s saw construction commence on, and the commissioning of, nine new NPPs based on the Magnox GCR Gen I design (Fig. 1). The first to begin power generation was Berkeley in 1962 with the last, Wylfa – North Wales, beginning power generation in 1971; operating until December 30th, 2015, when it stopped energy production and went into decommissioning marking the end of power generation by Gen I GCRs in the UK (Table 2).

2.1.2 Advanced Gas Cooled Reactors – Gen II GCRs

In 1964, shortly after the construction of Wylfa had begun, the Government issued a white paper, 'The Second Nuclear Programme', setting out plans for new plants with a combined capacity of 5,000 MWe to be built between 1970−76 [49]. This was later revised to 8,000 MWe in 1965. The aim was to expand the capacity for electricity production. This was to be the start of the era of AGRs (Gen II) after other designs, namely the American PWR, were rejected.

Seven twin-unit AGR stations were built between 1976−89 (Table 2). They too were graphite moderated with a carbon dioxide coolant; but, unlike the Magnox reactors, the AGRs use an enriched oxide fuel. The AGRs yield a higher thermal efficiency (Approx. 40%) due to high coolant temperatures (well over 600°C) [50]. The AGR design is exclusive to the UK.

Like the Magnox fleet, AGRs were designed and built by private industry. This led to little standardization across the reactor fleet leading to significant operational problems. Issues included: high capital costs, long construction times, unreliability, inefficiency, environmental concerns from radioactive waste disposal and distrust in regulators [42]. The construction of the AGRs was largely considered a disaster in planning and implementation. For example, construction of Dungeness B and Hartlepool power stations took over 20 and 21 years, respectively, to complete. Repeated delays, financial issues and even the collapse of one of the consortia lead to AGRs being described as 'one of the major blunders of British industrial policy' [51]. The final two AGR stations were ordered (Heysham II and Torness) but not until 1980. Their completion in 1988−89 marked the conclusion of the UK Government's 8,000 MWe programme.

2.1.3 Pressurised Water Reactors – The Third Wave

By the end of the 1970's, and after much debate over the choice of reactor type (Several designs were considered – Magnox, AGR, HTRs, SGHWR, CANDU and PWR) the government of the time announced 10 new PWRs were to be built, calling nuclear power "a cheaper form of electricity generation than any known to man" [52].

Government approval for a 1,188 MWe four-loop Westinghouse PWR (Sizewell B) was given in 1987; operational in 1995 (Table 2). Based on the SNUPPS (Standardised Nuclear Unit Power Plant System) with several modifications to meet UK requirements. However, construction costs rose from £1.69 bn to £2.03 bn (£3.71 billion, ₩5.33 trillion as of 2018, accounting for inflation) during construction [53].

Further PWRs were planned, namely Hinkley Point C, Wylfa B and Sizewell C; with consent for Hinkley Point C being given. However, in 1989 the UK Government announced a nuclear policy review which was scheduled to take place in

1994, effectively halting the construction of any new NPPs. Following the review (May 1995) the Government concluded that new nuclear would not receive public sector support, putting an end to Hinkley Point C under Thatcher's Government. At the end of that year, Nuclear Electric decided that "further nuclear plants were not economically viable" and abandoned its plans for new NPPs [43]. This would remain the case until 2008 when the UK Government gave approval for a new generation of nuclear power stations to be built [54]. Yet, a further 10 years would pass before construction began on Hinkley Point C on 11th December 2018; which remains the only site of eight designated sites to have begun construction as of the time of writing.

2.2 Sellafield

The Sellafield site, located along the Cumbrian coastline, is the UK's hub for fuel reprocessing and, along with the National Nuclear Laboratory (NNL), is at the heart of the UK's nuclear research. Together Sellafield and NNL make up the largest and most complex nuclear site in the UK covering approximately 6 Km^2, the site consists of more than 2,200 buildings, of which 200 are major nuclear facilities, and directly employs around 10,000 people.

Sellafield has a long and varied history from being a munitions factory supporting the war effort in the 1940s, home to the Windscale Piles, generating the world's first commercial nuclear power at Calder Hall in 1950s, through to development and operation of commercial nuclear fuel reprocessing to support the UK's Magnox and AGR fleets. The varied nature of the work conducted at Sellafield has generated a complex nuclear legacy that accounts for some of the most hazardous work done on the site today. Remediation of the site is one of the most significant environmental challenges in Europe [55]. In recent years primary activities at Sellafield focused on reprocessing fuel from UK and international reactors (until 2020/21) and supporting the decommissioning of historic plants around the UK.

With the end of reprocessing operations in 2021, moving forward the major operational focus will shift to Post Operational Clean Out (POCO), waste management and decommissioning activities. Decommissioning Sellafield is predicted to take more than 100 years to complete at a cost of almost £100 bn [56-59].

2.2.1 Site Infrastructure

The Sellafield site is a complex mix of facilities built at various points throughout its 70+ year history. Infrastructure at the site can be grouped under four main sections: Power plants and reactors; reprocessing; waste management; and support facilities. While the NPPs and associated infrastructure have been obsolete for many years (decommissioning activates are well under way), until recently the reprocessing plants (Thorp: 2018, Magnox: 2021) have remained major site operations with at least some level of waste treatment operations expected to continue throughout much of the sites decommissioning phases.

The Windscale Piles (Site of the Windscale fire of 1957) associated reprocessing plant, and fuel storage pond (Pile Fuel Storage Pond, PFSP) were built for the sole purpose of plutonium separation from the spent nuclear fuel. The Piles consisted of an air-cooled graphite core. Each pile held nearly 2,000 tonnes of graphite and stood at over 7.3 metres high by 15.2 metres in diameter. The fuel consisted of rods of uranium metal, approximately 30 centimetres long by 2.5 centimetres in diameter encased in aluminium. Calder Hall was the world's first NPP to produce electricity on an industrial scale (four 60 MWe reactors). At the time of the plants closure (31st March 2003), the first reactor had been in operation for nearly 47 years. The Windscale Advanced Gas Cooled Reactor (WAGR) was a prototype for the UK's second generation AGRs. The reactor generated a thermal output of approximately 100 MW and 30 MW electrical. Construction was completed in 1962. The reactor was finally shut down in 1981 and was part of a pilot project to demonstrate techniques for safely decommissioning a nuclear reactor [60].

The First Generation Reprocessing Plant (FGRP) was first used to reprocess fuel from the Windscale Piles, before being repurposed to process fuel from the Magnox reactors prior to commissioning of the Magnox Reprocessing Plant (MRP). The FGRP then became a pre-handling plant to allow oxide fuel to be reprocessed in the Magnox plant. The MRP was opened in 1964 to replace the UK's FGRP and reprocess spent Magnox fuel. The plant uses the Plutonium URanium EXtraction (PUREX) method for reprocessing spent fuel. The plant also needed another storage pond to cool the fuel before it was reprocessed (First Generation Magnox Storage Pond, FGMSP), and a waste silo to store the fuel's outer cladding (Magnox Swarf Storage Silo, MSSS). A new reprocessing facility for the reprocessing of fuel from the UK's AGR fleet was designed and built on the Sellafield site, opening in 1994. The THermal Oxide Reprocessing Plant (Thorp) recycled oxide fuel from UK and overseas reactors. When Thorp opened overseas contracts were secured with Canada, Germany, Italy, Japan, Netherlands, Spain, Sweden and Switzerland. Like the Magnox plant, Thorp employed the PUREX process for fuel reprocessing. Final operations at the Thorp plant ended on 14th November 2018. The MRP continues to operate until 2020/2021, at which point all fuel reprocessing operations in the UK will have ended.

With the development of the Magnox reprocessing plant, and later Thorp, the Sellafield site saw a shift in purpose from power generation to fuel reprocessing. To support the shift in operations to fuel reprocessing, additional infrastructure was built throughout the late 1980s and 90s including, the Site Ion Exchange Plant (SIXEP, 1985) [61], Waste Vitrification Plant (WVP, 1991) [62-64], Enhanced Actinide Removal Plant (EARP, 1994) [65, 66], the Mixed Oxide Fuel Plant (MOX Plant, 1997) [67], and the Highly Active Liquor Evaporation and Storage Plant (HALES) [64, 68].

The HALES plant conditions nuclear waste from the reprocessing plants (Magnox and Thorp). The conditioned waste is then transferred to the WVP which vitrifies the High-Level Radioactive Waste (HLW). The total storage capacity of the WVP is 8,000 containers (800 vertical storage tubes each containing ten containers), to which over 5,500 containers have been stored as of 2012 [64, 69]. The EARP plant is an effluent treatment plant designed to treat reprocessing liquid waste streams and several other on-site wastes. EARP works on the basis of precipitation-coagulation-flocculation producing a metal hydroxide flocculant precipitate [65]. SIXEP is an effluent treatment plant designed to decontaminate storage pond waters. SIXEP is based on ion exchange technology using a zeolite (clinoptilolite). The main purpose of SIXEP is to remove Cs and Sr radionuclides [61, 69].

