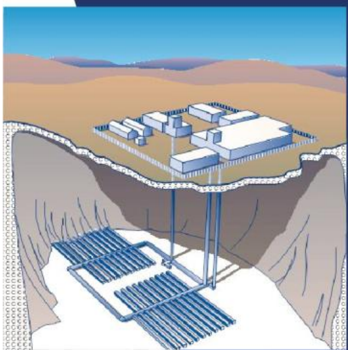

Joint Study on the Potential Impacts of Small Modular Reactors on Multinational Cooperation at the Back End of the Fuel Cycle

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Preface

This joint study project is an evaluation of how the challenges of managing radioactive wastes from Small Modular Reactors (SMRs) may affect the drivers for multinational radioactive waste management (RWM) solutions. The project is evaluating technical, strategic, economic and planning issues associated with SMR fuels and wastes. It includes an assessment of how a shared or a commercial multinational repository project could be impacted in terms of concept, design, economics and scheduling if a number of users were to require disposal of SMR fuels and wastes.

Any specific SMR vendors and SMR designs in this document have not been named as a result of any involvement in the project. They have been named based on references in the open literature. Furthermore, the down-selection of specific SMR designs has been conducted in a purely data availability-led process which is fully outlined in the document. This study does not advocate or endorse any specific SMR design but uses specific data available in the open literature to enable a more realistic understanding of the size and scale of SMR deployment and radioactive waste generation so as to better understand the potential impact on the back end of the fuel cycle.

Any specific countries in this document have not been named as a result of any involvement in the project. They are either named in regard to a scoping review of the open literature to understand global interest in SMR deployment, or are named as examples to illustrate the size and scope of typical nuclear power capacities, radioactive waste inventories, nuclear skills and expertise, radioactive waste facilities, etc.

This report is supported by detailed underpinning contained within the accompanying *Joint Study on the Potential Impacts of Small Modular Reactors on Multinational Cooperation at the Back End of the Fuel Cycle: Appendices 1, 2, 3, 4, 5 & 6* document. This report references each of the six appendices contained therein, by number, when relevant.

It should be noted that the specific technologies and national plans included or referenced in this report (and related appendices) reflect the SMR landscape at the time of initial drafting; April 2024.

Executive Summary

There is a growing interest in commercialising Small Modular Reactors (SMRs), which offer a promising pathway towards continued use and/or expansion of nuclear power. Although many challenges must be overcome if the adoption of SMRs is to be widespread, significant interest from global governments, energy providers and other potential users in their development and deployment has led to a global race for leadership in the future SMR market.

Although significant effort has been made to develop Small Modular Reactor (SMR) technologies, relatively little has been done to understand the impact of SMR deployment on global radioactive waste management (RWM). The management and disposal of radioactive waste is an increasingly important consideration for the expansion of nuclear power and, for all countries considering SMRs, safe and affordable SNF management solutions must be a key goal.

One of the key challenges for SMR deployment is ensuring safe and secure RWM. The most challenging task is the implementation of geological disposal for spent nuclear fuel (SNF) in a deep geological repository (DGR).

Hence, the purpose of our study is to consider the potential technical, strategic, political and commercial impacts of SMR commercialisation on the back end of the nuclear fuel cycle, focusing on the multinational aspects. This includes the potential impact of SMR adoption on multinational approaches to deep geological disposal, particularly multinational repository (MNR) projects. This purpose is addressed through the exploration of four major questions:

1. Which SMR designs and reactor types are attracting most interest?
2. How will the management of radioactive wastes differ for the deployment of SMRs in comparison to more conventional, large reactors?
3. What impact could SMR deployment have on a national RWM and/or DGR programme?
4. What impact could SMR deployment have on multinational RWM collaboration?

To address question 1, we use the open literature to select credible SMR designs. We down-select five SMR designs to represent five different reactor types: a Pressurised Water Reactor (NuScale's VOYGR Power Module); a High-temperature Gas Reactor (X-Energy's Xe-100); a Sodium Fast Reactor (TerraPower's Natrium SMR); a Molten Salt Reactor (Terrestrial Energy's IMSR400) and a Heat Pipe-cooled Reactor (Westinghouse's eVinci).

To address question 2, we use plans and assumptions published in the open literature to identify deviations from the way in which radioactive waste is currently managed for conventional reactors. We then use the open literature to identify metrics concerning the waste generation of the five down-selected SMR designs. The key properties of SNF that determine disposal boundary conditions are volume, heat production, fissile material density and physical / chemical characteristics.

To address question 3, we first use these metrics to explore the potential impacts of SMR deployment on national RWM programmes. This is done by defining five realistic, but hypothetical, countries, where variables include existing nuclear power generation capacity, nuclear skills and expertise and required new nuclear generation capacity. We find that:

- Countries with large to medium sized nuclear power programmes are likely to have mature DGR programmes that can readily absorb SNF from many SMRs. However, it is still likely to be cost efficient from a disposal perspective for SMR technologies to align closely with existing national nuclear technologies. SMRs are unlikely to be a driver towards opting for an MNR (rather than a national DGR) for these countries. However, it is potentially feasible, noting potential societal, political and regulatory barriers, that such a national DGR could be extended to accept wastes from other countries, effectively making it an MNR.
- For countries with small, or no, nuclear power programmes, the implementation of SMRs of the same, or similar, designs being deployed in other similar countries could be an incentive for enhancing cooperation on pre-disposal and disposal activities.

- Noting potential challenges, e.g., security, safeguards, public acceptance, a country hosting an SMR vendor that has a medium to large nuclear power programme may see benefit in offering SNF take-back to one or more countries that do not currently use nuclear power. Non-nuclear nations interested in only a small nuclear power capacity would be strongly motivated to seek MNR solutions and are the most likely to be responsive to market-led solutions, such as take-back offers. It is also these nations that would likely benefit most from implementing geological disposal by using a deep borehole concept (noting that significant research and development is still required to demonstrate safety and feasibility of deep borehole disposal), as this might be achieved more flexibly than through scheduling / strategy alignment with a MNR facility.
- Countries that do not have nuclear power, but have ambitious plans, may be the most likely to becoming new technology leaders for SMR implementation and the disposal of SMR SNF. An ambitious approach may make less conventional technologies more viable, given an appropriate, and significant, level of investment. Given their need for a DGR programme, such countries would also be better placed to investigate the option of hosting a commercial MNR, potentially offsetting the significant investment into nuclear power they require.

To address question 4, we define potential MNR models within two distinct frameworks: a) MNR development through partnership; and b) MNR development as a commercial endeavour with a lead country or organisation. We then explore the MNR scenarios using the previously established hypothetical countries, along with waste generation data RWM requirements for the down-selected SMR designs. We find that:

- The likelihood that more nations with small inventories of waste requiring geological disposal will arise through the widespread deployment of SMRs makes MNR interest more likely as an opportunity to avoid, or share, the economic burden.
- The technical implications of accepting SMR SNF into an existing disposal programme are mostly the same for either a national DGR or an MNR.
- Countries involved in MNR development through partnership are likely to be motivated to align their selection of SMR technology and attempt to optimise their SMR deployment scheduling. Should multiple MNR users be interested in a particular SMR technology, it might ease the decision to deploy SMRs if a common solution is being investigated.
- An MNR is more likely to require the disposal of multiple different types of SNF, which will be more complex and costly than an MNR (or DGR) in which only one type of SNF is disposed of. Any commercial MNR will therefore likely need to design a system that can handle a wide range of SMR wastes. Additional up-front costs can be expected when compared to adopting an existing DGR design, safety case and operational procedures.
- Depending on the approach to MNR development (either a partnered or commercial approach), the varied nature of waste arisings could necessitate a significant interim storage facility accompanying the MNR or could otherwise place significant constraints on the upstream activities and facilities.
- Scheduling of waste arrivals at an MNR will require careful management and planning and would be more easily controlled if the MNR participants extended their collaboration upstream.
- An MNR will utilise an expanded transport network when compared with a national DGR, extending across countries, potentially throughout a region, or even globally. The complexity of transportation may be increased, e.g., through increased rate and volume, should upstream collaboration be included.
- The widespread nature of potential SMR deployment and the necessary transport infrastructure for an MNR heighten the security and safeguards concerns outlined for a national DGR. Each aspect would become more pronounced, with the added complexity of cross-national regulatory and legal compliance: potentially, significantly so, if the MNR involved shared upstream activities.
- SMR deployment is likely to make MNR development efforts more likely and could help with public engagement and acceptance. Technical, security and safeguards concerns are not unique

to MNRs and will need to be dealt with to enable widespread SMR deployment. Upstream activity alignment and scheduling of waste transports, along with varied regulatory regimes and the legal status of exporting radioactive waste for disposal are likely to be the most challenging.

Acronyms & Abbreviations

Table 1: Key acronyms and abbreviations used in this document.

Acronym	Expansion
ARIS	IAEA Advanced Reactors Information System
BWR	Boiling Water Reactor
CCCS	Core Component Conditioning Station
DBF	Deep Borehole Facility
DGR	Deep Geological Repository
EBS	Engineered Barrier System
EC	European Commission
ERDO	Association for Multi-national Radioactive Waste Solutions
FCM	Fully Ceramic Microencapsulated
GE	General Electric
GIF	Generation IV International Forum
HALEU	High Assay Low Enriched Uranium (5% to 20% U235 enrichment)
HIP	Hot Isostatic Pressing
HLW	High Level Waste
HPR	Heat Pipe-cooled Reactor
HTGR	High Temperature Gas-cooled Reactor
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
LCA	Lifecycle Assessment
LEU	Low Enriched Uranium (up to 5% U235 enrichment)
LWR	Light Water Reactor
MFR	Metal-cooled Fast Reactor

Acronym	Expansion
MNR	Multinational Repository
MOX	Mixed Oxide Fuel
MPC	Multi-Purpose Container
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
NEA	Nuclear Energy Agency
NSDF	Near-Surface Disposal Facility
NWMO	Canada’s Nuclear Waste Management Organization
ORNL	Oak Ridge National Laboratory
PWR	Pressurised Water Reactor
RD&D	Research, Development and Demonstration
RWM	Radioactive Waste Management
SFC	Spent Fuel Canister
SFISF	Spent Fuel Interim Storage Facility
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
TRISO	TRi-structural ISOtropic
UCO	Uranium oxycarbide (chemical formula)
UN	Uranium nitride (chemical formula)
USDOE	US Department of Energy
WMO	Waste Management Organisation

Contents

1 Introduction

There is a growing interest in the commercialisation and global deployment of Small Modular Reactors (SMRs). Defined by the United Nations International Atomic Energy Agency (IAEA) as "advanced reactors that produce electricity of up to 300 MW(e) per module" [1], SMRs represent a promising pathway towards continued use and/or expansion of nuclear power.

The term 'advanced' is applied to nuclear reactor technologies which are either:

- Evolutionary: improving on existing designs through "small or moderate modifications with a strong emphasis on maintaining proven design features to minimise technological risk" [2]. These are typically referred to as Generation III and III+.
- Innovative: incorporating "radical changes in the use of materials and/or fuels, operating environments and conditions, and system configuration" [2]. These are typically referred to as Generation IV, through alignment with the goals around Sustainability, Economics, Safety and Proliferation Resistance as defined by the Generation IV International Forum (GIF) [3].

The modular design of SMRs, together with the simpler construction and assembly of reactor components and auxiliary systems, allows a more gradual introduction or increase of nuclear power capacity, which could greatly ease financing problems. Through their size and versatility, SMRs may also be more easily sited at regional and/or remote locations, closer to where the products of their operations (e.g., electricity, high-temperature heat, hydrogen, desalination) are required, which is an attractive feature for many potential user countries.

As an emerging technology group, there remain many challenges which must be overcome if the potential benefits of SMRs are to be realised and the adoption of SMRs is to be widespread. However, significant strategic commitment and financial investment in their development and deployment from global governments, energy providers and other potential users has led to a "global race for leadership in the future SMR market" [4].

In this race for leadership, a wide range of prototype SMR designs is being pursued by both national development agencies and commercial vendors, reflected in the number of SMR designs available in the open literature. There is interest in SMR deployment among countries with small, medium and large nuclear power programmes, in addition to those currently without nuclear power programmes.

Whilst significant effort has been made to develop SMR technologies, relatively little has been done to consider their decommissioning and to understand the impact of SMR deployment on global radioactive waste management (RWM). The management and disposal of radioactive waste is an important consideration where the expansion of nuclear power is concerned and, for all countries considering SMRs, safe and affordable spent nuclear fuel (SNF) management solutions must be a key goal.

The new technical landscape of nuclear energy offered through SMR commercialisation presents potential commercial, strategic and policy issues that require evaluation.

Any programme adopting SMR technologies will need to consider the technical RWM impacts, along with higher level implications for national RWM policy, strategy and planning. Existing policies and plans might need to be revisited to account for the technical factors introduced by SMRs. These new boundary conditions will directly influence how a country considering SMR adoption will interact with other countries or groups of countries in terms of sourcing SMR technology and planning and implementing decommissioning and RWM activities, including disposal, e.g., in national deep geological repositories (DGRs).

As a result, there may be significant potential for countries to work together to address common issues of SMR RWM. A significant area of interest is the impact of SMR deployment on the potential for international collaboration where radioactive waste disposal is concerned, e.g., in multinational deep geological repositories (MNRs).

1.1. Purpose and Approach

This document covers the findings of a joint study relating to multinational solutions for the management of SNF and other radioactive wastes, managed and executed by MCM Environmental Services Ltd. (MCM).

The purpose of the study was to consider the multinational aspects of the potential technical, strategic, and political impacts of SMR commercialisation on the back end of the nuclear fuel cycle. Specifically, this includes the potential impact of SMR adoption on multinational approaches to deep geological disposal, including MNR projects. The study was split into two stages and eight tasks, aimed at exploring four major questions:

1. **Which SMR designs and reactor types are attracting most interest?** This provides the background for our study and is covered in Section 2 and Section 3. We review published literature and news articles to determine national strategic interest and/or financial commitment to SMR designs in order to focus our study on those which are credible.
2. **How will the management of radioactive wastes differ for the deployment of SMRs in comparison to more conventional, large reactors?** This provides a technical context for our study and is covered in Section 4. We focus primarily on disposal experience and practice for SNF from operating and shut down conventional reactors and utilise data from the open literature.
3. **What impact could SMR deployment have on a national RWM and/or DGR programme?** This is tackled in Section 5. We do this by developing national profiles representative of countries with differing scales of nuclear power development and different waste inventories, which are likely to be interested in a various of SMRs. We then develop and scenarios that are illustrative of how SMRs might be deployed.
4. **What impact could SMR deployment have on multinational RWM collaboration?** This is tackled in Section 6. We do this by developing a range of feasible MNR collaboration models to assess how different MNR scenarios might be implemented.

2 Global SMR Deployment

The need for, and associated requirements of, back end solutions for SMR wastes are driven by the global deployment of different SMR technologies, and specific SMR designs. As a result of current widespread interest, a plethora of publications aim to assess SMR deployment scenarios.