2.2.2 Radioactive Waste Stores

Sellafield houses several radioactive waste stores, most on an interim basis, while a Geological Disposal Facility (GDF) is developed. The stores include [56]:

- Legacy Ponds and Silos – Storage of historic waste
- Sludge packaging plant – Treatment and interim storage of sludges from legacy ponds
- Sellafield product and residue store – Site store for plutonium and plutonium residues – The plutonium stockpile now estimated at 140 tons (2017) [70, 71].
- Engineered drum stores – Site stores for plutonium contaminated material
- Encapsulated product stores – Site stores for grouted wastes
- Vitrified product store – Vitrified high level waste

2.3 Other Nuclear Facilities

To support the UK's nuclear power programme and NPPs, several nuclear facilities have been situated across the UK with some of them still in operation to this day (Fig. 1). Several of the sites are now closed or scheduled to close in the near future with operations shifting focus to decommissioning under the stewardship of the Nuclear Decommissioning Authority (NDA) (see section; 3. Nuclear Decommissioning Authority).

Early in the UK's nuclear power programmes there was a need to set up a research centre to develop the necessary research and development knowledge with regards to nuclear fission. The Atomic Energy Research Establishment (AERE) was formed in 1946 and was situated at the Harwell laboratory complex. Harwell remained the UK's centre for atomic energy research and development for almost 50 years, closing in 1990.

Two sites to support the UK's nuclear fuel programme were set up at Capenhurst and Springfields hosting uranium enrichment facilities and nuclear fuel fabrication plants, respectively. Both are now transitioning towards decommissioning with several areas of both sites having been successfully cleared.

Other nuclear facilities include: Dounreay, the site of the UK's Fast Breeder Reactors (FBR). A total of three reactors were situated at the site. The site is now in a state of care and maintenance along with on-going decommissioning activities; Winfrith, a nuclear reactor test site set up in 1957 and was home to a total of nine test reactors including a SGHWR (Steam Generating Heavy Water Reactor) which provided up to 100 MWe to the UK's national grid until being shut down in 1990. The site is now undergoing decommissioning; Drigg LLWR (Low Level Waste Repository), situated 6 Km from Sellafield, is the UK's primary storage site for Low Level Waste (LLW). It has been in operation since 1959 and continues to receive waste from Sellafield, Ministry of Defence (MoD) sites and NPPs, as well as civilian sites such as hospitals, medical companies, universities, and private non-nuclear industries such as the oil industry; National Nuclear Laboratory, opening in 2008 across six UK locations NNL has focused on waste management and decommissioning, fuel cycle solutions, and reactor operations support. The NNL central laboratory is located on the Sellafield site, works closely with Sellafield operations, and is the flagship nuclear R&D facility in the UK. It supports nuclear new build, operation of reactors, fuel processing plant operations, and decommissioning-remediation activities.

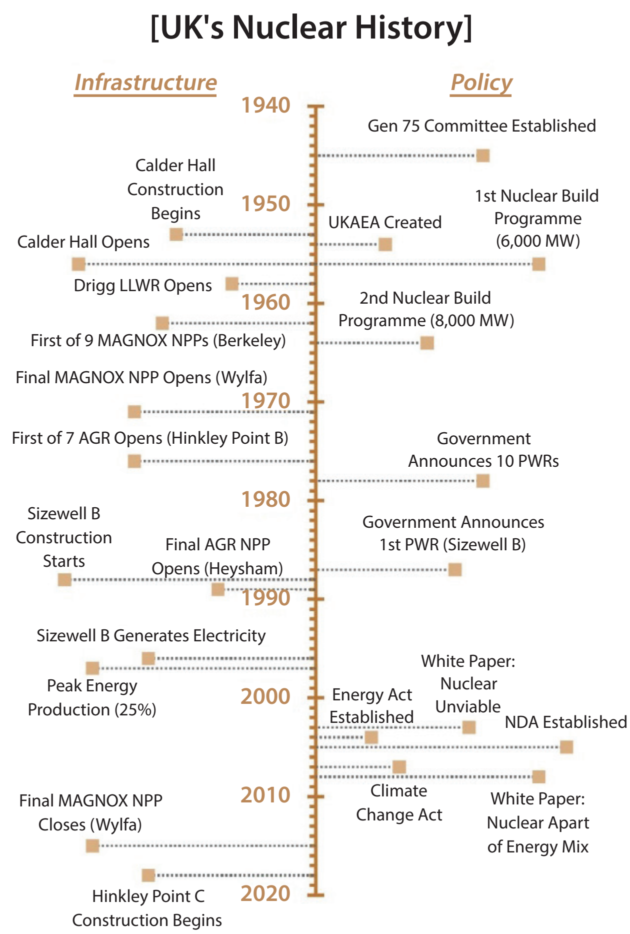

Fig. 2. Timeline of major infrastructure and policy events in the UK.

2.4 Clean-up of the Nuclear Legacy

During the early 2000s, and despite a continued reluctance at that time to pursue nuclear new build, there was ever growing pressure to solve the UK's growing nuclear legacy (Fig. 2). The Energy Act 2004 was an act of parliament to, in part, make provisions for the decommissioning and cleaning up of installations and sites used for, or contaminated by, nuclear activities, and make provisions for dealing with radioactive waste [72]. As part of the Energy Act 2004 the Nuclear Decommissioning Authority (See below) was established, beginning operations in 2005 [37, 72]. Its purpose is to deliver the decommissioning

Table 3. List of nuclear sites under the NDA umbrella and associated SLC [56]

Sites	Site Licence Company
Berkeley; Bradwell; Chapelcross; Dungeness A; Harwell; Hinkley Point A; Hunterston; Oldbury; Sizewell A; Trawsfynydd; Winfrith; Wylfa	Magnox Ltd A wholly owned subsidiary of NDA from 1 September 2019
Low Level Waste Repository (LLWR) near Drigg	LLWR Ltd
Dounreay	Dounreay Site Restoration Ltd
Sellafield	Sellafield Ltd A wholly owned subsidiary of NDA from 1 April 2016
Springfields	Operated by Springfields Fuels Limited under the management of Westinghouse Electric UK Limited
Capenhurst	Operated by Urenco Nuclear Stewardship Ltd (Owned by URENCO Ltd - and formerly known as Capenhurst Nuclear Services Ltd)

and clean-up of the UK's civil nuclear legacy and to solve the major decommissioning challenges faced by the UK's nuclear industry through contracts with specially designed companies, referred to as Site Licence Companies (SLC). Major decommissioning challenges include:

- Sellafield fuel ponds (PFSP, FGMSP etc)
- Sellafield Magnox plant decontamination & dismantling
- Sellafield Thorp Plant decontamination & dismantling
- Sellafield Windscale Piles
- Research Facilities (Dounreay)
- Research Facilities (Harwell)
- Reactor power plants Graphite
- Currently no GDF for ILW (Intermediate Level Waste) & HLW

3. Nuclear Decommissioning Authority

Since the early 2000s the UK has employed a state-oriented approach to nuclear decommissioning of facilities and nuclear power plants. The NDA, is a non-departmental public body that takes all necessary responsibility to deal with the UK's nuclear legacy. The NDA implements policies set by government and reports to the Department for Business, Energy and Industrial Strategy (BEIS); for some aspects of their work in Scotland, the NDA are responsible to Scottish ministers (Fig. 3). How the NDA implements these policies is set out in their Strategy, which reflects any policy changes introduced by the government. The NDA's key areas of responsibility are:

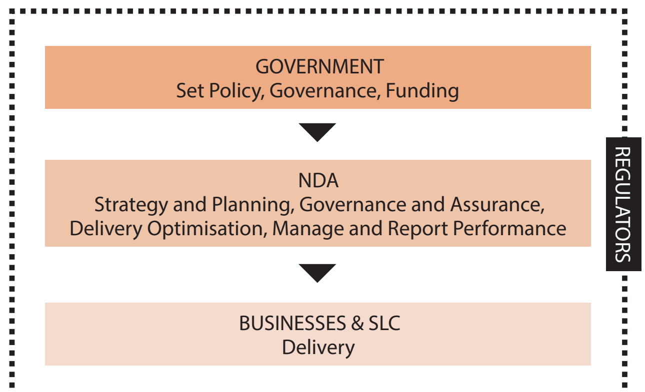

Fig. 3. Operational overview relating to the NDA.

- Waste management
- Managing nuclear materials
- Reprocessing spent fuels
- Decommissioning
- Other activities:
  - Research and development
  - Oversight of EDF Energy's decommissioning plans

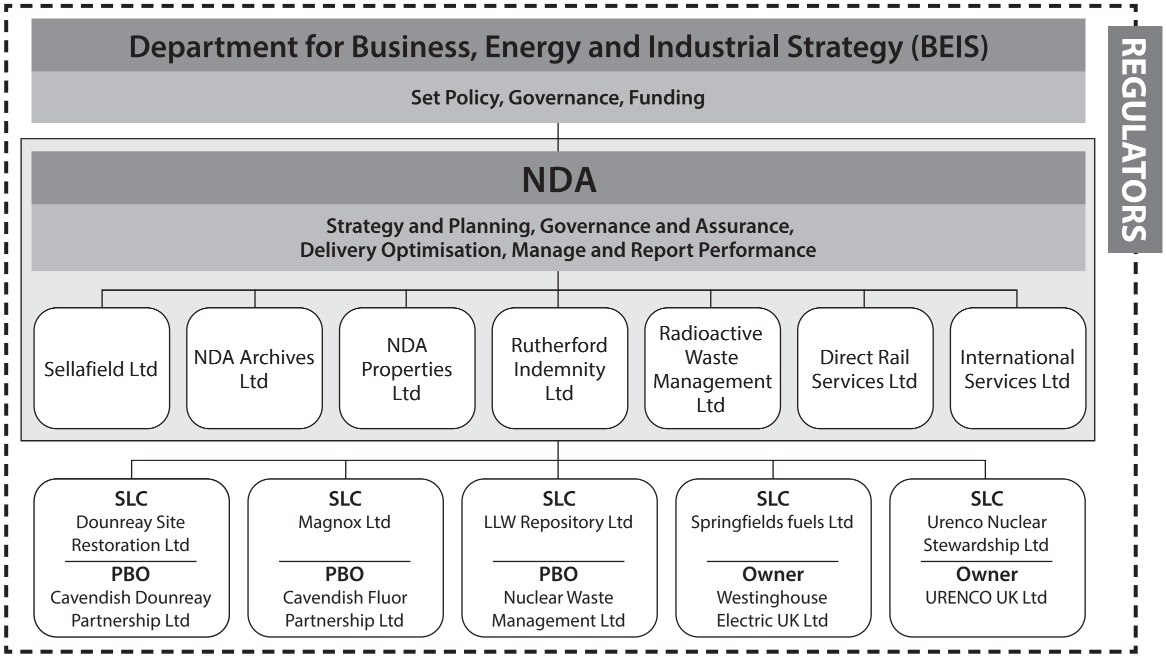

Fig. 4. NDA operational structure [73].

- Interim storage of fuels on behalf of the MoD
- Managing non-standard fuels, commonly referred to as 'exotics', which include fuel inherited from earlier nuclear industry activities (i.e Harwell & Winfrith sites)

The Department for BEIS and Her Majesty's Treasury (HM Treasury) set an annual operational budget. The NDA budget is a combination of government funding and income from commercial assets (e.g. Fuel reprocessing contracts). The total planned expenditure for the financial year 2021 to 2022 is £3.494 billion of which [57]:

- £2.530 billion is funded by UK government.
- £0.964 billion is income from commercial operations.

When the NDA was set up it became owner of the 11 Magnox reactor sites; Capenhurst uranium enrichment plant; Springfields fuel fabrication site; Sellafield site; Drigg LLWR; Dounreary FBR site; along with both atomic research sties at Harwell and Winfrith; collectively known as the NDA Estate. The NDA does not have a hands-on role in cleaning up the facilities, instead the role of the NDA is strategic: establishing the overall approach, allocation of budgets, setting of targets and monitor progress. They deliver their mission through others, primarily 12 businesses. The NDA plans and manages the overall decommissioning strategy which is implemented through SLCs (Table 3, Fig. 4).

3.1 Site Licence Companies

A SLC holds the nuclear site licence, granted by the Office for Nuclear Regulation (ONR), to operate the nuclear site(s) (Table 3). The SLC conduct the required decommissioning programs at each site on behalf of the NDA. Collectively, the SLCs employ around 16,000 workers across the NDA's estate. The NDA funds 4 SLCs directly:

- Dounreay Site Restoration Limited
- Low Level Waste Repository Limited
- Magnox Limited
- Sellafield Limited

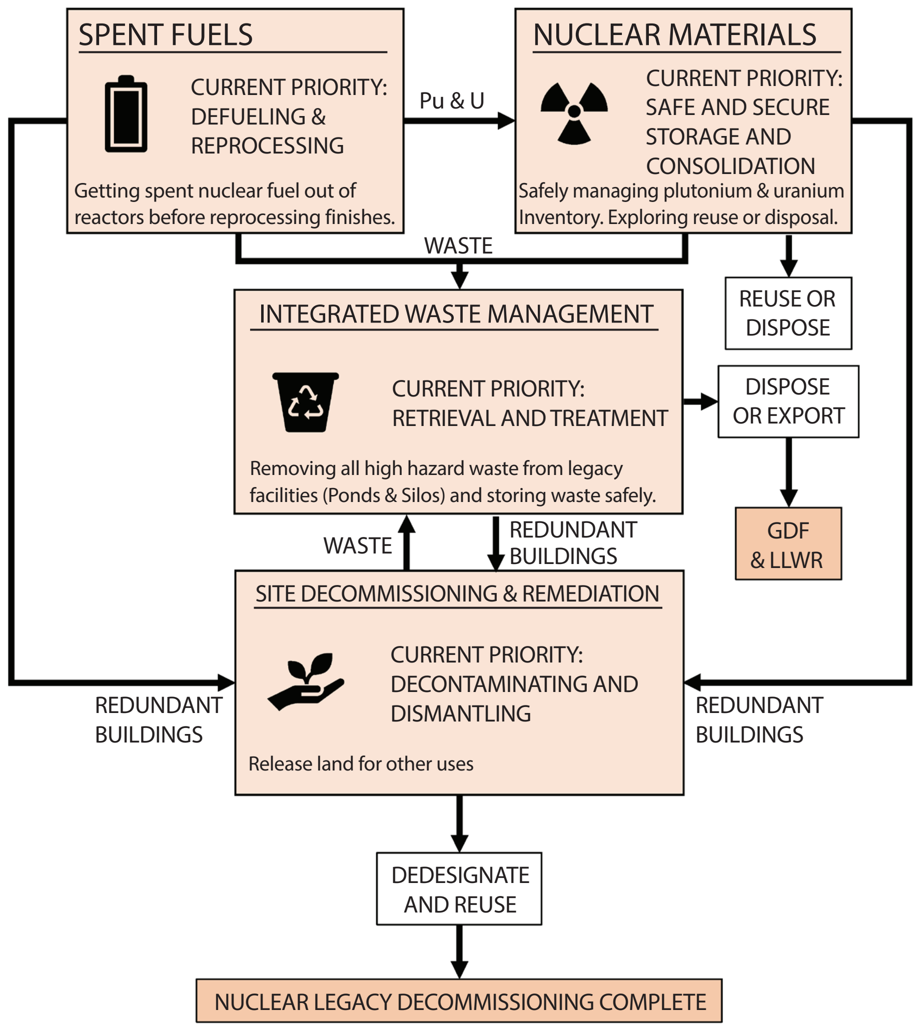

Fig. 5. Overview of the decommissioning themes as implemented by the NDA [73].

4. UK's Decommissioning Approach

4.1 NDA Strategy

The NDA is responsible for setting out a decommissioning strategy, while adhering to the UK Government's policy for dealing with the nuclear legacy. The strategy describes the high-level approach to delivering the NDA mission which is to "Deliver safe, sustainable and publicly acceptable solutions to the challenge of nuclear clean-up and waste management" [73]. Publication of the NDA strategy is a requirement of the 2004 Energy Act which covers the entire decommissioning period (+100 years) and is published in a revised form every five years. The NDA's strategy is implemented through its business plan which is published every year and covers the proceeding 3 years [57, 74]. Progress of both the short-term business plan and overarching NDA strategy are assessed through mid-year performance reports, mission progress reports and an annual report.

The NDA's strategy approaches the nuclear legacy in five parts, or what are known as 'Themes'. Each theme addresses a key aspect of the nuclear legacy while sharing a common goal of reducing the legacy in a safe and timely manner. These themes are:

- Site Decommissioning and Remediation
- Spent Fuels
- Nuclear Materials
- Integrated Waste Management
- Critical Enablers

The first four themes all relate to specific decommissioning challenges while the latter, critical enablers, essentially covers all aspects required to support decommissioning such as people and asset management; transport and logistics; socio-economics; Health, Safety, Security, Safeguards, Environment and Quality (HSSSEQ); Research and Development (R&D) etc. As critical enablers are common to all companies or government institutions in some way they shall not be discussed further. Site Decommissioning and Remediation is the driving theme of the NDA's mission. Spent Fuels and Nuclear Materials management constitute an early part of Site Decommissioning and Remediation; the entire mission is underpinned by Critical Enablers (Fig. 5).

4.1.1 Site Decommissioning and Remediation

Site Decommissioning and Remediation defines the NDA's approach to decommissioning redundant facilities and land remediation such that each site can be transitioned to its next planned use. Site decommissioning and remediation is the NDA's primary focus, to which the other themes support its delivery. The NDA aims to complete this as soon as reasonably practical while ensuring the reduction of risks and hazards. The NDA's preference is for prompt and continuous decommissioning, except when deferred dismantling offers clear advantages (e.g. Magnox reactors), for example, to take benefit from radioactive decay. Any deferrals to decommissioning must be met with appropriate levels of scrutiny and be a part of the agreed upon decommissioning plan on a site-by-site basis.

4.1.2 Spent Fuel Management

Spent Fuel Management defines the NDA's approach to managing the diverse range of spent nuclear fuels, including Magnox, oxide, and exotics ('exotics' typically refers to fuels from the early days of nuclear fuel R&D and are usually 'one-offs', 'non-standard' or produced in only small quantities). The strategy is to reprocess all Magnox fuel in line with the Magnox Operating Programme. For oxide fuels, the aim was to finish reprocessing of spent fuel in the Thorp plant. The remaining and future arisings of AGR spent fuel will be placed into interim storage pending disposal in a GDF. All exotic fuels will be consolidated at Sellafield. Some exotic fuels can be treated like Magnox and oxide fuels, but some present particular challenges that require custom-made solutions for their long-term management and final disposal.

4.1.3 Nuclear Materials

Nuclear Materials defines the approach taken to deal with the inventory of uranics (uranium containing materials produced during fuel cycle operations) and plutonium currently stored on some of the NDA's 17 sites. The overarching strategy is 'To ensure safe, secure and cost-effective lifecycle management' of the UK's nuclear materials' [56]. The priority for UK government policy is to provide a solution that puts UK owned plutonium beyond reach by reusing it as MOX fuel. However, this is now on hold due to economic changes primarily brought about by the events at the Fukushima Daiichi nuclear power plant in 2011 [73, 75].