Much of the open literature in this area focuses on the use of SMRs to provide electricity, either integrated into a national electrical grid infrastructure, or as stand-alone facilities at more isolated locations. Whilst electricity production is likely to remain the core use case, part of the appeal of SMRs is their versatility, making them suitable for a diverse range of applications[1]:

1. **New Commercial Electricity Production.** The SMR designs being proposed for the market generally supply anything between a few MWe and a little over 300 MWe. The smaller facilities involved may be chosen as alternatives to diesel electric generators at remote locations. This is already being done using the floating reactors being produced in Russia [5]. Reactors at the upper end of the scale may appeal to new nuclear nations with limited grid capacity, or to established nuclear programmes that prefer to increase their capacity incrementally because of the reduced capital requirements at each stage.
2. **Replacement Commercial Electricity Production.** This can be an attractive option in many countries, not only because of the CO_2 emission reductions, e.g., through the systematic replacement of coal-fired stations with SMR modules or plants, but also because existing commercial electricity production plants are almost always connected to the national grid, providing a 'grid ready' deployment solution.
3. **Desalination.** Many desalination plants are currently operational around the world. Most of these are powered by fossil fuels, where the rate of freshwater production scales with the power output. Large nuclear power plants can provide some power for desalination, while remaining primarily electricity producers. However, this requires the incorporation of additional desalination facilities and unique site conditions and, due to their size and flexibility, there is an increasing interest in the use of SMR units to provide power specifically for desalination activities only.
4. **Industrial Process (High-Temperature) Heat Production.** Certain industrial processes require a significant input of high-temperature heat 'on site', e.g., steel production, cement production, various mining activities and the extraction of oil from tar-sand deposits. Existing large nuclear reactors can provide such heat in some cases. However, the production applications require higher temperatures than can be provided by conventional reactors and the extraction applications are typically carried out in remote locations. Hence, smaller, more flexible SMRs, or those designed to supply particularly high temperatures, are being considered as low-carbon solutions. The use of SMRs to generate hydrogen is expected to become an increasingly important way to produce high-temperature heat, placing SMRs more centrally in the low-carbon landscape of the future.
5. **District (Low-Temperature) Heating.** There are around 3,500 district heating networks throughout Europe serving ~60 million people. Two-thirds of European district heating supply is generated using fossil fuels whereas low-carbon fuels such as biomass, biofuels and renewable waste account for only 25%. The situation is not much different elsewhere, with existing district heating systems accounting for about 3.5% of global CO_2 emissions. The commercial potential of the district heating market, the consistency of supply required and the lower required

[1] In this study, we do not consider specific use cases in significant detail. We focus scenarios on the total nuclear power capacity which may be required by representative nations, without breaking this down by usage. However, given the importance of varied use cases as a driver for SMR deployment over conventional nuclear power plants, we broadly consider how different use cases may impact the conclusions that we draw from those scenarios.

temperatures (which can be more easily supplied) have led to lower power output SMR designs being designed specifically for district heating[2]. [6]

It is primarily their versatility which makes SMRs a disruptive technology. The potential for SMR application to distinctive use cases, in innovative ways, makes their precise deployment, in terms of location and number, difficult to predict.

However, Appendix 1: Potential Global SMR Deployment illustrates that, at this time, a maximum of ~21 GWe in global SMR capacity can realistically be expected in 2035. Figures for later years are highly uncertain; the maximum deployment estimates of ~375 GWe in 2050 that are given in the Appendix would require an unprecedented acceleration in research, development, and implementation.

Based on the 300 MWe limit in the IAEA definition of an SMR [1], a global SMR capacity of 21 GWe would involve a minimum of 70 SMRs to become operational over the next 11 years. However, this value could easily be doubled given that the stated power output for many SMR designs is well below 300 MWe.

[2] The 50MWe 'LDR-50' under development by the VTT Technical Research Centre of Finland could supply around 400 GWh a year. However, SMRs would need to become ubiquitous to make an impact, as the energy supplied for district heating in the European Union in 2018 was ~445 TWh, meaning the fossil-fuelled component of ~300 TWh would require ~750 LDR-50 SMR units each supplying ~400 GWh.

3 SMR Designs

A wide variety of SMR designs are being pursued by national development agencies and commercial vendors. Partly due to the potential flexibility of SMRs, global interest is not limited to counties with existing nuclear power programmes, i.e., 'nuclear nations', but also includes countries currently without a nuclear power programme, i.e., 'non-nuclear nations'.

This is a generic study. However, specific SMR design data is required to avoid limiting the analysis. Figure 1 presents a high-level schematic of the approach followed in order to focus this study on a manageable subset of the large number of SMR designs that can be found in the open literature.

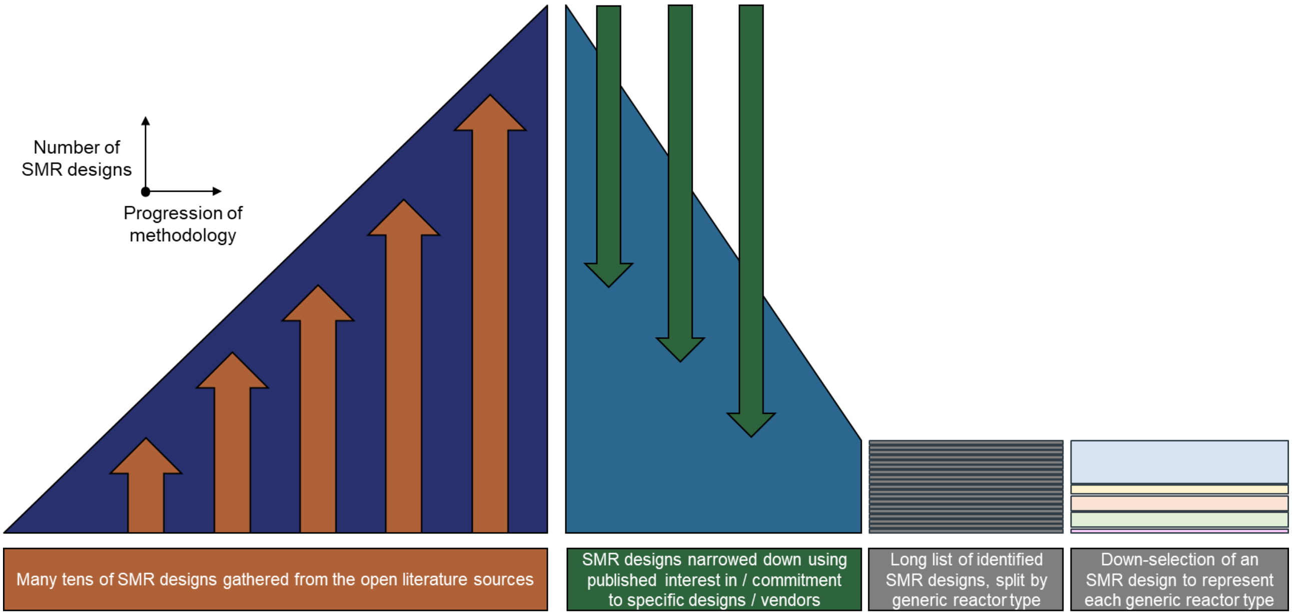

Figure 1: A schematic view of the method for down-selecting specific SMR designs across a mix of SMR technologies to represent the global SMR market.

The down-selection methodology summarised in Figure 1 enables a purely data availability-led process, avoiding the prioritisation of specific SMR designs for any reason other than there being widespread references to the SMR design in the open literature, along with data that can be used to replace generic assumptions about SMRs. The down-selection involved:

1. *Surveying the open literature to understand the maturity of SMR designs and the availability of associated design data.* A summary of key resources from the IAEA and the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (NEA) is presented in Table 2. In Figure 1, this is illustrated by the brown arrows and the increasing number of SMR designs represented by the dark blue triangle.
2. *Analysing the global strategic interest in, and/or financial commitment to, specific SMR vendors and designs.* A detailed scoping review of the current global end-user landscape for this purpose is presented in Appendix 2: Global Interest in SMR Vendors & Designs, where Figure 2 illustrates the countries analysed as part of that review. In Figure 1, this is illustrated by the green arrows and the decreasing number of in-scope SMR designs represented by the lighter blue triangle.
3. *Identifying a subset of the SMR designs that are of particular interest based on published commitment in the open literature, i.e., a 'long list' for consideration.* The long list identified in Appendix 2: Global Interest in SMR Vendors & Designs and is presented in Table 3. In Figure 1, this is illustrated by the twenty-two grey lines.
4. *Selecting one SMR design for each of the five generic reactor types represented in the long list, based primarily on data availability, which also acts as a rough measure of commercial maturity given the extent of references to those SMR designs in the open literature.* The five down-selected SMR designs are presented in Table 4. In Figure 1, this is illustrated by the five coloured

boxes, where box size is proportional to the number of SMR designs of that reactor type in the long list.

Table 2: Key sources of global SMR design information available in the open literature.

Resource	Description	Reference
IAEA SMR Book 2016	The IAEA SMR books provide a summary of the status of various SMR designs under development. Each book includes a 2-to-3-page data sheet for tens of SMR designs, covering core design data and additional information on safety features etc., for each SMR design. Notably, there is a Waste Management and Disposal Plan for each, but these are typically very brief. The books are supplemental summaries for the IAEA Advanced Reactors Information System (ARIS) [2], where they are underpinned by additional data and information.	[7]
IAEA SMR Book 2018		[8]
IAEA SMR Book 2020		[9]
IAEA SMR Book 2022		[10]
NEA SMR Dashboard	The NEA SMR dashboard briefly summarises key information associated with deployment (and hence, potential for commercialisation) of various SMR designs. The progress of the twenty or so SMR designs is briefly summarised in terms of Licensing, Siting, Financing, Supply Chain, Engagement and Fuel, but no dedicated underpinning is included.	[11]
NEA SMR Dashboard Volume II		[12]

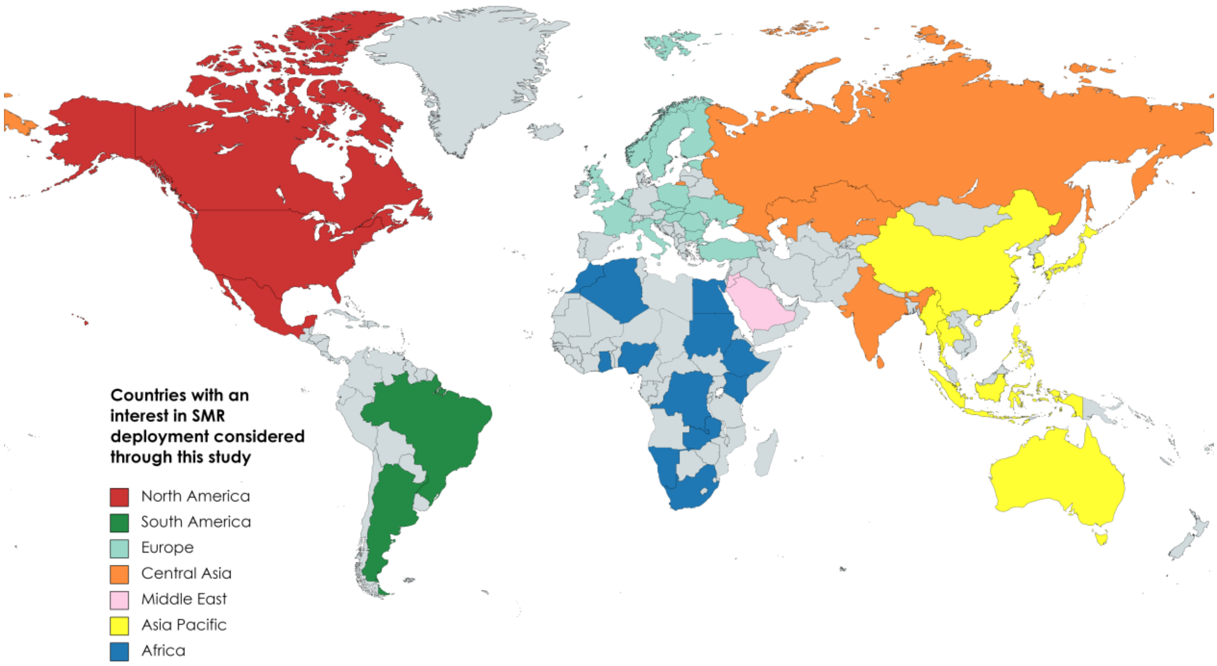

Figure 2: Countries with a significant, published interest in SMR deployment as found through a scoping review of the open literature, as of the end of December 2023, the details of which are presented in Appendix 2: Global Interest in SMR Vendors & Designs.

Table 3 presents a long list of twenty-two credible SMR designs. Here, credibility refers to the perceived readiness for commercialisation (based on published financial or strategic commitment, e.g., collaborative development agreements or direct funding of SMR vendors, as explored in Appendix 2: Global Interest in SMR Vendors & Designs, not necessarily on technical feasibility). China- and Russia-based designs / vendors are removed from scope due to a lack of information and these nations not being seen at this time as potential collaborators in multinational RWM solutions. The SMR designs in Table 3 cover the following five generic reactor types:

1. **Light Water Reactors (LWRs)** use 'light' water (H_2O, as opposed to 'heavy' water – D_2O) as both coolant and neutron moderator, with a solid fissile fuel. LWRs are commonly classified by their sub-type, most common of which are Boiling Water Reactors (BWRs), which use steam produced in the reactor core to drive the turbine for power generation, and Pressurised Water Reactors (PWRs), which use steam generators in a secondary loop. SMRs that are effectively BWRs or PWRs are treated together as LWRs in Table 3, given RWM commonalities.
2. **High Temperature Gas Reactors (HTGRs**) use an inert gas as coolant and graphite as a moderator, with a solid fissile fuel. HTGRs are the preferred and most prevalent sub-type of gas-cooled reactor technology in modern reactor design (as illustrated in Table 3, where all gas-cooled SMR designs are HTGRs). Two key sub-types of HTGR are the 'pebble-bed', which uses spherical fuel elements each containing many thousands of small TRi-structural ISOtropic (TRISO) fuel particles, and the 'prismatic block', where these TRISO fuel particles are contained in a graphite block reminiscent of a conventional reactor core. Similar to a PWR, a secondary loop is used to generate steam from the heat carried by the gas coolant.
3. **Molten Salt-cooled Reactors (MSRs)** use a salt mixture as coolant and/or fuel. The fissile fuel material can either be present in the molten salt coolant or in conventional fuel rods. In thermal neutron MSR variants, the moderating material – either graphite or a salt material, is separated from the molten salt coolant but it may or may not come into contact in the core elements. Similar to a PWR, a secondary loop is used to generate steam via heat exchangers.
4. **Metal-cooled Fast Reactors (MFRs)** use liquid metals as a coolant with no moderator, utilising fast neutrons for fission, hence the name 'fast'. There are no specific requirements outside of coolant type and neutron spectrum, but MFRs generally use a highly enriched solid fissile fuel and, similar to a PWR, a secondary loop is used to generate steam via heat exchangers. However, other fuel forms may be used, as shown by Dual Fluid's DF300 in Table 3.
5. **Heat Pipe-cooled Reactors (HPRs):** These reactors use heat pipe elements to transport heat out of the core to an energy conversion system, rather than conventional coolant circulation. Although the concept has a long history, it is a relatively novel emerging technology for decentralised electricity generation. Many different sub-types exist, with no one preferred approach, but bespoke fuel pins or rods containing either Low Enriched Uranium (LEU) or High Assay Low Enriched Uranium (HALEU) are typically fixed with heat pipes in a solid core, with or without a moderator.

Table 3: Data for SMR technologies identified through an analysis of global interest in Appendix 2: Global Interest in SMR Vendors & Designs. For reactor type grouping: blue cells show LWRs; yellow cells show HTGRs; green cells show MFRs (including Sodium-cooled Fast Reactors (SFRs) and a Lead-cooled Fast Reactor (LFR)); orange cells show MSRs; pink cells show HPRs; and grey cells show unavailable data.

Technology / Design	Vendor	Status	Origin	Type	Power (MWth)	Power (MWe)	Fuel	Enrichment (%)	Burnup (MWd/kg)	Coolant	Moderator	Reference(s)[3]
CAREM[4]	CNEA	Under construction (prototype)	Argentina	PWR	100	30	Rods containing typical LWR UO_2 pellets, in a hexagonal assembly array	3.1	24	Light Water	Light Water	[10]
VOYGR Power Module[5]	NuScale	Design licence approved, equipment manufacturing in process	USA	PWR	250	77	Rods containing typical LWR UO_2 pellets, in 17x17 assembly array	4.95 (max)	45 (min)	Light Water	Light Water	[10, 13, 14]
PWR-20[6]	Last Energy	Pre-licensing, parallel prototype construction	USA	PWR	60	20	'Off the shelf' UO_2 pellet and fuel rod	< 4.95	30 (min)[6]	Light Water	Light Water	[10, 15]
AP300	Westinghouse	Pre-Application Regulatory Engagement	USA	PWR	990	300	'Off the shelf' UO_2 pellet and fuel rod	< 5		Light Water	Light Water	[16]
SMART	KEPCO & KAERI	Detailed Design	South Korea	PWR	365	107	Rods containing typical LWR UO_2 pellets in 17x17 assembly array	< 5	36 to 54	Light Water	Light Water	[9, 10]
BWRX-300	GE-Hitachi Nuclear Energy	Detailed Design	USA, Japan	BWR	870	270 to 290	Standard GE GNF2 (UO_2 Pellet) in 10x10 assembly array	3.4 (avg) to 4.95 (max)	50	Light Water	Light Water	[10, 17]
BANDI-60	KEPCO	Conceptual Design	South Korea	PWR	200	60				Light Water	Light Water	[18]
UK SMR	Rolls-Royce and Partners	Detailed Design	UK	PWR	1358	470 (note 7)	Rods containing UO_2 pellets in 17x17 assembly array	< 4.95	50 to 60	Light Water	Light Water	[10]
Nuward	EDF and Partners	Conceptual Design	France	PWR	(2×)540	(2×)170	Rods containing UO_2 pellets in 17x17 assembly array	< 5		Light Water	Light Water	[10]
IRIS	IRIS	Basic Design	Multiple Countries	PWR	1000	335 (note 7)	Rods containing UO_2 MOX pellets in 17x17 assembly array	4.95	65 (max)	Light Water	Light Water	[9]
MMR	Global First Power	Preliminary Design	USA	Micro HTGR	15	5	Fully Ceramic Microencapsulated (FCM)[8] TRISO particle fuel	19.75	60 (min)	Helium	Graphite	[10]
Xe-100	X-Energy	Basic Design	USA	Pebble Bed HTGR	200	82.5	TRISO-X[8] TRISO particle fuel	15.5	165	Helium	Graphite	[9]
BANR	BWXT		USA	HTGR	50		UCO TRISO pebble or UN TRISO prism	< 20				[12]

[3] Efforts were made to supplement the publicly available data with data from vendor organisations. Specific staff at vendor organisations were contacted directly during October and November 2022 and through attendance and discussion at international events, e.g., the NEA 'Management of Spent Fuel, Radioactive Waste and Decommissioning in SMRs or Advanced Reactor Technologies' session in Ottawa, Canada. 7-10th November 2022. No data besides high-level information issued to all attendees of such events was able to be acquired.

[4] Versions with a power of 25 / 27 / 32 MWe are also offered, but data for the 30 MWe version are shown.

[5] Versions with a power of 50 / 60 MWe are also offered, but data for the 77 MWe version are shown.

[6] Data only available for the 'OPEN20', an 'academic version' of PWR-20 design which has a different power of 73 MWth and 22 MWe, but the same UO_2 Pellet with enrichment of < 4.95% in a 17x17 array.

[7] With a power of over 300 MWe, this reactor does not strictly align with the IAEA SMR definition of "*advanced reactors that produce electricity of up to 300 MW(e) per module*". However, it remains in scope as a 'smaller than conventional' reactor which generally aligns with the GIF goals with plans for a scalable / modular approach for commercialisation.

[8] This is a proprietary version of a TRISO particle fuel. These TRISO particle fuels have a central fissile 'kernel' made of uranium, carbon and oxygen (UCO).

Technology / Design	Vendor	Status	Origin	Type	Power (MWth)	Power (MWe)	Fuel	Enrichment (%)	Burnup (MWd/kg)	Coolant	Moderator	Reference(s)[3]
DF300	Dual Fluid	Component Testing	Canada	LFR	600	300	Spent fuel recycled to create fuel - salt mixture (constituent materials unknown).	10		Lead	None	[12]
ARC-100	ARC	Preliminary Design	Canada	SFR	286	100	Metal U-Zr Alloy based on enriched Uranium	13.1 (avg)	77	Sodium	None	[9]
Traveling Wave Reactor	TerraPower		USA	SFR	1475	Likely > 300 (note 7)	Hexagonal arrays of metallic U-10%Zr fuel bundles	13.1 (avg)	77	Sodium	None	[19]
Natrium SMR	TerraPower and GE-Hitachi Nuclear Energy		USA	SFR	840	345 (note 7)	Hexagonal arrays of annular metallic U fuel rods without sodium bond; breed-and-burn aspiration	5 to 20 *(DEMO will use 19)*	150-200 *(DEMO will reach 150)*	Sodium	None	[20, 21, 22]
CMSR	Seaborg	Concept Verification	Denmark	MSR	250	100	HALEU molten salt fuel	Variable, where [34] uses 7% / 31 MWd/kg.		Fluoride fuel salt	Patented NaOH salt	[10, 23]
IMSR400	Terrestrial Energy	Detailed Design	Canada	MSR	440	195	UF_4 infused into molten salt coolant	< 5	14	Near-eutectic fluoride salt	Graphite	[10]
SSR-W300	Moltex Energy	Conceptual Design	Canada	MSR	750	300	SNF recycled to create fuel salt mixture (45 mol% KCl and 55 mol% actinide & lanthanide trichlorides)	N/A	~100	Molten MgCl/NaCl Salt	None	[9]
ThorCon Module	ThorCon	Preliminary Design	Indonesia, USA	MSR	557	250	UF_4 infused into molten salt coolant	Startup 2.3 / makeup 4.95	145.8	Molten salt	Graphite	[10]
eVinci	Westinghouse	Vendor Design Review (VDR)	USA	HPR	7 to 12	2 to 3.5	Encapsulated particle fuel, e.g., TRISO	5 to 19.75		Sodium-filled heat pipes	Metal Hydride	[24, 25, 28, 29, 47]

Table 4: Down-selected SMR designs with data and information for key design parameters.

SMR Vendor	**NuScale**	**X-Energy**	**TerraPower and GE-Hitachi Nuclear Energy**	**Terrestrial Energy**	**Westinghouse**
SMR Design	**VOYGR Module**	**Xe-100**	**Natrium SMR**	**IMSR400**	**eVinci**
Reactor Type	PWR	HTGR	SFR	MSR	HPR
Power (MWth)	250	200	840	440	7 to 12
Power (MWe)	77	82.5	345	195	2 to 3.5
Fuel Cycle	LEU once through	HALEU once through	HALEU once through	LEU once through	HALEU once through
Fuel	Standard 17x17 fuel rod assembly using UO_2 pellets	UCO TRISO particle fuel pebbles	Hexagonal arrays of annular metallic U fuel rods without sodium bond	UF_4 in molten salt coolant	Particle fuel, e.g., TRISO
Enrichment (%)	4.95 (max)	15.5	5 to 20 *(DEMO will use 19)*	< 5	5 to 19.75
Burnup (MWd/kg)	45 (min)	165	150-200 *(DEMO will reach 150)*	26-29	*Data unavailable*
Core	37 fuel assemblies	220,000 pebbles (each with 18,000 particles) in the core at any one time	*Data unavailable*	Continual circulation of molten salt fuel-coolant mixture	Monolithic block with fuel, moderator, and heat pipe channels
Fuel Re-loading Pattern	Nominal 18-month three batch shuffling	Online refuelling: 170-179 pebbles in/out per day, each in-core for ~1,320 days	Fuel in reactor for 1.5 years	Core replaced after 84-month operation	Canister return after ~8-year operation
Reactor Vessel	Height: 17.7 m Radius: 1.35 m Mass: Unknown	Height: 16.5 m Radius: 2.44 m Mass: 274 t	*Data unavailable*	Height: 7 m Radius: 1.75 m Mass: 170 t	*Data unavailable*
Design Life (Years)	60	60	Data unavailable	56	40
Coolant	Light water	Helium	Sodium	Fluoride salt	Sodium-filled heat pipes
Moderator	Light water	Graphite	None	Graphite	Metal hydride
Reference(s)	[10, 13]	[10, 33, 40]	[20, 26]	[10, 27]	[10], [28], [29]

4 Radioactive Waste Management at the Back End of the Fuel Cycle

One of the key challenges for SMR deployment is ensuring safe and secure RWM. The process of electricity production through nuclear power is supported by various activities referred to as the nuclear fuel cycle. A schematic view of the nuclear fuel cycle is shown in Figure 3.

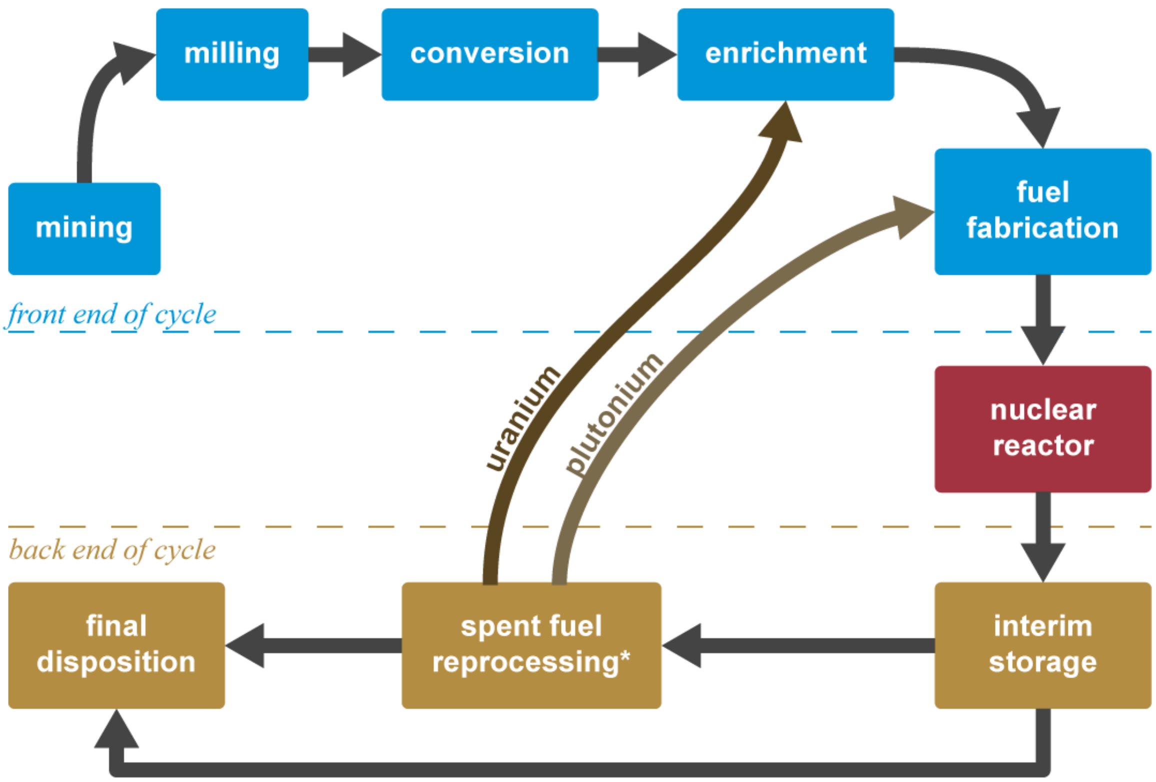

Figure 3: A simple schematic of the nuclear fuel cycle, taken from [30], where * denotes the fact that SNF reprocessing is not carried out in most countries.

Typically, as illustrated in Figure 3, the back end is considered to include the storage, reprocessing, and disposal of SNF. However, reprocessing is not carried out routinely by all nations with nuclear power and, in the context of SMR deployment, a 2022 National Academy of Sciences report [31] recommended “the current U.S. policy of using a once-through fuel cycle with the direct disposal of commercial SNF into a repository should continue for the foreseeable future”. Whilst not the case for all SMRs, the baseline assumption for all our down-selected SMR designs is a once-through fuel cycle, as presented in Table 4 (noting that TerraPower explicitly plans to explore a closed fuel cycle in future iterations of its SMR designs [20]). The once-through fuel cycle is therefore the reference case for the analysis in our study.

The once-through fuel cycle ends with the disposal of SNF. However, while SNF is the most hazardous source of radioactive waste arising from the operation and decommissioning of a nuclear reactor, to consider the back end of the fuel cycle holistically, all the following sources of waste should be considered:

- **SNF:** Nuclear reactor fuel is considered ‘spent’ after it has been removed from the reactor core. SNF is typically managed through safe, secure storage in a dedicated facility, either until it can be re-processed / recycled or until a disposal route is available. As it is the most hazardous component associated with reactor operations (from both a safety and a security perspective), SNF is generally considered separately from other waste streams. We explore this from a disposal perspective for our down-selected SMR designs in Section 4.8.2.

- **Operational Waste:** This includes the radioactive materials that are generated (including by contamination or activation) and extracted from the reactor system during operations. The wastes can vary greatly by generated volume and characteristics depending on reactor type but include any radioactive component or substance – apart from SNF – which is replaced and/or recycled over the operating lifetime of the reactor. Operations end with the shut-down of the reactor and removal of any SNF; all wastes arising through this process (apart from the SNF) are categorised as operational waste. We explore this from a disposal perspective for our down-selected SMR designs in Section 4.8.1.
- **Decommissioning Waste:** The decommissioning process begins once the reactor is in a shut-down state with all SNF removed. The process starts with a post-operational clean out and, depending on the approach prescribed by the relevant regulator, covers decontamination, dismantling and remediation. All wastes arising through the decommissioning process are categorised as decommissioning waste. We explore this from a disposal perspective for our down-selected SMR designs in Section 4.8.1.

The most challenging RWM task is the implementation of geological disposal for SNF and long-lived Intermediate-Level Waste (ILW) in a DGR. However, there are various activities that must be conducted prior to disposal. The focus of this study is primarily on the back end, i.e., storage, processing and disposal. However, front-end and operational activities are also relevant, as “decisions made in isolation can result in sub-optimal solutions with respect to the entire waste management system” [32].

Figure 4 builds on Figure 3 by specifying activities of interest for the holistic consideration of SMR deployment at the back end. We define these activities broadly, from the perspective of a conventional reactor (typically chosen to be a PWR in open literature studies, e.g., [33], [34], due to the global prevalence of PWRs), so they are not necessarily equally applicable to all reactor types.

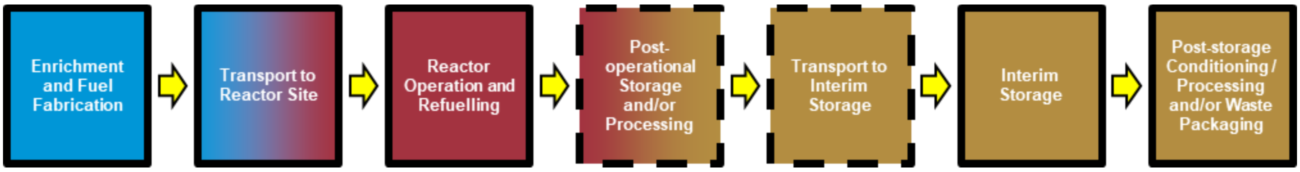

Figure 4: Grouping of activities for our purposes, colour coded as in Figure 3.