4.1.4 Integrated Waste Management

Integrated Waste Management (IWM) describes how all sites will manage all forms of waste from operating and decommissioning activities; This includes any wastes retrieved from legacy facilities. The accepted strategy for dealing with the UK's Higher Activity Waste (HAW) is two-fold: geological disposal in a GDF (England & Wales) and long-term management in near-surface facilities (Scotland). For LLW the strategy is disposal in fit for purpose facilities.

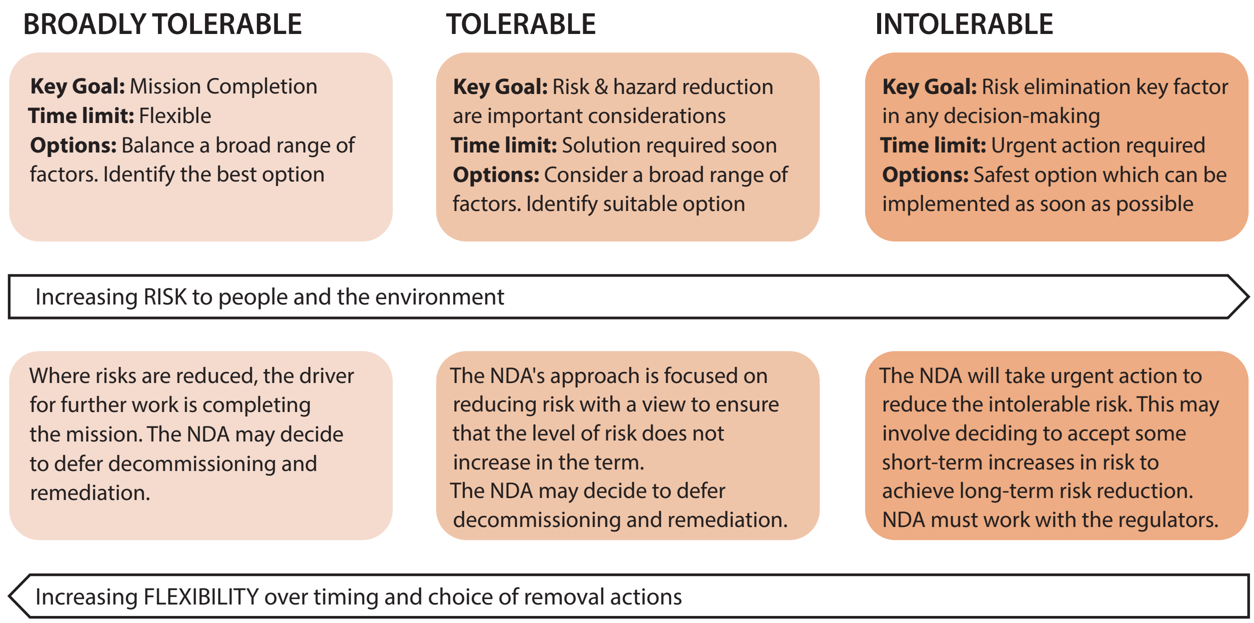

Fig. 6. NDA approach to prioritising risk.

Priority is to achieve a risk reduction by removing wastes from ageing storage facilities (E.g. Legacy ponds and silos at Sellafield) and placing them into safer, more secure modern storage conditions, as and when these become available.

As the NDA strategy has developed over many years there has become an understanding that a more flexible approach to the management of radioactive waste maybe possible. This is reflected in the Waste Management Lifecycle (see section; 4.6 Waste Management Lifecycle). This takes into consideration the entire lifecycle of a waste and aims to allow flexibility between waste handling, treatment and disposal stages.

4.2 NDA Business Plan

The NDA's business plan sets out how the NDA's strategy is to be realised. The business plan is developed by the NDA and implemented across the entire estate through the relevant SLC. It consists of a breakdown of key activities for each site grouped under the five strategic themes. It is then the role of the individual SLCs to determine how best to accomplish each individual decommissioning activity in accordance with the NDA and regulatory bodies. Sellafield and the Magnox fleet represent the bulk of decommissioning activities laid out in the business plan.

4.3 NDA's Decommissioning Approach: Sellafield

A key focus of the early strategy for Sellafield was two-fold: to obtain a full and knowledgeable understanding of the site and its hazards to enable safe and timely decommissioning to be complete; and to identify and prioritise treating the most hazardous areas of the site to dramatically reduce the level of remaining hazards as quickly as possible.

The NDA set about identifying those hazards that are most significant, or regarded as intolerable risks, and those that are broadly tolerable (Fig. 6). The NDA were also able to identify those risks that, through a suitably planned program of care and maintenance, were seen as tolerable risks thus allowing decommissioning resources to be diverted to more significant challenges. From this preliminary gathering of information, the NDA identified the legacy storage facilities, some of the oldest on the site, as being the most intolerable risks and of the highest priority and developed the "hazard and risk-reduction programme" to tackle them.

The areas of principal focus are the redundant Legacy Ponds and Silos (LPS) facilities. These consist of the Pile Fuel Storage Pond (PFSP); Pile Fuel Cladding Silo (PFCS); First Generation Magnox Storage Pond (FGMP); and Magnox Swarf Storage Silo (MSSS) and hold large quantities of nuclear materials. LPS decommissioning includes the removal of nuclear fuel, sludge and solid materials and treatment and storage of these wastes prior to decontamination and dismantling or re-purposing of the individual LPS. The radioactive inventory and lack of modern standards in the ponds and silos makes them one of the major components in the NDA's "hazard and risk-reduction programme", which aims to decommission the waste storage facilities at Sellafield [56]. Clean-up of the LPS will take decades to complete. Such tasks often require specialised equipment to retrieve wastes, treat, and store them in passive conditions. Thus far the focus for LPS has been on developing the required infrastructure and capabilities to enable waste retrieval.

Although the LPS are a primary focus for the NDA, other site operations continue towards final decommissioning. Defueling and fuel transfers were completed in 2019, with Wylfa and Calder Hall being the final two Magnox reactors to be defuel. Sellafield continues to receive fuel from the Gen II AGR stations for safe storage (planned closure mid-2030s). Reprocessing operations at Sellafield will be complete by the end of 2021 (Covid-19 restrictions permitting). Following the completion of fuel reprocessing operations, decommissioning of the rest of the site will become a new focal point. Plans are being put in place to allow this to begin, however, this work has a lower priority than the decommissioning of the LPS. Decommissioning of the site is expected to account for almost 75% of the costs of the NDA's clean-up mission and is not expected to be completed until 2120 at the earliest.

4.3.1 Strategy End State

As part of site end-state planning, the site has been divided into two; the 'Inner Zone' and the 'Outer Zone'. Any new disposal facilities or long-term storage activities are planned to be located within the Inner Zone. This is to ensure no further unnecessary expansion of the site occurs and that the overall foot-print of the site begins to reduce overtime [56, 73]. The site end state to be secured by the NDA for the [56, 73]:

(A) Inner Zone comprises the following:

- The Inner Zone will be subject to institutional controls to manage risks to people and the environment.
- Remediation infrastructure will be used as necessary to ensure groundwater quality is consistent with the requirements of the relevant regulatory regime.
- Structures and infrastructure will be made safe or removed where necessary.

(B) Outer Zone comprises the following:

- 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 does not require a nuclear site licence the licence may be surrendered with any residual radioactive or non-radioactive contamination being subject to appropriate institutional control.
- 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 reuse.

Setting clear and achievable end state goals as part of the NDA strategy for the Sellafield site enables a clear and concise picture to be developed and disseminated to all

Table 4. UK Reactors undergoing decommissioning as of 31st December 2017 – IAEA 2018 [46]