Sections 4.1 to 4.7 consider each of the Figure 4 activities for a typical Reference PWR, in a necessarily generic manner, given the different design and operational boundary conditions for conventional PWRs worldwide. These sections provide a background against which the corresponding activities for SMRs can be compared. Table 5 considers each of the Figure 4 activities from the specific perspective of our down-selected SMR designs.

4.1. Enrichment & Fuel Fabrication

Most commercial reactors currently in operation use fuels with an enrichment of up to 5%, the limit for classification as Low Enriched Uranium (LEU). The fabrication of fuel assemblies with such an enrichment is carried out routinely and commercially, i.e., competitively in an open market, but the dimensions and geometries of fuel assemblies used worldwide vary.

4.2. Transport to Reactor Site

Fresh fuel pellets, rods and assemblies of LEU are not only fabricated but also transported routinely. However, this is carried out under strict licensing arrangements using licensed transport containers and established protocols and processes. Conventional reactors benefit from many decades of experience, which has led to fuel transport being routine.

4.3. Reactor Operation and Refuelling

Once the fuel has been loaded into a reactor core, power generation operations involve the irradiation of the fresh fuel assemblies. Commercial reactors are typically shut down every ~18 months to undergo refuelling.

Refuelling is generally carried out by removing one-third of the irradiated fuel assemblies and replacing them with fresh fuel assemblies. The part-used assemblies are generally 'shuffled' into different locations in the core, to optimise the core reactivity. The process is managed extremely carefully according to well-established procedures.

During outages, any irradiated fuel assemblies removed from the reactor are transferred into an on-site spent fuel pool. Those considered SNF do not re-enter the reactor.

4.4. Post-operational Storage and/or Processing

SNF continues to emit heat after removal from the reactor. Wet storage is generally required until the temperature has reduced to a manageable level, as shown in Figure 5. The duration varies by case but "6 to 8 years" is typical. [35]

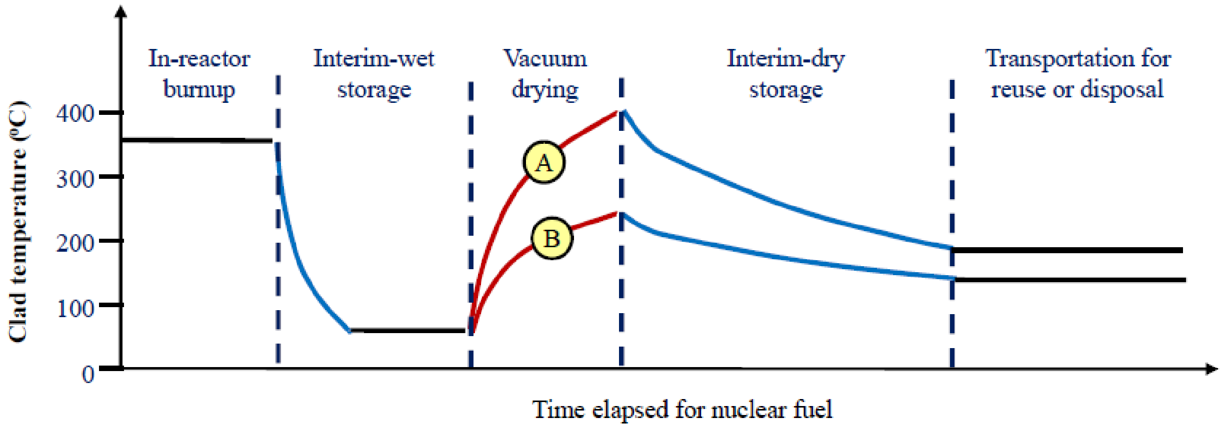

Figure 5: Fuel cladding temperature variation during nuclear fuel cycle, taken from [36]. The Vacuum drying variants labelled A and B are not important here.

4.5. Transport to Interim Storage

Depending on the availability, on-site, off-site, or centralised facilities are used for the interim storage of SNF until a disposal or reprocessing solution becomes available. As shown in Figure 5, SNF is often transported to an interim dry storage facility. Prior to transportation, drying removes moisture from the SNF so that it can be placed in licensed transport containers.

4.6. Interim Storage

Once SNF has reached a dry interim storage facility, around "30 to 40 years" is needed to further bring the temperature down to an acceptable level for disposal, as shown in Figure 5. [37] Both wet and dry interim storage for conventional SNF are well-established approaches currently carried out around the world.

4.7. Post-storage Conditioning / Processing and/or Waste Packaging

Typically, a national Waste Management Organisation (WMO) is responsible for determining requirements for conditioning / processing prior to packaging for disposal. This varies by country, but the waste packaging solution requirements are determined in line with DGR development.

Table 5: Documented plans and assumptions for the down-selected SMR designs across the fuel cycle activities defined in Figure 4.

SMR Vendor	NuScale	X-Energy	TerraPower / GE-Hitachi Nuclear Energy	Terrestrial Energy	Westinghouse
SMR Design	**VOYGR Module**	**Xe-100**	**Natrium SMR**	**IMSR400**	**eVinci**
Reactor Type	LWR	HTGR	SFR	MSR	HPR
Enrichment & Fuel Fabrication	NuScale has worked with Framatome to develop an adapted 'half height' version of the HTP fuel assembly that is used routinely in conventional large PWRs. The fuel is yet to be fabricated at the commercial scale but this will be carried out in collaboration with Framatome.	As the Xe-100 TRISO particle fuel is not currently available commercially, X-Energy plans to construct a TRISO-X Fuel Fabrication Facility (TF3), thus establishing a baseline capability for fuel fabrication. It appears the TF3 will be constructed in the USA, where, as highlighted by the National Academies of Sciences, there is currently no domestic capacity for the commercial enrichment of HALEU. Hence international collaboration or a USA licensing process for enrichment will be required.	The same challenges regarding HALEU enrichment as for the Xe-100 apply here. In the National Academies of Sciences report, concerns are raised around the use of sodium-bonded fuels. This may be why TerraPower is currently developing a metallic fuel without a sodium bond. The status of developing a fabrication methodology for bespoke fuel pins and assemblies. and whether fabrication will take place at a bespoke facility or in collaboration with an established supplier of nuclear fuel, is not available.	Terrestrial Energy's pilot plant will be powered using fuel fabricated by Westinghouse subsidiary Springfields Fuels Ltd. Collaboration that aims to deliver a dedicated "pilot IMSR fuel plant" in the UK is underway.	No specific information regarding fuel fabrication is available. The same challenges as for Xe-100 apply, given the use of similar TRISO particle fuel.
Transport to Reactor Site	As part of their collaborative design efforts with Framatome, it appears that NuScale will use existing transport arrangements within the existing regulatory framework. However, it is unclear whether a new transport cask is under development to account for the reduced fuel assembly length.	Even if a TF3 is made available in each country (or region) in which an Xe-100 unit is deployed, the routine transportation of HALEU TRISO particle fuels will still be required. Therefore, significant regulatory interaction will likely be required here.	TerraPower have noted that "transportation casks [for fresh fuel] have to be licensed for HALEU with higher fissile content and different assembly shape/size", and work is underway to address this.	Based on their collaboration with Springfields Fuels Ltd., Terrestrial Energy expects that the fuel will be able to "be transported using reactor fuel packaging already in use today". The fuel will be "brought to the [...] site as a solid, where it [will be] melted and added to the IMSR Core-unit".	Transport of the fuel to the reactor site is not directly applicable as Westinghouse envision the "protective canister", which acts as an overpack for the whole eVinci unit, to be "factory built, assembled, fuelled and tested", when it will be "transported by road, rail and sea […] to site". The transportation of a reactor in a "fully assembled state", including the presence of HALEU TRISO particle fuel is a first-of-a-kind activity and will likely require significant regulatory interaction.
Reactor Operation & Refuelling	During operations, the adapted HTP fuel assemblies will be irradiated in the core as with a conventional PWR. During refuelling outages, irradiated fuel assemblies will be stored in the on-site spent fuel pool.	The Xe-100 design uses an 'online refuelling' philosophy, where refuelling is an integrated part of reactor operations. At full power, "170-190 fresh fuel spheres are added to the core daily and the same number of [spent] fuel spheres are removed", with "approximately 220,000 fuel spheres in the core at any given time", subject to irradiation.	During operations, the metallic fuel will be irradiated in the core. During refuelling, spent fuel 'pins' (assumed to be removed from an assembly) will exit step-by-step via a "Pin Removal Cell", "Ex-Vessel Handling Machine", "Core Component Conditioning Station" (CCCS) and "Pool Immersion Cell" (PIC). Fresh fuel will enter through the opposite route.	As with the Xe-100, the IMSR400 also uses an 'online refuelling' philosophy. The molten salt fuel-coolant mixture will be continually circulated through the core, undergoing irradiation. The core will not be opened on-site at "start-up fuelling or during refuelling". However, "small amounts of 'makeup' fuel salt" will be added during operations. The entire core unit will be removed and replaced following shut down after ~7 years of operation.	Reactor operations are design to be carried out entirely autonomously with "no moving or mechanical parts, except for reactivity control drums". The 'as-shipped' particle fuel arrives isolated in fuel channels, where they will be irradiated in the solid monolithic centre. Westinghouse's design plans specify that refuelling will not be performed on-site.

SMR Vendor	NuScale	X-Energy	TerraPower / GE-Hitachi Nuclear Energy	Terrestrial Energy	Westinghouse
SMR Design	**VOYGR Module**	**Xe-100**	**Natrium SMR**	**IMSR400**	**eVinci**
Post-operational Storage and/or Processing	After irradiation and transfer out of the reactor, the on-site spent fuel pool will provide "up to 10 years of used spent fuel storage". The SNF assemblies will then be dried before they are transferred to dry storage casks.	Spent pebbles will be deposited into Spent Fuel Canisters (SFCs) which "will be uniquely identified to support inventory tracking" and are "designed to store up to 6,000 spheres" each. The on-site Spent Fuel Interim Storage Facility (SFISF) will ensure "passive cooling […of the SFCs…] through natural convection".	TerraPower's plant design enables SNF to be "stored [for] 1.5 years in [the] reactor vessel" and, upon removal, for up to a further "10 years in [the] spent fuel pool". It is not clear from available information, but it is assumed that sodium cleansing (required due to the reactive nature of sodium in water) will be carried out in the CCCS so that the SNF assemblies (given their lack of sodium bond) can be placed into a standard water-based spent fuel pool. If this is not the case, then either the spent fuel pool would need to be sodium-based or some barrier between the SNF and water-based spent fuel pool would be required. An Argonne National Laboratories report notes that for SFR plant designs which "incorporate spent fuel storage in [a] primary sodium pool", the "handling process becomes more complex when the [SNF is] removed from the sodium pool". It is unclear whether there are plans to use the PIC as an 'air lock' between the sodium-contaminated SNF and the water-based spent fuel pool, but this is likely to be just as complex.	Terrestrial Energy refer to the fuel-coolant mixture used over a ~7-year operational period as a 'charge'. It is envisioned that the SNF charge is "shipped to a [secure] central facility" for either fuel recovery or processing. Terrestrial Energy is currently collaborating with the Australian Nuclear Science and Technology Organisation (ANSTO) to process IMSR400 SNF into a Synthetic Rock (Synroc) wasteform. A 3-step process under development involves "mixing of wastes with […] chemical additives", "calcining of waste at elevated temperatures" and "hot isostatic pressing (HIP) of calcined waste" into a Synroc wasteform container. No post-operational processing is noted for the removable core itself.	After its ~8-year operational lifetime, Westinghouse plans for the canister to "be transported back to the factory where it can be refuelled and its components can be refurbished".
Transport to Interim Storage	Transport to an off-site interim storage facility is not required as part of NuScale's design plans.	Transport to an off-site interim storage facility is not required as part of X-Energy's design plans.	Little information regarding post-operational plans is available in the open literature, but "TerraPower has initiated efforts to develop the capabilities for SFR interim dry storage, eventual transportation to a central storage location, and repository disposal". For transportation, TerraPower notes that "the extreme simplicity and high burnup fuel" is expected to minimise "the number and type of shipments".	Terrestrial Energy notes that the Synroc / HIP processing into cans allows for "simplified transport and handling", but it is unclear if the Synroc wasteform containers would be transported to a further interim storage facility or whether they would remain at the Synroc / HIP processing site. It is planned that the empty, removable core(s) will be moved to "a long-term storage silo", assumed to be an off-site, central location.	No specific information regarding the transport of a 'spent' eVinci canister is available, where this would need to account for the post-operational state of the reactor and in-place SNF.
Interim Storage	An "on-site dry-cask" interim storage facility will be constructed which will be sufficient for "all the spent fuel produced during the 60-year life of the plant".	The SFISF is designed to "safely store […] all spent fuel generated over a 60-year plant design life" for "a minimum of 80 years".	TerraPower assumes that "similar dry storage and transportation casks" as for LWR SNF will be used noting, as with the fresh fuel transport, that licences "will need to be revised" due to "assembly shape, heat load, and fissile content". TerraPower notes that "the challenges for repository storage are also required to be addressed for transportation" and the "licensing basis will conservatively assume 100% radionuclide release on engineered barrier breach", implying that the transport solution may involve a container that is suitable for use as a disposal waste package.	No specific interim storage approach is specified for the Synroc wasteform containers, but dry storage at an interim storage facility / at the Synroc / HIP processing site is assumed. Terrestrial Energy plans for the empty, removable core(s) to remain in storage for "an extended period".	No specific information regarding the process through which a 'spent' eVinci canister will be dismantled, and the SNF contained therein removed, is available. However, Westinghouse plans for SNF to be "returned to the manufacturer or [sent to a] DGR [for] long-term storage" and the establishment of an "eVinci microreactor accelerator hub" may be the planned research, development and demonstration (RD&D) path.
Post-storage Conditioning / Processing and/or Waste Packaging	In a datasheet for its older design, NuScale notes that "fuel assembly radionuclide composition and radiotoxicity are well understood, which will facilitate transport to an interim storage facility [presumably if required from a DGR programme	It is not clear whether X-Energy plan to process the TRISO SNF particles prior to disposal, but existing studies assume that direct disposal will be required. This is because no commercial solution is currently available for such processing		Terrestrial Energy is also collaborating with Canada's Nuclear Waste Management Organization (NWMO), aiming "to size Synroc wasteform containers for maximal compatibility with planned […] DGR equipment and processes".	

SMR Vendor	NuScale	X-Energy	TerraPower / GE-Hitachi Nuclear Energy	Terrestrial Energy	Westinghouse
SMR Design	VOYGR Module	Xe-100	Natrium SMR	IMSR400	eVinci
	perspective] and final disposal in a national fuel repository when available." Although this reactor / plant design has been superseded it is assumed that, as with most national DGR programmes involving PWR waste, the SNF will be transferred to a dedicated encapsulation facility to be placed into a disposal container.	activities. However, significant investment into RD&D around this is currently ongoing, e.g., in the USA through the USDOE, partly because of the expectation that HTGRs will generate a volume of "25x more SNF than [LWRs] per ton of fuel" (assumed to imply per ton of uranium).		Terrestrial Energy plans for the empty, removable core(s) to "be shipped to a central facility, to be recycled or prepared for geological sequestration."	
References	[38], [10], [13]	[39], [31], [10], [40], [33], [41], [42]	[31], [20], [43]	[27], [44], [45], [46]	[47], [28], [48]

4.8. Disposal

Different types of radioactive waste require different disposal routes, based primarily on the activity of the waste and the duration for which the waste is expected to have that level of activity.

Most Low-level Waste (LLW) and some ILW (typically short-lived) can be disposed of in near-surface facilities. These engineered facilities ensure that the radioactive waste is safely separated from humans and the environment for the period within which they pose a danger.

However, SNF, High-Level Waste (generated through the reprocessing of SNF and hence not covered in detail given the focus on a once-through fuel cycle) and some ILW (typically long-lived) require geological disposal deep underground in a DGR. A DGR is a facility implemented for the disposal of solid radioactive waste that is “located underground in a stable geological formation so as to provide long term containment of the waste and isolation of the waste from the accessible biosphere” [49].

Disposal of SNF in deep boreholes is of particular interest at this time, given various potential benefits. The IAEA defines a Deep Borehole Facility as achieving the same function as a DGR but using “specially engineered and purpose drilled boreholes” which “offers the prospect of economic disposal on a small scale while, at the same time, meeting all the safety requirements”. [50] However, it is perhaps better considered for the context of this study as simply a potential DGR variant, broadly referred to as a ‘disposal concept’, as is done in a report published by the Nuclear Decommissioning Authority (NDA) in 2008 [51], in which “Concept 12: Very Deep Boreholes” refers to a Deep Borehole Facility as defined by the IAEA.

Geological disposal, using one (or more) of many potential DGR concepts is the most challenging disposal route, with no DGRs currently operating worldwide. As a result, through this study, no SMR vendor has been found to specify precisely how waste generated by one its SMR designs will be disposed of. In fact, few SMR vendors provide much information regarding the expected volumes and characteristics of the different wastes that will be generated through the operation and decommissioning of their SMR designs.

In order to cover this gap, a high-level analysis of the waste generated by the down-selected SMR designs requiring disposal is carried out in Appendix 4: Down-selected SMR Design Waste Data & Information, which provides significantly more information and discussion than shown here. The main findings of this analysis are presented in Section 4.8.1, Section 4.8.2 and Table 7.

4.8.1. Operational and Decommissioning Wastes

The VOYGR, Natrium SMR and eVinci designs are expected to generate small amounts of activated metals and, in the latter two cases, activated sodium, which will require geological disposal. Following appropriate treatment of sodium wastes using existing techniques (which have yet to be upscaled to the level required for commercial operations at the scale of SMR deployment expected), the characteristics and amounts of these materials are likely to be similar to those from conventional LWR decommissioning wastes and present no significant issues with respect to their inclusion in a DGR programme. As an example, the extensive Onkalo SNF repository under construction by Posiva, the Finnish WMO, is planned to include a small cavern disposal facility, at a higher level (180 m depth) than the SNF disposal regions, which will contain around 1500 m^3 of operational and decommissioning LLW and ILW from the on-site SNF encapsulation plant. Other advanced national DGR programmes (e.g., Sweden, Switzerland) include equivalent facilities of a similar scale (relative to the SNF or HLW repositories) for disposing of nuclear power plant and/or encapsulation plant operational and decommissioning wastes. Inclusion of light water or sodium fast SMR wastes in a DGR is unlikely to require any substantial adaptation of scale, concept or approach.

The large volumes of graphite wastes that will be generated by the Xe-100 and eVinci SMRs could further extend the requirements for disposal-related RD&D that are already raised by the carbon content of the fuel particles that they use.

The degree of uncertainty relating to IMSR400 waste streams means that no clear conclusions around its implications for geological disposal can be made beyond the fact that major RD&D will be required. However, the issue for operational and decommissioning waste streams could potentially be simplified should the separation of SNF from the molten salt SNF-coolant mixture be viable.

4.8.2. SNF

Direct disposal of VOYGR and Xe-100 SNF appears feasible using canisters and Engineered Barrier Systems (EBSs) of similar dimensions and materials to those that have already been designed for LWR SNF and HLW in a range of geological environments. This is also true of some types of Natrium SMR fuel, in contrast to sodium-bonded SNF which would be unsuitable for geological disposal without processing. Xe-100 and eVinci waste packaging design for the disposal of TRISO SNF is likely to require the most RD&D effort. A major decision affecting DGR planning and overall RWM programmes will be whether to separate out the graphite from the fuel particles, with the critical factors being how to manage the activated graphite and how to condition the extracted fuel particles.

Whilst the geological properties of IMSR400 waste immobilised as Synroc are unclear, the liquid nature of the SNF-coolant mixture directly prior to immobilisation means that waste package dimension is not expected to be a significant issue. Waste packages designed for SNF disposal may be suitable, as they are for vitrified HLW. However, significant RD&D on the material compatibility of such waste packages and other EBS components would be necessary.

In general, for SMR fuel types which do not use standard fuel assembly matrices or materials, additional issues such as criticality, dissolution rate and the presence of impurities will need to be resolved. Other options may also be considered within existing reprocessing or recycling processes such as PUREX, or with advanced processes, e.g., those being assessed by Orano in France. For those SMRs that do not use fuel assemblies in a conventional sense (i.e., Xe-100, IMSR400 and eVinci), novel conversion, separation and multi-recycling processes will need to be developed and tested in addition to disposal solution feasibility studies.

Design development work will be required for all SMR types and DGR safety cases will need to be extended to include these packages and assess their contributions to the overall performance of any repository system.

4.9. SNF Disposability

Disposing of SNF in a DGR requires consideration of many factors. We explore some of the criteria that are considered when determining the 'disposability' of a waste type in Appendix 3: Disposability of SNF. Through our analysis, we present the five topics in Table 6 as those that should be considered, at a high-level, for disposability in a generic study such as this.

Table 6: Disposability topics and their consideration in the context of this study, based on analysis in Appendix 3: Disposability of SNF.

Disposability Topic	Consideration within the context of this study
Volume	The volume of waste generated by an SMR, per unit of **electrical power**, over its operational lifetime has a direct impact on the size of a DGR, which directly affects the cost of a DGR and other strategic elements, such as siting.
Heat Output	The heat output generated by SMR fuel (a function of **fuel type**, **fuel enrichment** and **fuel burnup**), per unit **volume** of waste (and therefore per unit of **electrical power**), has a direct impact on the size of a DGR, as waste packages with a higher level of thermal activity will require greater spacing between waste packages. The post-disposal decay of the heat output is also important – for the same initial thermal power, a longer heat pulse leads to higher temperatures.

Disposability Topic	Consideration within the context of this study
Fissile Material	The amount of fissile material in an SMR waste stream (a function of **fuel type**, **fuel enrichment** and **fuel burnup**), per unit **volume** of waste (and therefore per unit of **electrical power**), has a direct impact on the size of a DGR, as SMR waste streams with a greater amount of fissile material will require separation across a greater number of waste packages.
Physical Characteristics	The **geometry**, **dimensions** and **physical form** of an SMR waste stream may directly impact the waste package in which it can be disposed of and/or the suitability of a DGR disposal concept / EBS.
Chemical Characteristics	The **chemical make-up** of an SMR waste stream may directly impact the waste package in which it can be disposed of and/or the suitability of a DGR disposal concept / EBS.

Through further analysis of our down-selected SMR designs in Appendix 4: Down-selected SMR Design Waste Data & Information, we identify quantitative and qualitative metrics for the topics in Table 7, where:

- Volume is represented by a quantitative value for the SNF volume generation rate in m^3 per GWe-year of reactor operations. Volume is used instead of mass, as no waste processing is assumed, and volume is considered more of a concern with respect to DGR size. Hence, the values are linked to the SNF form factor (assembly, pebble, etc.). ILW and LLW volume generation rate in m^3 per GWe-year of reactor operations is also included where available.
- Heat Output is represented by quantitative values for SNF decay power in kW per GWe-year of reactor operations, at times of 10 and 100 years after discharge from the reactor. The assumptions made around inventory definition in the software packages used to estimate these values for SNF following extraction from the reactor core are not known. Variance among these 'starting' inventories could arise through different assumptions around fuel makeup or depletion and burnup calculations, for example.
- Fissile Material is represented by a semi-quantitative 'number of flags' to show the likely amount of fissile material in the SNF following reactor operations.
- Physical & Chemical Characteristics are represented by a semi-quantitative 'number of flags' to show the degree of RD&D required to establish an accepted waste packaging solution for the SNF.

The analysis in Appendix 4: Down-selected SMR Design Waste Data & Information provides significantly more information and discussion than shown here. However, the analysis remains high-level and draws directly from referenced open literature wherever possible. An explanation of our interpretation of literature sources, and the justification for combination or interpolation of different values is explained.

Table 7: Metrics for the disposability topics presented in Table 6, based on high-level analysis in Appendix 4: Down-selected SMR Design Waste Data & Information using data and information from the open literature. Where possible, the Appendix uses quantitative data directly from the open literature. However, availability was found to be limited, so a justification of calculations and/or assumptions made to produce estimates in lieu of source material data is included in the Appendix. This was particularly difficult for ILW (discussed more thoroughly in the Appendix) as these values typically depend on the deployment scenario for a given reactor module. As a result, the data are often unlikely to be fully representative, especially for the PWRs. The LLW values are less important as LLW is not typically disposed of in a DGR. For metrics where quantitative data are not appropriate, flags are used, where a greater number of flags represents a greater challenge or degree of complexity.

SMR Vendor	Reference Reactor	NuScale	X-Energy	TerraPower and GE-Hitachi Nuclear Energy	Terrestrial Energy	Westinghouse
SMR Design	Conventional, Large Reactor	VOYGR Module	Xe-100	Natrium SMR	IMSR400	eVinci
Reactor Type	PWR	PWR	HTGR	SFR	MSR	HPR
SNF Volume (m^3 / GWe-year)	9.58	10.4	118	5.56	22.7	165
SNF Decay Heat at 10 years (kW / GWe-year)	40.6	42.2	32.2	24.5	4.18	32.2
SNF Decay Heat at 100 years (kW / GWe-year)	9.76	10.3	6.36	4.65	2.09	6.36
SNF Fissile Content	-	-	⚑ ⚑	⚑ ⚑ ⚑	⚑	⚑ ⚑
SNF Waste Packaging	-	-	⚑ ⚑	⚑	⚑ ⚑ ⚑	⚑ ⚑
ILW Volume (m^3 / GWe-year)	0.13	0.72	24.5	74.1	27.1	2.08
LLW Volume (m^3 / GWe-year)	645	573	Insufficient data available to estimate	21.9	Insufficient data available to estimate	Insufficient data available to estimate

4.9.1. SNF Volume

The volume of SNF generated by the Xe-100 and eVinci SMRs stand out amongst the other reactors. Their high volume generation rate is due to the use of TRISO particle fuels.

In a comparison of the extremes, the eVinci is estimated to generate almost thirty times the volume of SNF as the Natrium SMR, for the same amount of electricity generation. This information should be considered in the context of deployment: a Natrium reactor is designed to operate as one module within a relatively conventional power plant, whereas the eVinci is designed for bespoke and specialist use cases (e.g., it could be more efficient if district heating was our baseline use case, rather than electricity production). However, even with this context, this value remains notably high.

The estimated SNF generation rates of the VOYGR Module and Reference PWR are close, with a difference of 8%. The PWR figure of ~10 m^3 per GWe-year is almost double that of the Natrium SMR, but around half that of the IMSR400.

4.9.2. Decay Heat

At a time 10 years after extraction from the reactor, the highest heat output (42.2 kW per GWe-year for VOYGR Module SNF) is over ten times that of the lowest (4.18 kW per GWe-year for IMSR400 SNF). The IMSR400 value is a relative outlier here, but the Natrium SMR is also notable, with the SNF having around half the decay heat of the PWR type reactor designs.

This means that, from a heat output perspective only (i.e., not including physical form), it would be easier to handle and store IMSR400 and Natrium SMR SNF, as they produce less heat in this ‘early phase’ of the RWM process.

At a point 100 years after extraction from the reactor, the spread in decay heat is lower. At this point, the VOYGR Module produces only around five times the heat of the IMSR400 fuel. For a geological disposal concept where temperature rises must be controlled, increased spacing between waste packages would be required to account for the decay heat-induced temperature rise in a DGR. In this study, and the sources from which quantitative data are drawn, the decay heat at this 100-year point in time is a rough substitute for the decay heat at the time of emplacement in a DGR. SMRs with a higher decay heat at this point would require greater spacing at the time of emplacement, and therefore a larger volume of rock within which to site a DGR, which is one of various surrogates for cost, i.e., in such a case, a higher thermal load equates to a larger rock volume and higher costs. However, the relationship between thermal load, spacing and cost is complex. Furthermore, the point of ‘DGR emplacement’ is only one part of the picture; the thermal characteristics of these wastes beyond that 100-year point would be essential for the consideration of a DGR safety case.

4.9.3. Fissile Material & Criticality Safety

As the SNF generated by a VOYGR Module will be very similar to SNF generated by Reference PWR, and the latter is routinely managed, neither SNF is likely to pose unmanageable criticality safety concerns.

Whilst molten salt SNF-coolant is exotic from a chemical and physical characteristic perspective, the level of fissile material present is not expected to be significantly greater than existing SNF, which is managed routinely.

TRISO SNF presents more of a potential issue due to the presence of graphite in the fuel matrix. Graphite is used as a neutron moderator and is therefore problematic when considering criticality events. Care would therefore be required to deal with this issue when mitigating criticality concerns.

The most challenging SNF from a criticality safety perspective is likely to be that generated by the Natrium SMR, due to the use of the fast neutron spectrum and hence increased breeding of Pu239.

4.9.4. Waste Packaging

The success experienced by advanced DGR programmes in pushing forward towards key licensing milestones continually reduces concerns associated with conventional SNF assembly waste packaging solutions, i.e., for Reference PWR SNF. Because Reference PWRs and VOYGR Modules use very similar fuel assemblies, with a difference only in size, there is no greater concern for the latter beyond a conventional reactor.

Besides a requirement for post-operational sodium cleansing, the fuel assemblies used in the Natrium SMR are not significantly different from conventional PWR fuel assemblies. Hence, besides potential criticality safety concerns, they are unlikely to pose a significantly greater challenge.

The SNF generated by the Xe-100 and eVinci will be similar, as both are designed to use TRISO particle fuels. The key challenge here is the presence of graphite and silicon carbide in the fuel matrix, especially the graphite, and their different properties and potentially complex interactions from a long-term safety perspective. Such SNF could be significantly less challenging should a processing solution be available, separating the different materials within the SNF.

The most problematic SMR design from a waste packaging perspective is the IMSR400. Acknowledging this, Terrestrial Energy have begun RD&D efforts, but the effort required to license a waste package for disposal of IMSR400 SNF will likely be significant.

4.9.5. ILW Volume

Based on the detailed exploration in Appendix 4: Down-selected SMR Design Waste Data & Information, it is not clear whether all the ILW from each of the SMR designs would require disposal in a DGR. Hence, this is not covered quantitatively in Section 5 and Section 6, although it is considered qualitatively, e.g., in terms of facilities, skills, expertise and experience.

The volumes reported in, or calculated from, the open literature (as presented in Table 7) imply that the ILW volume generation rate for the PWRs (both conventional, large PWR and VOYGR Module SMR) and TRISO-fuelled SMRs is negligible in comparison to the SNF volume generation rate. However, this is likely due to the exclusion of operational wastes from ILW volume calculations. The specific volume of such ILW is difficult to find for reactors that have yet to be commercially deployed, as it would depend on their intended deployment strategy (e.g., whether as a single reactor unit or as part of a large power station, and whether operational wastes will be generated by the operator or the vendor) and the manner that they are actually operated (e.g., the fuel loading pattern, or the rate of component replacement).