Name	Reactor Type	Model	Gross	Closure	Closure reason	Decom. strategy	Current decom. phase	Decom. Licensee	Expected license termination
Calder Hall-1	GCR	MAGNOX	240	2003	A, C	Dd+PD+SE	5	Sellafield Ltd.	2117
Calder Hall-2	GCR	MAGNOX	240	2003	A, C	Dd+PD+SE	5	Sellafield Ltd.	2117
Calder Hall-3	GCR	MAGNOX	240	2003	A, C	Dd+PD+SE	5	Sellafield Ltd.	2117
Calder Hall-4	GCR	MAGNOX	240	2003	A, C	Dd+PD+SE	5	Sellafield Ltd.	2117
Chapelcross-1	GCR	MAGNOX	240	2004	A, C	Dd+PD+SE	1, 2, 3	Magnox Ltd.	2128
Chapelcross-2	GCR	MAGNOX	240	2004	A, C	Dd+PD+SE	1, 2, 3	Magnox Ltd.	2128
Chapelcross-3	GCR	MAGNOX	240	2004	A, C	Dd+PD+SE	1, 2, 3	Magnox Ltd.	2128
Chapelcross-4	GCR	MAGNOX	240	2004	A, C	Dd+PD+SE	1, 2, 3	Magnox Ltd.	2128
Berkeley-1	GCR	MAGNOX	332	1989	A, C	Dd+SE	5	Magnox Ltd.	2083
Berkeley-2	GCR	MAGNOX	332	1988	A, C	Dd+SE	5	Magnox Ltd.	2083
Bradwell-1	GCR	MAGNOX	292	2002	A, C	Dd+SE	5	Magnox Ltd.	2104
Bradwell-2	GCR	MAGNOX	292	2002	A, C	Dd+SE	5	Magnox Ltd.	2104
Hunterston A-1	GCR	MAGNOX	346	1990	A, C	Dd+PD+SE	5	Magnox Ltd.	2090
Hunterston A-2	GCR	MAGNOX	346	1989	A, C	Dd+PD+SE	5	Magnox Ltd.	2090
Hinkley Point A-1	GCR	MAGNOX	534	2000	A, C	Dd+PD+SE	5	Magnox Ltd.	2104
Hinkley Point A-2	GCR	MAGNOX	534	2000	A, C	Dd+PD+SE	5	Magnox Ltd.	2104
Trawsfynydd-1	GCR	MAGNOX	470	1991	A, C	Dd+PD+SE	5	Magnox Ltd.	2098
Trawsfynydd-2	GCR	MAGNOX	470	1991	A, C	Dd+PD+SE	5	Magnox Ltd.	2098
Dungeness A-1	GCR	MAGNOX	460	2006	A, C	Dd+PD+SE	1, 2, 3, 5	Magnox Ltd.	2111
Dungeness A-2	GCR	MAGNOX	460	2006	A, C	Dd+PD+SE	1, 2, 3, 5	Magnox Ltd.	2111
Sizewell A-1	GCR	MAGNOX	490	2006	A, C	Dd+SE	1, 2, 3, 5	Magnox Ltd.	2110
Sizewell A-2	GCR	MAGNOX	490	2006	A, C	Dd+SE	1, 2, 3, 5	Magnox Ltd.	2110
Oldbury	GCR	MAGNOX	460	2012	-	-	-	Magnox Ltd.	-
Wylfa	GCR	MAGNOX	1060	2015	-	-	-	Magnox Ltd.	-
Winfrith	SGHWR	-	-	1990	Others	ID	6	UKAEA	2019
Dounreay	DFR	-	-	1977	Others	Dd+PD+SE	2	DSR	2333
Dounreay	PFR	-	-	1994	Others	Dd+PD+SE	2	Magnox N	2333
Windscale AGR	AGR	-	-	1981	Others	Dd+PD+SE	4	Sellafield Ltd.	2065
Windscale Pile-1	GCR	-	-	1957	B	Dd+PD+SE	-	Sellafield Ltd.	-
Windscale Pile-2	GCR	-	-	1957	B	Dd+PD+SE	-	Sellafield Ltd.	-

Closure reason:
A) The process was no longer profitable; B) After an operating incident; C) After major component failure or deterioration

Decom. Strategy:
ID) Immediate dismantling and removal of all radioactive materials; Dd+SE) Deferred dismantling, placing all radiological areas into safe enclosure; Dd+PD+SE) Deferred dismantling, including partial dismantling and placing remaining radiological areas into safe enclosure.

Current decom. Phase:
1) Waste conditioning on site – only for decommissioning waste; 2) safe enclosure preparation; 3) partial dismantling; 4) active safe enclosure period; 5) passive safe enclosure period; 6) Final survey

those involved with the sites decommissioning program. It also allows for a clear 'checklist' of events to be marked against as projects conclude on the way to reaching the end state. Such an approach of establishing a facility's end state is imperative for successful completion of nuclear facility decommissioning. Although set, there is room to further tighten end state requirements (i.e. targeted transition from a brown-field to green-field end-state) considering new information or advances in technology.

4.4 NDA's Decommissioning Approach: Magnox Fleet

Due to the complexities of dealing with radioactive graphite, the baseline decommissioning strategy for all Magnox NPPs is deferred reactor dismantling and site decommissioning for around 85 years following shutdown. This is to allow for sufficient radioactive decay to occur, enabling safer decommissioning (Table 4) [46]. Such an approach will require a period of Care and Maintenance (C&M). Advantages of this strategy include:

- Beneficial radioactive decay
- Avoidance of requiring interim storage of reactor waste prior to a GDF opening
- Reduction in decommissioning costs with increased deferral time

Preparing each site to enter a passive state involves defueling (including transferring all used Magnox fuel to Sellafield for reprocessing; complete as of 2019/20) followed by decommissioning and dismantling auxiliary buildings, and retrieving, treating and processing any wastes remaining at a site. Each site will then be left in a passive state, allowing radiation levels in the reactor core to decay naturally over time, approx. 80–90 years. Sites will be continuously monitored along with periodic maintenance as required. Final site clearance is the last stage in a site's lifecycle. In the case of the Magnox NPPs this will involve dismantling the reactor vessels and shipping any outstanding wastes to their final destination (i.e. GDF). Completion of this work will allow the sites to be released from regulatory constraints for a new uses. Decommissioning this legacy will involve numerous steps, and a substantial workforce.

By the start of 2018 decommissioning is on-going across the entire Magnox fleet with many of the older reactors being close to a state of passive safe enclosure during their care and maintenance period with the others entering the final stage of safe enclosure preparations. Due to the nature of the Magnox reactor design and decommissioning strategy employed (Deferred dismantling), most of the Magnox reactors will not have their nuclear licenses terminated before the year 2100 (Table 4).

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

- Reactor Defuelling (completed as of 2019/20)
- Ponds
- Plant and Structures
- Waste Projects
- Waste Operations
- Reactors
- Asset Management
- Care and Maintenance
- Site Restoration

These nine programs have been established to create a one-stop decommissioning service for the sites. Approaching the work in this manner allows Magnox Ltd to use innovative techniques and methods as well as providing a sequenced approach to work using a 'Lead and Learn' approach. 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.

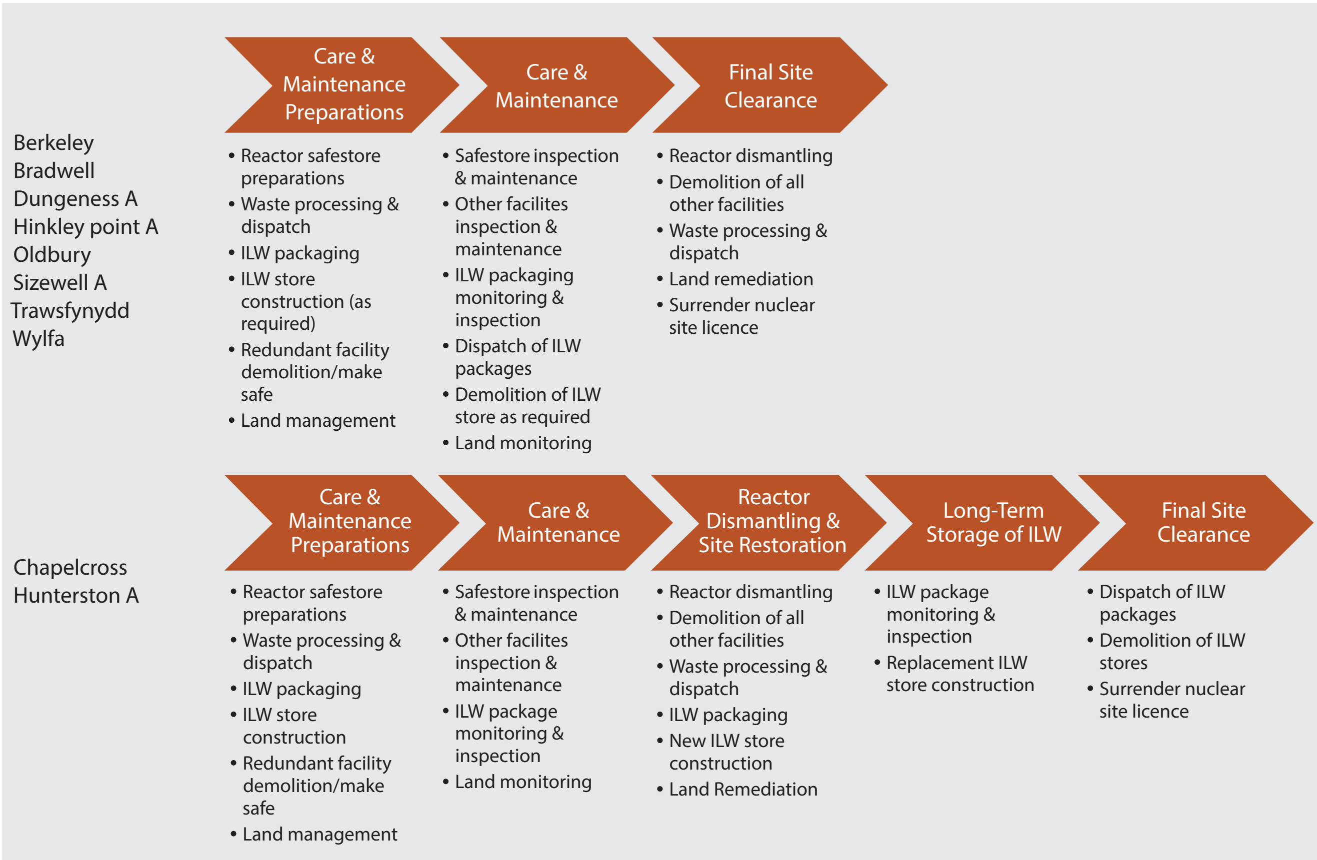

Fig. 7. Decommissioning strategy phases and associated work programmes.