Whilst the Xe-100 ILW generation rate is negligible in comparison to the SNF generation rate, this is partly because the latter is so high. Likely to be more accurate than the very low values for the PWRs, the ILW volume generation rates for the Xe-100Natrium SMR and IMSR400 could drastically increase the total volume requiring disposal in a DGR. However, the predominantly graphitic Xe-100 and IMSR400 ILW is more likely to require disposal in a DGR than the metallic Natrium SMR ILW.

eVinci is an interesting case because the very small nature of the reactor unit, and its sealed nature, limits the volume of overall material (highlighting the need to scale using volume per GWe-year) and, in theory, removes any possibility of ‘operational’ ILW. However, the intended approach for operations, where the sealed unit is returned to the manufacturer for refurbishment after ~8 years, means that ILW generation through refurbishment could become very significant, especially over the course of multiple deployments.

Overall, ILW volume is a complex metric, as it is difficult to compare SMRs in a ‘like-with-like’ manner, due to a variety of factors As a result, we primarily focus on SNF.

5 SMR Impacts on National Radioactive Waste Management Programmes

As covered in prior sections, the deployment of SMRs by a country will result in an increase and probable diversification of the radioactive waste inventory that requires disposal. This will include LLW, ILW and, assuming a once-through fuel cycle, SNF. As also covered in prior sections, LLW and some ILW is routinely disposed of in near-surface facilities around the world, whereas SNF and other types of ILW require disposal in a DGR.

5.1. Deep Geological Disposal

SMR SNF and ILW that requires disposal in a DGR could affect two key design factors:

1. The overall size and layout of the DGR to accommodate the volumes, thermal output and fissile content of the wastes; and
2. The DGR disposal concept, where EBS components might require further RD&D if novel solutions are needed to cater for the physical and chemical characteristics of the wastes.

These design factors would both affect the cost and scheduling of disposal activities. Depending on the number and type of SMR designs deployed, these impacts might be small and readily absorbed in a national DGR programme, or may result in significant additional work, depending primarily on the country's existing nuclear power programme and disposal planning.

5.2. Near-Surface Disposal

Whilst specific limits on activity level and decay lifetimes of waste classified as LLW exist, high-level considerations for LLW disposal in a Near-surface Disposal Facility (NSDF) are simply:

1. The volume of LLW requiring disposal; and
2. Whether a disposal route exists or not.

Hence, the primary consideration is whether a country has an operating NSDF or mature plans for implementation of one.

5.3. National SMR Deployment and RWM Scenarios

Rather than evaluating the impact of SMR designs on any one specific national RWM programme, we aim to carry out a high-level assessment of the impact of introducing SMRs to generic national energy generation portfolios.

In Appendix 5: National Radioactive Waste Management Programme Scenarios, data and information from the open literature are used to define five categories of country, around which analysis and assessment can be conducted in a generic or high-level manner to make general or widely applicable conclusions.

The key differentiators between the categories are the size and diversity of the national radioactive waste inventory, the approach taken to radioactive waste disposal and the availability of fuel cycle facilities and expertise.

Table 8 presents summary data for five hypothetical countries named OneLand, TwoLand, ThreeLand, FourLand and FiveLand, representing the five categories of country. Sections 5.4 and 5.5 use the waste metrics from Table 7 to assess how deploying either Reference PWRs or each of the five down-selected SMR designs to obtain specified additional nuclear capacities would affect the RWM programme of each of those countries.

The discussion here is general in nature, as the respective 0.5 GWe and 0.2 GWe in additional nuclear capacity required by ThreeLand and FiveLand outlined in Table 8 would not in reality be provided by a Reference PWR. This is because the calculations in Appendix 4: Down-selected SMR Design Waste Data & Information assume a Reference PWR power output of 1.175 GWe.

Table 8: Hypothetical countries around which our scenarios for the consideration of SMR deployment are built. The parameters used, particularly the values for assumed installed nuclear capacity and additional nuclear capacity required, are supported by discussions presented in Appendix 5: National Radioactive Waste Management Programme Scenarios.

	Hypothetical Country				
	OneLand	TwoLand	ThreeLand	FourLand	FiveLand
Nuclear power programme	Large	Medium	Small	None, with ambitious plans	None, with limited plans
Existing radioactive waste inventory	Highly diverse	Relatively uniform	Relatively uniform	Minimal	Minimal
National disposal strategy and/or programme	Highly mature	Highly mature	Relatively immature	None	None
Nuclear fuel cycle facilities & expertise	Considerable facilities & world-leading expertise	Various facilities with sufficient expertise	Limited (primarily on-site SNF storage)	Research reactor(s) / RD&D facilities only	Research reactor(s) / RD&D facilities only
National SMR vendor(s)	Yes	No	No	No	No
Installed Nuclear Capacity (GWe)	44	12	1.5	0	0
Additional Nuclear Capacity Required (GWe)	2	1	0.5	2.5	0.2

5.4. SMR Deployment in 'Nuclear Nations'

OneLand, TwoLand and ThreeLand have some level of installed nuclear capacity and are therefore referred to as 'nuclear nations'. As such, they share some potential opportunities and challenges that are not shared for 'non-nuclear nations'.

5.4.1. Inventory size and diversity, and DGR implications

Figure 6 presents a broad view across OneLand, TwoLand and ThreeLand. Each scenario assumes that conventional power plants provide the current installed capacity, with the additional capacity coming from either Reference PWRs or one of the five SMR designs. For further simplicity, wherever there is installed capacity, we assume that that it is generated by conventional 'Reference' PWRs. The SNF volumes are scaled from the volumes per GWe-year that are given in Table 7. Hence, as expected based on the values in Table 7, only the TRISO particle fuel used in the Xe-100 and eVinci SMRs make a significant difference to the total SNF volume. Outside of this, the committed waste from the existing Reference PWRs dominates any potential SNF inventory where there is existing capacity. The upper and lower end bounds are of most interest: OneLand (see Figure 7) and ThreeLand (see Figure 8).

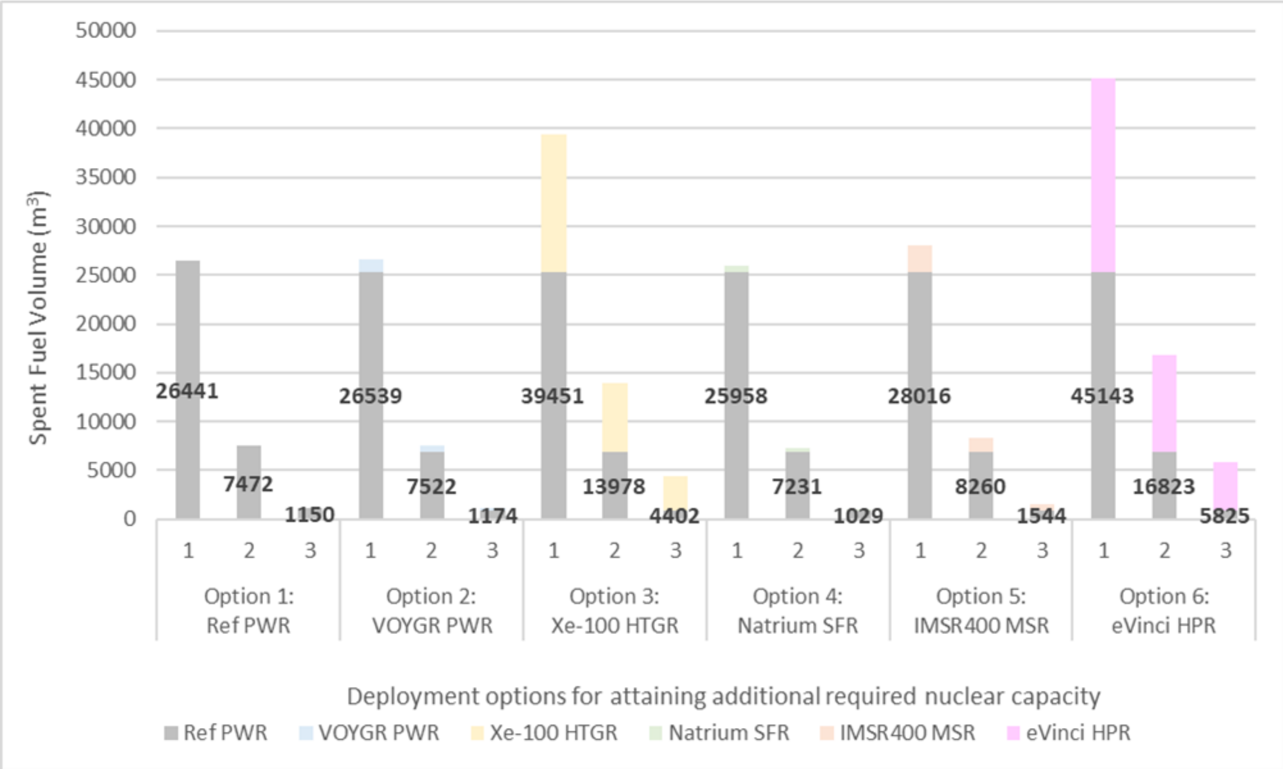

Figure 6: SNF Volume generated by OneLand (column 1), TwoLand (column 2) and ThreeLand (column 3) over a 60-year period. Reference PWRs are assumed to provide all currently installed capacity and six different deployment options (either a Reference PWR or one of the five down-selected SMR designs) are outlined for the provision of new nuclear capacity.

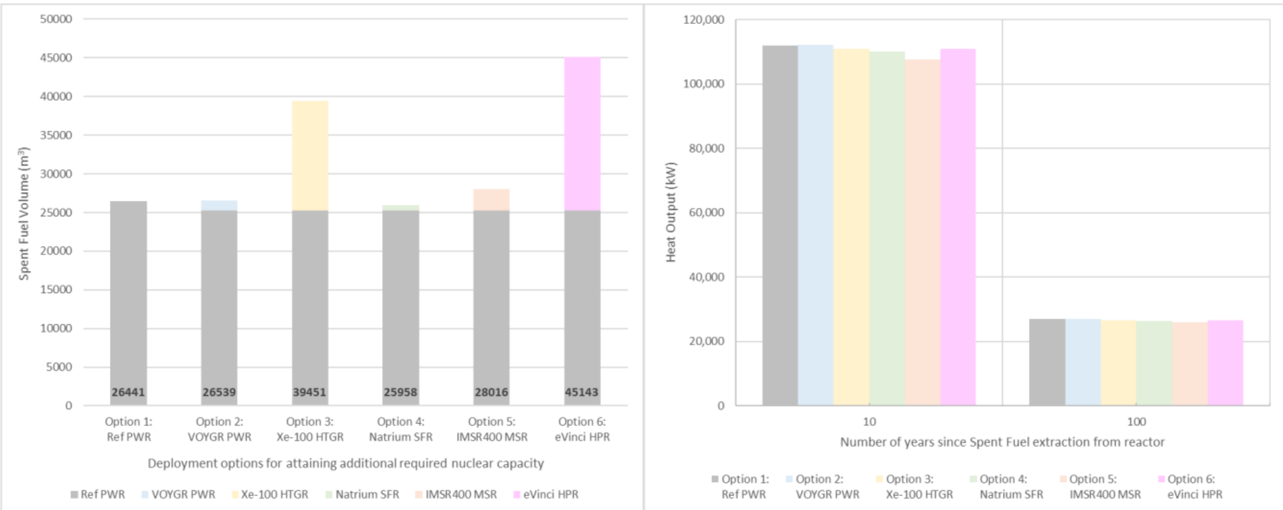

Figure 7: SNF Volume generated by OneLand over a 60-year period, using different deployment options – either a Reference PWR, or different SMR designs, to provide new nuclear capacity; and a simplified (heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment) view of total heat output of OneLand's SNF inventory assuming the same deployment options over a 60-year period.

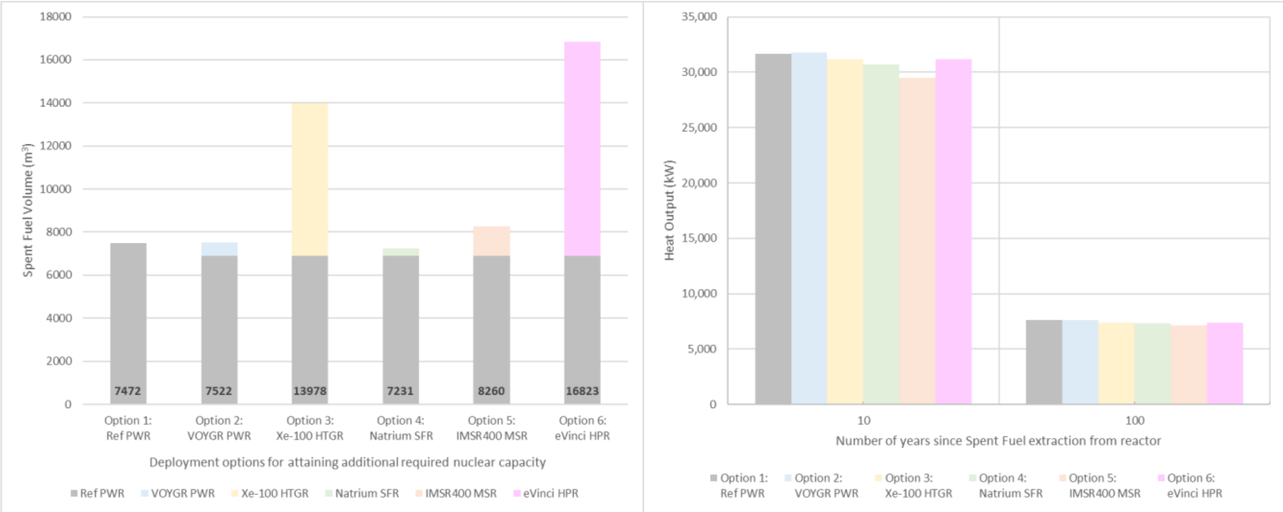

Figure 8: SNF Volume generated by ThreeLand over a 60-year period, using different deployment options – either a Reference PWR, or different SMR designs, to provide new nuclear capacity; and a simplified (heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment) view of total heat output of OneLand's SNF inventory assuming the same deployment options over a 60-year period.

Figure 7 shows that the deployment of any reactor which does not use TRISO particle fuel would have very little impact on the SNF inventory volume. The change in SNF volume through the use of Natrium SMR and IMSR400 units would be 2% lower or 6% higher, respectively. These changes are considered negligible for OneLand, where large DGRs are assumed to already be deployed prior to any ramp-up in nuclear capacity using conventional reactors or SMRs. However, the high fissile content of the Natrium SNF and the high potential for IMSR400 SNF packaging complications could make them significantly less desirable.

In contrast, the deployment of Xe-100 or eVinci units would result in SNF volume increases of, respectively, ~56% or ~78% on the estimated 25,291 m^3 of Reference PWR spent fuel arising from the existing 44 GWe capacity. This would result in similar increases in DGR excavated volume, which could have a significant impact on cost. This is a major implication, even for OneLand, which already requires a relatively large DGR for its committed waste. However, this high SNF volume is a result of the composition of TRISO fuel, due to a large volume of graphite and matrix materials contained in the SNF pebbles. No commercial approach currently exists, but calculations in [33] imply that if some form of processing (including the separation of graphite) were viable, the mass of SNF materials requiring geological disposal would be significantly lower. Hence, for the adoption of any SMR that utilises TRISO fuels, the impact of unprocessed SNF volume on inventory size would be closely tied to OneLand's policy towards, and access to, reprocessing facilities. Without taking other drivers or specific use cases into account, the waste metrics for TRISO-fuelled SMRs, plus the high fissile content and RD&D required for waste packaging, make them less attractive options.