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. To ensure a state of C&M can be achieved hazards will be removed to make sure any remaining risks are tolerable and As Low As Reasonably Practicable (ALARP). The near-term objective is to deliver the Magnox sites into a safe and secure interim state. 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

4.4.1 Decommissioning Phases

A staged approach to the decommissioning and restoration of the sites is being undertaken. Three major decommissioning phases are scheduled (Fig. 7):

- Care and Maintenance Preparations

- Care and Maintenance Period
- Final Site Clearance

For the Scottish sites (Chapelcross and Hunterston A) two additional phases will be incorporated after care and maintenance but before final site clearance:

- Reactor Dismantling and Site Restoration
- Long-Term Storage of ILW

For each of the 10 Magnox sites the preliminary stage of care and maintenance preparations will involve reactor safestore preparations; waste processing and dispatch; ILW packaging and storage; as well as demolition of redundant facilities; and land management programs on areas of the site clear of facilities. The end of this phase will mark the beginning of the sites interim state. The C&M period predominately focuses on inspection and maintenance of the site to ensure necessary utilities such as water and electricity remain functional. Any ILW also stored at the site will be regularly inspected and shipped to long-term disposal sites as and when they become available.

Due to a difference in governmental policy in Scotland, the two nuclear sites at Chapelcross and Hunterston A will store HAW in on-site, near-surface storage facilities for up to 300 years. After which the waste will be finally disposed in a near-surface disposal facility in Scotland, which is yet to be built. To enable this the construction of new waste stores on-site for long-term waste storage will occur alongside reactor dismantling after the care and maintenance period.

The final phase will focus on site clearance. In most cases this will involve reactor and remaining building dismantling, land restoration and dispatch of the final wastes to an appropriate waste disposal facility. For the Scottish sites, site clearance will be the same just minus reactor dismantling which will have been completed prior. Final clearance of all the sites will be marked by the surrender of any and all nuclear licences.

4.5 NDA 'Nuclear Provision'

In the UK there was a sustained lack of funding assurances throughout much of its nuclear history. This lack of assurances and concerns regarding decommissioning costs led the UK government to legislate provisions as part of the 2008 Energy Act [76]. The new legislative measures require the operator of any new NPP to ensure that secure financing arrangements are in place for all decommissioning and waste management costs. It also requires the operator to submit a funded decommissioning program for approval by the secretary of state before construction of the new power station commences. Despite the introduction of the Energy Act 2008, a substantial financial burden remains from the nuclear legacy. These costs are to be covered by the UK government with taxpayer money over the duration of the decommissioning program through the NDA, up to a pre-determined limit (NDA budget, currently £3 billion annual) [56].

As decommissioning in the UK is expected to take over a century to complete, a forecast of the total expenditure is difficult to accurately predict and is affected by technological advances, developments in government policy, economic circumstances and environmental issues etc.. Therefore, an estimate is made and regularly updated annually factoring in changes to the decommissioning landscape. This is known as the 'Nuclear Provision' [59].

The Nuclear Provision is the best estimate of how much it will cost to clean up the nuclear legacy over the next 100+ years. Different assumptions produce figures for the nuclear provision of somewhere between £115 billion and £246 billion [59]. In the interests of simplicity the NDA provides a single figure. This results in a undiscounted nuclear provision of £131.6 billion [59, 73, 74]. The estimate is based on the expected costs of:

- Decommissioning
- Dismantling and demolishing the buildings
- Managing and disposing of all waste

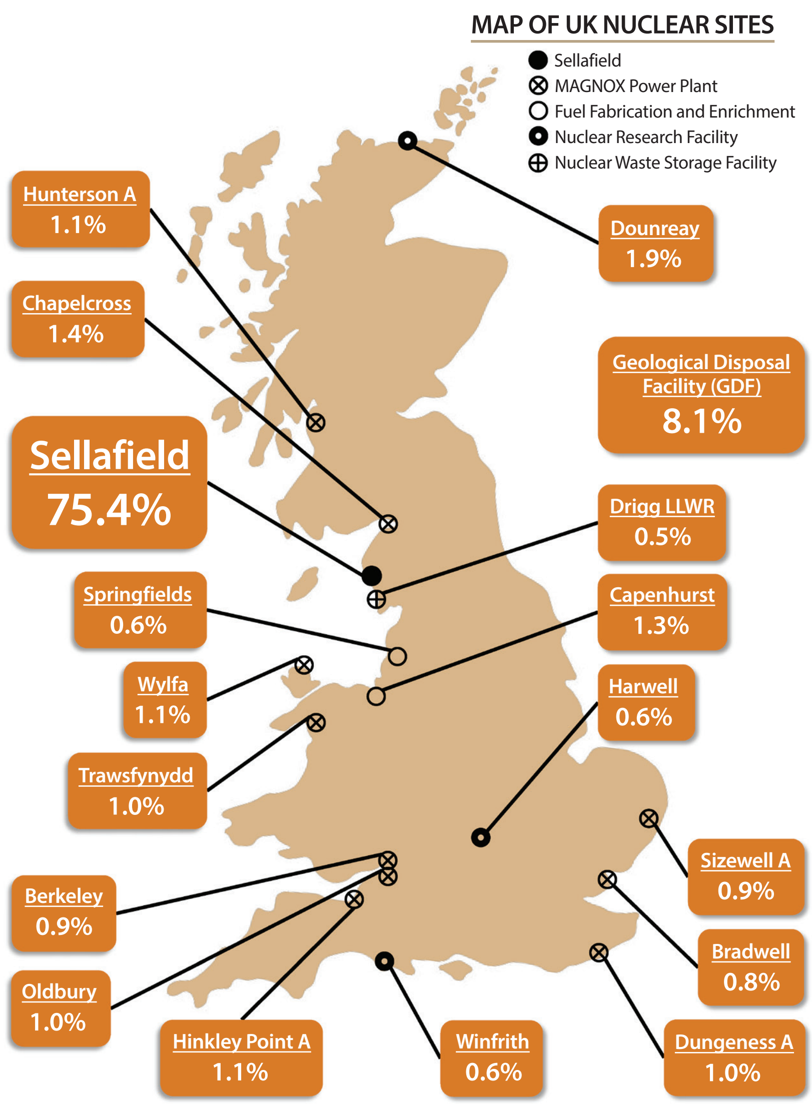

Fig. 8. Allocation of the 'Nuclear Provision'.

• Remediation of land

At those sites where decommissioning is relatively straightforward, costs can be calculated with relative confidence. This has occurred across the 11 Magnox NPPs as well as the research sites Dounreay, Harwell and Winfrith. At these sites, cost estimates have been reduced, in some instances by multi-millions of pounds, and work accelerated. Collectively they account for approx. 16–17% of the entire undiscounted nuclear provision forecast.

However, Sellafield poses levels of complexity and uncertainty that are unique in the global nuclear sector. As such Sellafield is predicted to account for approximately 75% of the nuclear provision based on current estimates (Fig. 8) [73]. As understandings of the challenges faced at Sellafield develop, it is expected that the estimate will begin to drop, similar to other NDA sites. However, significant uncertainties remain, and unforeseen increases cannot be ruled out.

Électricité de France Energy (EDF Energy, private-sector operator) will pay for decommissioning the second generation of NPPs (AGR fleet), and are not a part of any NDA budgets or nuclear provision forecasts. Future decommissioning programmes are to be funded via the 'Nuclear Liabilities Fund' [73]. The next generation of NPPs will be built by the private sector, with decommissioning plans and cost forecasts in place at the outset.

4.6 Waste Management Lifecycle

Control, safe handling, treatment and suitable disposal methods for wastes arising from decommissioning activities are of the upmost importance to ensure both public and environmental safety is maintained at all times [33]. Due to the complexity and variety of decommissioning tasks, the types of wastes arising are numerous often requiring novel treatment methods [1, 2, 11, 13-15, 33, 34].

In order to streamline the waste management process within the UK, the NDA has moved towards a single radioactive waste strategy for the entire estate [73]. The radioactive waste strategy, known as the Waste Management Lifecycle (WML), places "greater emphasis on the nature of wastes (radiological, chemical and physical properties) rather than the classification (e.g. ILW and LLW)" [73]. The WML does not replace the use of categories but instead aims to "help identify the most appropriate waste management route while recognising the challenges posed by waste classification boundaries" [73]. The waste management lifecycle strategy involves the following key steps:

- Planning and preparation
- Treatment and packaging
- Storage and disposal

This lifecycle approach to waste management is not new and is supported by all of the NDA's existing UK waste strategies and the IWM principles including the Waste Hierarchy (Fig. 9, Fig. 10). The main difference will be in developing a single radioactive waste management framework for all sites that will provide greater clarity of strategic needs, promote cross-category opportunities and support a risk-based approach to waste management.

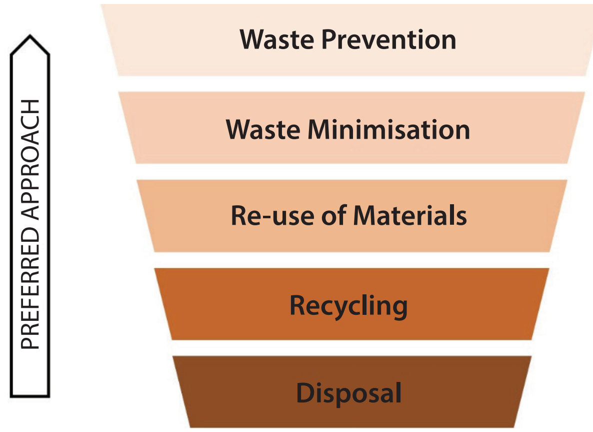

Fig. 9. Waste hierarchy implemented by the NDA.

4.6.1 Planning and Preparation

Characterisation plays an important role in the decommissioning of nuclear facilities [7]. It forms the basis for, planning; identification of the extent and nature of contamination; assessment of potential risk impacts; cost estimations; implementation of decommissioning methods; and waste management, radiation protection, protection of the environment. Comprehensive characterisation also supports decisions regarding the final release of nuclear buildings and sites.

4.6.2 Treatment and Packaging

Treatment and packaging involve transforming raw wastes into forms that are suitable for long-term storage and/or final disposal. To achieve this, several steps and technologies are utilised including [73]:

- Retrieval of waste – the safe removal of waste from temporary storage facilities or legacy storage facilities for further management

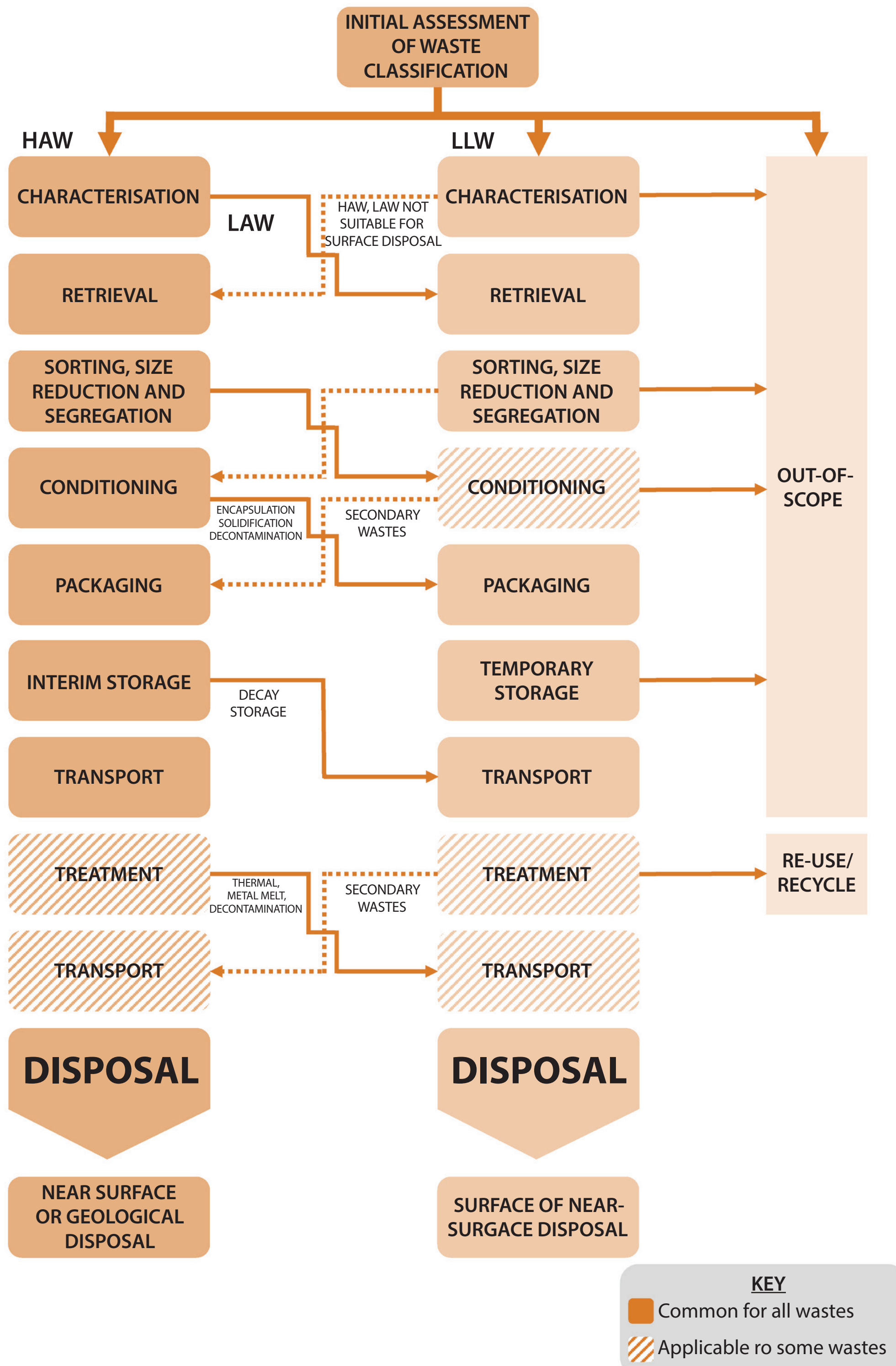

Fig. 10. NDAs Waste Management Lifecycle [73].

- Sorting and segregation – an activity where types of waste or material are separated or are kept separate on the basis of radiological, chemical and/or physical properties to facilitate waste handling and/or processing
- Size reduction – a treatment method that decreases the physical size of a waste item
- Decontamination – chemical or physical
- Thermal/chemical/physical treatment – operations intended to benefit safety, security and/or economy by changing the characteristics of the waste
- Conditioning/immobilisation – operations that produce a waste package suitable for handling, transport, storage and/or disposal

4.6.3 Storage and Disposal

Currently, the approach taken by the NDA for waste treatment is to immobilise wastes within cement. These cement wasteforms will then be stored within purpose-built facilities. Across the entire NDA estate new storage facilities are being built to house these wastes until final disposal routes become available (i.e. GDF).

Disposal of treated wastes is the final stage and involves placing wastes in an appropriate facility without the intention of future retrieval. The NDA owns the UK LLWR which is managed by LLWR Limited on their behalf (see section; 4.7 Geological Disposal Facility). Some of the SLCs also carry out on or near-site disposal of LLW and/or VLLW (Very Low Level Waste). Dounreay Site Restoration Limited (DSRL) operates a VLLW and LLW disposal facility sited next to Dounreay, while Sellafield Limited operate an on-site VLLW disposal facility. The NDA continues to provide effective support for UK Government's "Implementing Geological Disposal Programme" (See below).

4.7 Geological Disposal Facility

It is largely accepted internationally that some form of underground or GDF is the best course of action for the long-term disposal of high-level nuclear waste [77, 78]. A number of countries around the world have already begun to develop their own GDFs for the disposal of a range of wastes including HLW, ILW and LLW [79, 80].

The UK currently has no GDF for the disposal of HAW. Currently radioactive waste disposal within the UK occurs primarily at Drigg LLWR. In addition, two landfill sites at Kingscliffe (Northamptonshire) and Lillyhall (Cumbria) are permitted for the disposal of high volume, LLW such as rubble debris and ex-building materials.

As pressure mounts to find a suitable long-term disposal option for the UK's HAWs and with the end of fuel reprocessing in 2020/21, the need for geological disposal of higher activity radioactive waste became government policy in 2008. The NDA is responsible for implementing geological disposal through its subsidiary Radioactive Waste Management Ltd (RWM). RWM is responsible for implementing geological disposal of HAWs (England and Wales only). The UK currently pursues a public voluntary siting scheme. The latest public consultation took place in January 2018 [81]. The UK has opted for a community volunteer approach to siting a GDF with Cumbria being seen as an ideal location for a number of reasons:

- Close proximity to the Sellafield Site
- Wealth of local nuclear related expertise
- Adequate local infrastructure and industry able to support a GDF
- Generally positive local public acceptance and support

4.8 UK Approach to Nuclear Site Licence Termination

The final aspect of decommissioning is licence termination. In the UK, licence termination is referred to as 'delicensing'. Major nuclear facilities are licensed under the Nuclear Installations Act 1965 [34]. In 2005, and to coincide the establishment of the NDA and a move towards

Table 4. Status of NPP decommissioning in Korea

Reactor unit	Reactor Type	Shutdown date	Shutdown reason	Decom. strategy	Decom. phase	Management phase
Kori-1	PWR	18-June-2017	Termination of continued operation	Dismantling	Planning	Wet storage on-site
Wolsong-1	PHWR	24-Dec-2019	Economic	Dismantling	Planning	Wet & dry storage on-site

Table 5. Prompt decommissioning schedule for Kori-1 [86]

Year	Activities
2022[a]	Development and approval of the decommissioning plan
2025	Cooling and moving spent fuels • Cooling spent fuels underwater • Temporary storage of spent fuels in on-site dry casks • Moving spent fuels to high radioactive waste disposal facilities
2030	Dismantling contaminated facility and radioactive waste treatment • Dismantling turbine and generators • Cutting and volume reduction of the dismantled system and waste • Installation of waste treatment facilities
2032	Site restoration

[a] KHNP submitted its FDP (final decommissioning plan) in May, 2021. If the review of FDP proceeds as planned, approval will be granted after 2023.

large-scale decommissioning in the UK, the Health and Safety Executive (HSE), who are the principle regulator, issued formal criteria for delicensing within the UK. The main features are [82, 83]:

- Delicensing is taken to mean 'ending of the period of responsibility under the Nuclear Installations Act' and happens when the HSE gives notice in writing to the operator that in its opinion there has 'ceased to be any danger from ionising radiations' from anything on the site. There must be no licensable activities remaining on the site.
- Any residual radioactivity, above natural background, which can be satisfactorily demonstrated to pose a risk of less than one in a million per year (of the order of 10 μSv a^{-1} or less) for any foreseeable future land use is taken to be broadly acceptable.
- Additionally the operator should demonstrate that the risk has been reduced to levels ALARP and should take into account the views of other relevant regulators.
- All risks are taken to be additional to natural background for the area, including an allowance for impacts from authorised discharges and artificial background from worldwide sources.
- The IAEA safety guide on the application of the concept of exclusion, exemption and clearance contains radionuclide specific values that may be used to demonstrate achievement of the risk criteria. HSE accept that demonstrating that the land meets these criteria also demonstrates meeting the residual risk criteria of less than one in a million per year. Where these generic values are not used a site-specific risk assessment may be submitted by the operator.