In terms of heat output, there is little difference between the deployment options. This is because the greater decay heat of the committed PWR waste dominates any option. For OneLand, it would therefore be beneficial to explore the timing of waste arisings in more detail, as the decay heat currently emitted by its existing PWR SNF inventory will sit somewhere between the upper (10-year cooling) and lower (100-year cooling) values. However, the timings depend on the programmes for power plant closure and decommissioning, and the approach to SNF storage, none of which is examined from a country-specific perspective in this study.

Figure 8 presents a view less dominated by Reference PWR SNF. For ThreeLand, the increased SNF volume generation rates of the IMSR400, Xe-100 and eVinci are more pronounced. The deployment of 0.5 GWe of the first of these results in an 80% increase over the 862 m^3 of committed PWR SNF volume produced by the baseline 1.5 GWe capacity. Deployment of the other two TRISO-fuelled SMRs would result in the generation of an additional four (Xe-100) or six (eVinci) times that of the IMSR400's 862 m^3 value. A four- to six-fold increase in SNF, with a significant impact on DGR volume, could prove prohibitive for ThreeLand, given its aim of conservatively increasing its nuclear capacity by a small increment. Furthermore, the limited fuel cycle facilities and expertise of ThreeLand implies a lack of readiness to establish a significant TRISO SNF processing capability, when compared to OneLand.

Any SNF generated by the Natrium SMR, Xe-100, IMSR400 and eVinci options would represent additional requirements to those involved in managing the majority of SNF present in nuclear nations. In this respect, OneLand is more likely to have at least some experience of these exotic SNFs through their nuclear research programmes. Without reprocessing, the development of disposal container designs for each additional type of SNF represents a requirement for RD&D efforts, including verification of the design compatibility with any planned approach to the direct disposal of conventional LWR SNF. This non-LWR RD&D burden – potentially required in addition to similar RD&D, but for LWR SNF – would be required for what is likely to be a relatively small amount of SNF mass, particularly for OneLand, which is assumed to be responsible for safely managing a large inventory of such LWR SNF. The additional RD&D burden would be compounded for a programme with more than one SMR reactor type, no matter how few were incorporated into the energy mix. As a result, the alignment of SMR choice with reactor types already in operation would be beneficial for nuclear nations. For example, the prevalence of large PWRs in France, could make a PWR-type SMR overwhelmingly attractive, despite the opportunity for SNF volume and/or decay heat reduction through other SMRs. Similarly, the opportunity to use expertise gained through the historic deployment of GCRs in the UK could make a HTGR-type SMR more attractive, despite the enormous increases in volumes of SNF (assuming direct disposal) or of problematic graphite ILW, if this is separated.

Overall, with significant experience in assessing geological disposal concepts, and any upstream impacts, the WMO in OneLand would likely be well equipped to consider all of the available options and develop solutions for managing any additional SNF. ThreeLand, on the other hand, would likely have a less developed disposal programme, where only conceptual studies on DGR design and siting have taken place to date. These studies are likely to be based on importing conceptual solutions for the disposal of the committed PWR wastes from larger, more developed DGR programmes. The impact of larger volumes of SMR fuels on DGR development would therefore be a major driver, and the WMO in ThreeLand would be motivated to become actively involved in joint programmes aimed at developing DGR concepts and packaging options for SMR fuels.

5.4.2. Upstream implications: storage and transport

Ten years after the removal of SNF from the reactor core, it is assumed that its storage, and potentially transport, is the key concern for a national programme. The heat output of the SNF is an important consideration in this respect. Figure 7 shows that the domination of the committed PWR waste for OneLand results in little difference in terms of heat output (at the universal 'total inventory' scale at least, noting that a particularly high heat output on a package-by-package basis would remain of concern). However, the lower decay powers for the non-PWR reactor types are observable for ThreeLand in Figure 8. Without accounting for new handling processes, equipment and container design, this will be of little concern for a nuclear nation, as the heat profile of the more exotic SNF is well within the existing storage and transport envelope.

An additional consideration, however, is the number and location of new SMRs, especially with respect to a DGR and associated SNF encapsulation plant, and to any centralised SNF storage facility that might exist or be planned. OneLand's existing 44 GWe might typically be distributed across fifteen or so sites, each with two or three reactor units. In order to acquire the required additional 2 GWe in capacity, it would be feasible to find a single new site to host two Reference PWRs, or even construct one new Reference PWR at each of two existing sites. For the deployment of SMRs, this would equate to around: six Natrium SMRs, likely across three sites; twenty-six VOYGR Modules, potentially across four different sites based on the NuScale plans for four-, six- and twelve-module plants; or many hundreds of eVinci units, noting that in reality this option is improbable, as these would not be deployed in a like-for-like replacement of conventional reactors. These numbers would be reduced for TwoLand or ThreeLand, but the same arguments remain. The special consideration for ThreeLand would be the fact that its existing capacity of 1.5 GWe would likely be supplied by one or two reactors at a single site, whereas any 0.5 GWe SMR deployment option would result in at least two reactors, i.e., two 345 MWe Natrium SMRs, but potentially many more, e.g., seven 77 MWe VOYGR Modules. This step change from one or two operational nuclear reactors at one site to multiple reactors, potentially at different locations, would directly necessitate an increase in radioactive waste transport infrastructure and suitably qualified and experienced operational personnel, and would also have secondary impacts, e.g., a requirement for more staff in the national regulatory organisation(s).

In short, the definitively ‘smaller’ nature of SMRs means, for all countries, that a greater number of SMRs would require deployment for a given nuclear power capacity. Hence, the potential benefits and drawbacks associated with centralised storage of SNF will become an important consideration for national policy in the event of widespread SMR deployment, and any solution will have implications for SNF transport routes to such a facility and to a DGR. The principal difference between OneLand, TwoLand and ThreeLand is their ability, in terms of facilities, infrastructure and human resources, to be able to deal with an increased number of reactors. The eVinci units are a special case, where a RWM infrastructure network would need to be able to transport irradiated reactor cores with SNF present inside, a new challenge in terms of transport regulation, safety and safeguards for even OneLand. Hence, eVinci deployment, especially if spread uniformly throughout a country, would require an overhaul in transport strategy, with associated regulatory changes and logistical challenges.

Overall, it can be expected that the transportation of a marginally higher or lower volume of SNF through the VOYGR Module, Natrium SMR and IMSR400 options would not be an issue for OneLand, as well established and robust waste transport services are expected to be in place. However, the potential ~56% and ~78% increase in SNF volume which would require management through the pre-disposal chain for the Xe-100 and eVinci HTGRs would likely have large and unavoidable impacts on radioactive waste transport infrastructure. The deployment of TRISO-fuelled SMRs would likely necessitate major improvements and increased manpower, at potentially great cost, even for OneLand. This might lead to consideration of more innovative and/or strategic approaches to reduce the degree of transportation required, e.g., co-location of SMRs at nuclear hubs around the countries at which deep borehole disposal could be carried out, noting that significant R&D is still required to demonstrate safety and feasibility of deep borehole disposal.

With no fuel production or management facilities other than on-site SNF storage at its existing reactor site(s), ThreeLand would be expected to make use of existing international supply chains to provide it with most of the materials and infrastructure it requires to manage SMRs. This will include the fuel itself and storage and transport containers. The existing national RWM programme is likely to have focussed on ensuring adequate on-site storage up to the point of transfer for disposal, and thus be most concerned with the lifecycle of facilities at one or two sites. With the introduction of multiple SMRs dispersed across the country, this picture will change considerably. The timing of SMR deployment, operation and SNF discharge will affect the decision to implement centralised or local storage solutions. Using SMRs for non-grid applications implies that several owners would be involved, with different priorities, making a national SNF management strategy more complex.

5.4.3. Upstream implications: fuel fabrication and SNF processing

Given the use of typical LWR UO_2 pellet fuel assemblies in the VOYGR module, any small increase in SNF volume over the lifetime of operations shown is likely a minor concern for operations in OneLand national fuel fabrication (or reprocessing) facilities. This is likely also true of TwoLand, assuming that it has such a capability, where the required facilities and manpower are likely to be scalable when averaged out over the lifetime of the reactor operations. However, issues could potentially arise even for OneLand, if the increase in a need to store, transport or process fresh fuel or SNF occurs at a specific time leads to a ‘spike’ in overall fuel cycle activities. This could arise from, for example, the commissioning and/or decommissioning of all SMR VOYGR Modules at one time.

The lower volume associated with the Natrium SMR SNF option implies that fuel cycle burdens would be reduced when compared with the Reference PWR option. However, the Natrium SMR fast reactor is designed to use U-Zr metallic fuel and the fuel fabrication process for these fuels is not as commercially established as that for the ceramic fuels used is most reactors. Significant investments may be needed to produce the volume of fuel required for the roll-out of the required number of reactors. Although OneLand may have access to experience of decommissioning sodium-cooled reactors (e.g., the USA's Sodium Reactor Experiment, the UK's Prototype Fast Reactor and France's much more recent Phénix / Superphénix reactors), the decommissioning of sodium-cooled reactor systems and the associated management of sodium-contaminated wastes, including SNF, is not established as a routine process at the scale required for a commercial nuclear power programme. Significant investment into facilities and expertise would therefore be required at the back end of the fuel cycle, even for OneLand.

The TRISO pebbles to be used by the Xe-100 and eVinci are not currently available commercially, although the Xe-100 vendor, X-Energy, has announced plans to construct its 'TF3' fabrication facility [39], thus establishing a baseline capability for fuel fabrication. Even so, the stated capacity of the facility, to produce eight metric tons per year of TRISO pebble fuel would account for only a fraction of the fuel required to operate the additional capacity required. However, TRISO-X plans to double its fuel production by the 2030s.

The higher SNF volume shown in Figure 6 for the TRISO-fuelled SMRs, when compared with those utilising conventional fuel assemblies, is due to the 'inefficient' form of the pebble fuel from a disposal perspective. However, even without a full SNF reprocessing policy that can separate and re-use constituent material, OneLand may be well placed to carry out some level of deconstruction of spent pebble fuels to reduce the volume of SNF for disposal, if it adopted the Xe-100 or eVinci.

No front or back end facilities currently exist that can produce fuel for a commercial fleet of IMSR400s, nor carry out the processing that would be required to either stabilise the molten salt coolant-fuel mix or separate out the heat-generating SNF material. The IMSR400 vendor Terrestrial Energy is working with Springfields Fuels Ltd. to fabricate a fuel for use in a 'pilot IMSR fuel plant'. [44] At the back end, ANSTO's Synroc processing methodology is being investigated by Terrestrial Energy, where it should be noted that the claim that the "Synroc innovative nuclear waste treatment technology also significantly reduces the volume of waste for disposal" has already been taken into consideration in our down-selection of SMRs (see Appendix 4: Down-selected SMR Design Waste Data & Information). It is expected that, in order to support commercial SMR deployment with MSR fuel and molten salt SNF processing, a significant investment would be required to build on the existing front and back end capability that even OneLand might have access to. However, the necessary RD&D appears to be progressing.

5.5. SMR Deployment in 'Non-nuclear Nations'

FourLand and FiveLand do not currently use nuclear power and are therefore referred to as 'non-nuclear nations'.

5.5.1. Inventory size and diversity, and DGR implications

For countries with no committed Reference PWR waste, Figure 9 indicates that SNF volume would not be a consideration for choosing between a Reference PWR and VOYGR PWR, given the similar values between FourLand Option 1 and FourLand Option 2. Figure 10 and Figure 11 enable a more in-depth exploration of the FourLand scenarios.

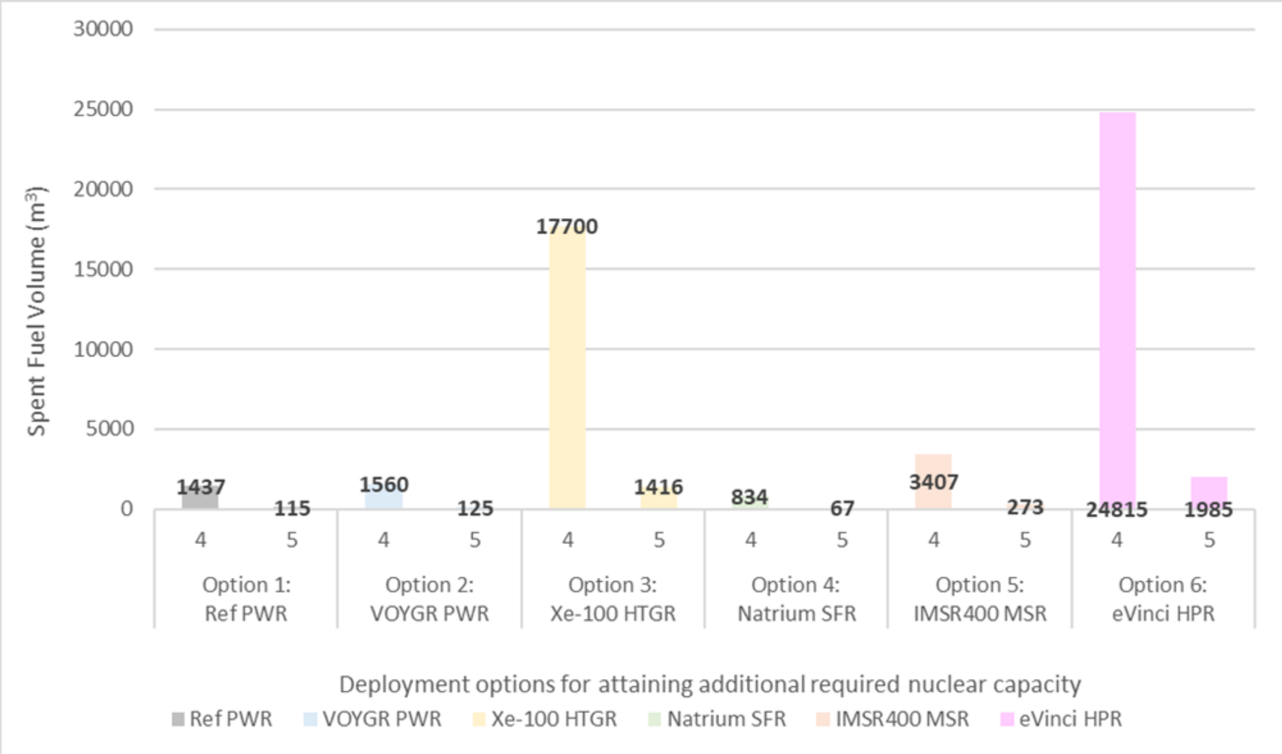

Figure 9: SNF Volume generated by FourLand (column 4) and FiveLand (column 5) over a 60-year period. Six different deployment options (either a Reference PWR or one of the five down-selected SMR designs) are outlined for the provision of new nuclear capacity.