Delicensing in the UK follows arrangements suggested by the IAEA while opting to implement the lower of the range of optimisation for unrestricted use and has no arrangements for licence termination under restricted uses. These criteria have been applied to delicense significant parts of nuclear sites across the UK. An example would the recent delicensing in the UK of parts of the former UKAEA Harwell site by Research Sites Restoration Ltd (RSRL) [84].

Submissions to the ONR have to demonstrate that that residual, isotope specific, activity levels are below levels set in IAEA guidance or meet the criteria through carrying out a case specific risk assessment. This means performing intensive surface and subsurface analysis. Levels around background are taken as meeting the criteria. Where levels exceed the background, further characterisation is carried out, and ALARP arguments assembled as necessary. The risk criteria given in the HSE delicensing policy can be met by either:

- Demonstrating that residual, isotope specific, activity levels are below levels set in IAEA Safety Standard Series No.RS-G-1.7
- Carrying out a site specific risk assessment to demonstrate the risk level is met

For delicensing to be considered appropriate 'Delicensing Case Documents' have to be submitted. In the case of the UK such documents should contain details about, or references to the following:

- History of land, buildings and facilities
- Identification of new site boundary
- Control of access to the remaining licensed site
- Delicensing criteria and clearance levels
- Demonstrating the clearance levels have been achieved
- Effect on safety cases for facilities on remaining licensed site
- Location and integrity of active drains
- Off-site environmental monitoring arrangements
- Transport of radioactive material across the delicensed site
- Emergency arrangements for the delicensed site

5. Strategic Nuclear Decommissioning Blueprint for Korea

Currently, nuclear power generation in Korea accounts for approximately 25% of the nation's energy needs across a total of 24 reactors. Korea has historically been, and to some extent remains, a prominent nuclear energy-generating nation. However, with changing government policies and an aging nuclear fleet, nuclear decommissioning will soon become the major focus of the nuclear industry in Korea.

The Energy Transition Policy was initiated in 2017 with a special focus on nuclear safety, decommissioning and decontamination, and the management of radioactive wastes [85, 86]. The Kori-1 NPP, the first such plant in Korea, was permanently shut down in 2017 with prompt decommissioning to be completed over the next 15–20 years (Table 4, Table 5). Other units in Korea will face the same fate in series when they reach the end of their operating lifetime; beginning with the recent closure of Wolsong-1 in late 2019. A further five reactors are scheduled for closure between 2023–2026, bringing the total to seven. Such a rate of closures within a relatively short space of time will significantly increase the demand for decommissioning activities in Korea over the coming years. It is therefore imperative that appropriate steps are taken now to ensure a successful decommissioning campaign of the nation's own nuclear legacy.

In Korea, under the Nuclear Safety Act (NSA), Korea Hydro & Nuclear Power Co., Ltd. (KHNP, the sole NPP operator in Korea) is responsible for decommissioning NPPs. Currently there is no independent body for the oversight of nuclear decommissioning within Korea that can be considered similar to the UK's NDA. Decommissioning in Korea is seen as relatively straightforward compared to that of the UK. Therefore, it may be seen as unnecessary or even cumbersome to establish a body whose sole responsibility is to act as a central oversight for all decommissioning activities. However, decommissioning is, in some cases, a 100+ year problem. Even in Korea, while decommissioning is beginning at Kori-1, construction continues at Shin-Hanul and Shin-Kori sites with design lifetimes of 60 years for the APR-1400 reactors. It is therefore reasonable to expect decommissioning within Korea to last 50+ years in one form or another; even without the building of new NPPs beyond those currently planned. Setting up a 'Korean – NDA' as a central oversight independent of government, regulators and stakeholders would enable decommissioning challenges to be understood, addressed, and solved by establishing the overall approach to decommissioning, setting of decommissioning targets and monitor progress. Expertise developed during decommissioning can be collated centrally and disseminated to the relevant sites in order to optimise future decommissioning tasks, or pass on technical understandings developed at one site to be adapted by another. It would also enable records, management, and the exchange of information to be kept throughout the lifespan of Korea's decommissioning industry, however long that may be. In addition, adapting the UK's approach of establishing SLCs for implementing decommissioning activities at individual sites would ensure focus can be maintained throughout the decommissioning lifecycle of a specific site by off-loading site-specific responsibilities from the central body; while individual SLCs would remain accountable by the overarching 'Korean – NDA'. Due to the relative simplicity of decommissioning in Korea, establishing individual SLCs for the PWRs collectively, Wolsong PHWR, research reactors, and non-reactor nuclear sites (e.g. KAERI), respectively, may be a more practical approach in Korea.

As nuclear decommissioning is multifaceted, it is therefore unsurprising that the response to the challenge of decommissioning is also multidimensional. The implementation of 'themes' as part of a national decommissioning strategy, similar to those used by the NDA (Site Decommissioning and Remediation; Spent Fuels; Nuclear Materials; Integrated Waste Management; and Critical Enablers), would enable the nuclear industry in Korea to identify the key aspects of their own legacy and work towards safe decommissioning in a timely manner. Another key aspect of any decommissioning strategy is the understanding of risks. As shown, the UK's nuclear legacy is one of the most complex in the world. The nuclear legacy facing Korea is relatively less complex than that of the UK's and will remain so in the near future with only Kori-1 and Wolsong-1 currently shutdown for decommissioning. Nonetheless, with the proposed aggressive nuclear power phase out policy in Korea there is potential for a rapid increase in the number of decommissioning challenges being faced by a decommissioning industry in Korea that is still relatively in its infancy. Setting out clear guidelines regarding 'Tolerable Risks vs Intolerable Risks', similar to those used by the NDA, can facilitate the industry to appropriately direct resources and manpower ensuring overall risks of decommissioning are kept to a minimum. As the NDA has proven through tolerable vs intolerable risk identification, not all decommissioning challenges can, nor need to, be completed simultaneously if in doing so heightens the risks to the workforce, public or environment unacceptably or needlessly.

Establishing both short- and long-term end states for individual sites is vitally important to ensure safe decommissioning in a timely manner and at an economical cost acceptable to taxpayers. Factors such as previous site use, waste volumes, levels and types of contamination, technology readiness, final disposal site availability, and planned site reuse should be considered. As part of end-state planning any C&M activities that are deemed necessary can also be taken into consideration. For successful end-state planning appropriate license termination requirements should also be fixed, in effect providing a 'checklist' of termination criteria which can be checked off as a site progresses towards its final designated end-state. Knowing in advance these license termination criteria can also help significantly reduce the economic impact of decommissioning projects and help ensure public trust in the nuclear decommissioning industry remains.

Like many nations, Korea is not immune to changing governments, policies, and public opinion. This can mean decisions surrounding power generation can take a long time to settle, with delays and set-backs common. This can cause significant delays for the implementation of nuclear new build due to the long-time frames and complex construction associated with building a new NPP; approval of Hinkley Point C a case in point. However, in the case of decommissioning, once a decision has been made to decommission a reactor it is extremely difficult, and uneconomical, to bring it back into service. Further, as shown with the case of the UK, any nuclear legacy, no matter how small, cannot be simply left to decay. Therefore, policy decisions about nuclear new build and decommissioning should be made separately. In other words, decisions concerning decommissioning responsibilities (i.e. decommissioning strategy, site end-states etc.) should be made irrespective of any decisions to pursue or abandon nuclear power generation to minimise any unnecessary delays to decommissioning responsibilities. Public education and raising public acceptance are also key to ensure the public can view the questions surrounding nuclear new build and decommissioning in their own rights, respectively, and express their opinions on each independently from one another.

Summary of key aspects of the UK's strategy for the nuclear legacy to be considered as a blueprint for the Korean case:

- Implement independent decommissioning body (e.g. Korean-NDA).
- Adapt a 'Lead and Learn' approach.
- Identify key 'Themes' along the path to complete decommissioning.
- Develop guidelines for Tolerable Risks vs Intolerable Risks.
- Pinpoint site end-states and develop site-reuse business case during planning phases to direct decommissioning goals.
- Establish any necessary C&M activities.
- Secure funding for nuclear decommissioning in advance (e.g. Nuclear Provision).
- Establish license termination procedures to ensure a smooth transition from operation through decommissioning to site closure.

6. Conclusions

With final closure of the Magnox fleet and aging nuclear facilities such as Sellafield the UK is left with a substantial decommissioning challenge. This challenge is being tackled by the NDA who, through the development of an overarching strategy and business plan, are well on their way to decommissioning the nuclear legacy. The NDA have successfully obtained knowledge of site hazards, prioritised the most hazardous areas by means of tolerable vs intolerable risks identification, and established SLCs for implementation of the decommissioning strategy. This has allowed the NDA to implement a prompt decommissioning strategy for the most hazardous areas of the Sellafield site and those risks deemed intolerable; develop a deferred decommissioning approach for Magnox fleet that will benefit from radioactive decay, including C&M work programs; introduced a 'Lead & Learn' approach between sites and relevant SLCs; establish a better waste management lifecycle; and identify site end-states. All of which is underpinned by the NDA's 100-year strategy and allocated nuclear provision. 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.

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