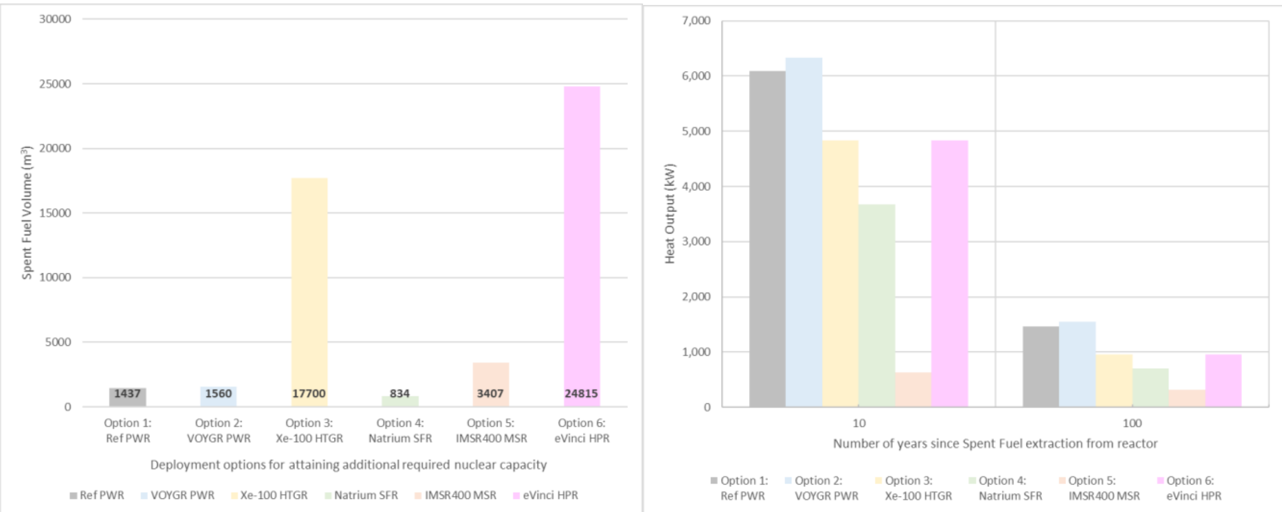

Figure 10: SNF Volume generated by FourLand over a 60-year period, using different deployment options – either a Reference PWR, or different SMR designs, to provide new nuclear capacity; and a simplified (heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment) view of total heat output of FourLand's SNF inventory assuming the same deployment options over a 60-year period.

Given the large-scale commitment to nuclear power for FourLand, it may be interested in becoming a global leader, or at least major player, for a specific nuclear technology or technologies. Hence, alignment with other nuclear nations is less likely to be a driver than it might be for FiveLand. This includes reactor type, fuel type and the associated RWM infrastructure. Given this relatively open outlook where technology choice is concerned, strategic country-specific drivers will likely dominate the choice of nuclear reactor type for deployment.

If collaboration with established nuclear nations is considered important, this would need to be considered in the context of the much greater heat output of the PWR SNF (Options 1 and 2) in Figure 10, as this could place a greater burden on upstream storage, as is discussed in Section 5.5.2. However, should FourLand see itself at the leading edge of new nuclear, it might opt to be an early adopter of a more exotic technology.

For example, the benefit of the ‘inherent safety’ of particle fuel could be a compelling argument (from both a technical and public acceptance perspective) to drive FourLand towards the Xe-100 and/or eVinci, despite the significantly larger volumes of SNF waste observed in Figure 10.

When considering SNF volume and decay heat in combination, the IMSR400 and Natrium SMR could provide significant potential benefit where DGR dimensions are concerned, as the potential for reducing package spacing would have a significant impact on DGR dimensions. However, a holistic approach requires the consideration of criticality safety and design and operational feasibility. As indicated by the flags in Table 7, deployment of the Natrium SMR would mean that managing the fissile material would become a dominant factor in DGR design. The need to spread fissile material across waste packages could result in a higher packaged SNF volume than implied by Figure 10, or a greater package spacing, potentially counteracting any benefits gained as a result of the unpackaged SNF volume assumptions and low decay heat. Criticality safety is of less concern for the IMSR400, as the concentration of fissile material is expected to be close to that of the VOYGR Module. However, the flags in Table 7 show that, although significant RD&D is underway, MSR SNF waste packaging solutions are far less advanced than those for other wasteforms. This highlights a key aspect that is not captured by the purely numerical inventory data, namely the commercial maturity and ubiquity of the skills, expertise, infrastructure, and processes from which the PWRs benefit. This is explored further in Section 5.5.2.

Despite these considerations, factors that impact only the expected DGR volume are unlikely to play a major factor in FourLand’s decision on choice of technology. This is because selecting any option would trigger the binary switch from not needing a geological disposal solution to needing one. The need for a DGR where none previously existed will always have more impact on national RWM strategy than the potential requirement for some DGR expansion to accommodate new wastes. In order to implement its own DGR programme, FourLand would need to develop expertise across the wide range of relevant disciplines and technologies. For example, it would need to develop the protocols and infrastructure for handling fissile materials, including more enriched fuels for some options — an area where it would have little or no experience. Were it to opt for an SMR design that generated a more exotic SNF, it could take a lead role internationally in developing the specific DGR concepts and design solutions required. This could include, for example, the development of deep borehole disposal, perhaps at dispersed locations that allow flexibility with respect to the large number of SMR sites envisaged.

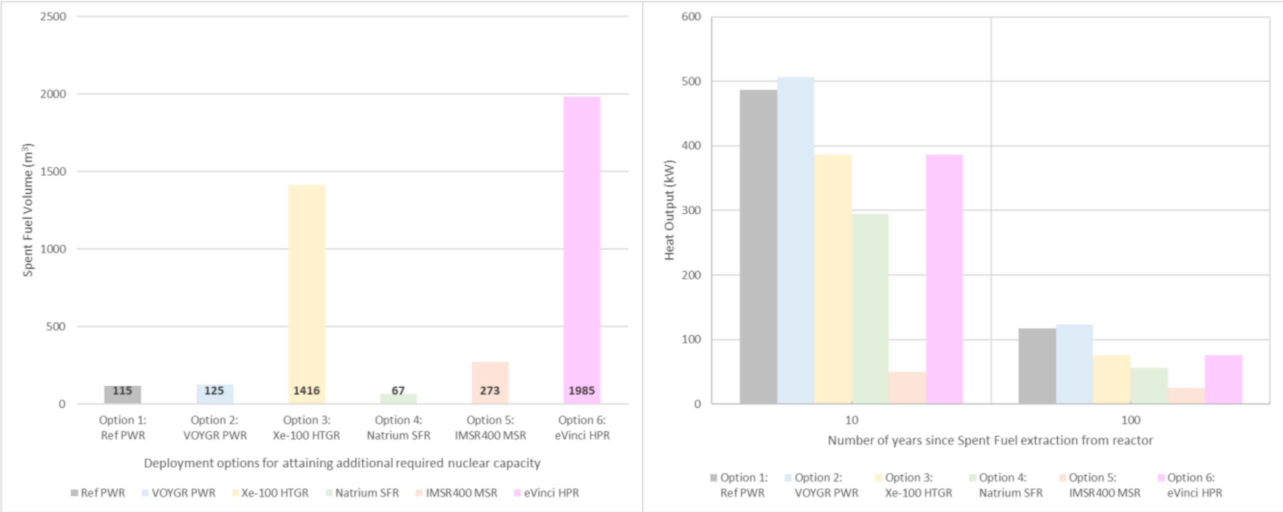

Figure 11: SNF Volume generated by FiveLand over a 60-year period, using different deployment options – either a Reference PWR, or different SMR designs, to provide new nuclear capacity; and a simplified (heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment) view of total heat output of FiveLand's SNF inventory assuming the same deployment options over a 60-year period.

The profile of FiveLand is similar to FourLand, but with a less ambitious nuclear roll-out plan, as shown in the identical trend between Figure 10 and Figure 11, which differ only in scale. The down-scaling results in a strong driver for collaboration: as well as expecting to use an off-the-shelf SMR design, and FiveLand's limited RWM requirements, existing disposal competence, and capacity, are more likely to push it towards an MNR rather than developing its own DGR. Developing a DGR for only 67–125 m^3 of SNF from Natrium SMR units, Reference PWRs or VOYGR Modules is unlikely to be cost-effective. In the type of shared European MNR solutions investigated by ERDO, these volumes would likely be a minor fraction of the total MNR inventory. In such a scenario, FiveLand might be expected to be a minor player in reactor or infrastructure technology development and, indeed, a minor participant in an MNR project. For these reasons, FiveLand, as a service user, would also be likely to have an interest in any commercial MNR services that come available. It would also be especially interested in any cradle-to-grave solution, or SNF take-back service, which might be offered by an SMR vendor.

A comparison of FourLand and FiveLand SNF inventory decay heat values leads to the same conclusion. A commonly cited figure for the KBS-3 geological disposal concept limits the power output for each waste package ('disposal container') to 1.7 kW [52]. On this basis alone (i.e., not accounting for any other metrics), the FiveLand VOYGR Module scenario (maximum heat output, with a total SNF inventory decay heat of 500 kW at 10 years) would require ~300 waste packages, compared to only 15 for the FiveLand IMSR400 scenario (minimum heat output, with a total SNF inventory decay heat of 25 kW). Whilst these values represent entirely simplified scenarios, dealing with 15 waste packages would be significantly more manageable for FiveLand, making a small and efficient deep borehole disposal programme (if considered technically feasible and accepted as safe by regulators) much more realistic, and negating the need to fit in with more complicated waste packaging requirements and more constrained timeframes that would likely be involved in a shared MNR project.

Minimising the number of waste packages for disposal above anything else would provide FiveLand with more strategic flexibility. However, taking advantage of this flexibility would require further investigation to determine whether the ILW generated by the Natrium SMR (with a generation rate of approximately 39% of the SNF generation rate) could be processed to enable disposal in a NSDF, shallow vault or shaft facilities, or be manageable using boreholes. Otherwise, the number of waste packages requiring disposal in a DGR would increase.

5.5.2. Upstream implications: storage and transport

Without existing nuclear power, FourLand would need to invest in the infrastructure required to support commercial reactor operation, such as fresh fuel transport and SNF handling, storage, transport and processing. For these activities, regulations may make it easier to use established norms and benefit from experience acquired from countries with established nuclear programmes. However, the degree of RD&D investment in this area may be similar, whether commercially proven technologies or only more ‘research-proven’ technologies are used.

It is conceivable that FiveLand would essentially be a consumer of off-the-shelf and imported technologies and solutions. This would also apply to upstream aspects of its RWM programme. For example, commercially available storage solutions would be used, and it might be expected that transport services would be contracted in, as required (e.g., to move SNF to an MNR). This also has an impact on the level and range of expertise on disposal technologies that FiveLand might wish to, or need to develop. While some specific technologies might be available in national specialist organisations (e.g., Australia is similar in profile to FiveLand, but is the home of ANSTO and its development of the Synroc process and wasteform), it seems unlikely that FiveLand would possess all the expertise needed to mount a national DGR programme. This could make a dual-track approach challenging – or at least necessitate significant additional effort.

However, should FiveLand be a highly technologically developed country, with nuclear RD&D experience, it might see opportunities to direct its industrial know-how towards the nuclear industry. For example, there may be certain niche areas of disposal system development solutions, such as packaging for a specific type of non-LWR SNF, or the implementation of deep borehole disposal concepts, which would make investment towards developing a world- or region-leading capability sufficiently attractive.

5.5.3. Upstream implications: fuel fabrication and SNF processing

Whilst FiveLand is unlikely to be involved in either fresh fuel fabrication or SNF processing, the same is not necessarily true of FourLand, given its large-scale commitment to nuclear power.

The early adoption of a TRISO-fuelled SMR could provide an opportunity for FourLand to become a leader in the TRISO fuel cycle. For example, developing and hosting a TRISO fuel fabrication facility, such as X-Energy’s TF3 [39], could enable the country to become a self-sufficient expert in this niche, enabling it also to become a vendor and exporter of nuclear technology.

Investing heavily in fuel cycle capacity and facilities, which could be purchased from other countries, could provide strategic benefit. For example, in contrast to FiveLand’s cautious, incremental approach to deploying nuclear capacity, FourLand is more likely to be interested in ‘closing the fuel cycle’ through the reprocessing of SNF, thereby improving its energy security. Nevertheless, the challenges and upstream financing involved in reprocessing are significant.

In any case, an investment into nuclear on a large scale may make necessarily enormous, investments into becoming a leader in a commercially unproven technology unattractive.

5.6. Conclusions and Considerations for Nuclear and Non-nuclear Nations

5.6.1. Operational and Decommissioning Waste

The implications for existing national RWM and disposal programmes of having to accept SMR operational and decommissioning LLW and ILW are relatively small. Such wastes only become an issue for new nuclear programmes and, although existing graphite wastes remain a problematic issue, they generally do not represent difficulties that are new to the field of RWM. Consequently, the primary issues for consideration are focussed on the management and disposal of SNF, which is the most differentiating in terms of potential impacts.

5.6.2. Technology Alignment and Inertia

As a result of inventory diversity and fuel cycle infrastructure drivers, nuclear nations may benefit greatly from selecting an SMR design which aligns with their existing commercial power production reactors (only the case of a Reference PWR has been considered in this study, but this could be equally valid for other examples, e.g., a HWR for Canada or a GCR for the UK). Costs associated with the development, construction and operation of new SNF handling, storage, processing and transport solutions could be a major disincentive, especially if any expertise and facilities for existing SNF types is generally more limited (e.g., in the case of ThreeLand). Furthermore, any negative impact of such an alignment policy on DGR size is likely to be less significant, given the existing commitment to a large DGR for OneLand and TwoLand, in particular.

OneLand is also more likely to use a nationally developed SMR design. This is because collaboration between OneLand and the SMR vendor would be relatively straightforward and would better ensure that the relevant front and back end fuel cycle facilities are available and capable of the required throughout.

Whilst disposal is unlikely to be an overwhelming driver here, as no DGR for SNF is currently operational, FiveLand is also likely to benefit from the deployment of SMR designs that are compatible with available SNF management solutions. Given its conservative nuclear deployment plans, FiveLand is likely to be more interested in an off-the-shelf SMR design, where it can benefit from the transfer of skills, expertise and experience.

FourLand's ambitious plans for a nuclear power programme mean that it is well positioned to become a global leader, or at least major player, for a specific reactor type, including specific design(s), fuel(s) and associated RWM infrastructure. From this perspective, the premium that would be required to transfer expertise and know-how from nuclear nations would make the cost of growing a national capability more attractive.

5.6.3. Deployment of Mixed Reactor Types

Each scenario assumes a wholesale commitment to a single reactor design. In reality, it is likely that a country would utilise different SMR designs for different use cases, e.g., the use of modular SMR plants to replace conventional reactors, with a targeted use of microreactor units for demand in rural communities.

FourLand's ambitious plans also make it more likely to invest in more than one reactor type. Aspects of waste inventory that impact potential DGR size are unlikely to be a significant driver for FourLand, as the requirement for a geological disposal solution is a step change, with impacts that subsume relatively small changes to DGR size. Here, the drivers will be highly country-specific, where the ambitious approach may make less-conventional SMR reactor types / designs more viable, given an appropriate and significant level of investment, should the case for those specific types / designs be particularly attractive.

Should any country opt to deploy a mix of reactor types, disposal waste package flexibility, i.e., using one waste package for disposing of SNF from any reactor, is likely to be a major RD&D focus. This is because designing, licensing, constructing and utilising a range of waste packages would be costly and time consuming. Further benefits are likely to be gained if this waste packaging solution could be applied to upstream RWM activities.

The management and disposal of a variety of SNF in combination is explored further in Section 6, but through the lens of different MNR participants, rather than of a national programme deploying a range of reactor types.

5.6.4. Reprocessing

The reference case for the analysis in our study is a once-through fuel cycle, mirroring the baseline assumption for down-selected SMR designs. However, the benefits and challenges associated with reprocessing of SNF have been considered throughout discussions in Section 5.4 and Section 5.5, most notably in association with SNF from the TRISO-fuelled Xe-100 and eVinci. The large volume generation rates involved could make the establishment of a (re-)processing capability viable, should a significant commitment to TRISO-fuelled SMRs be actioned.

Overall, OneLand is best positioned to build on the existing nuclear skills, expertise and facilities it has available in order to establish a reprocessing capability. FourLand may also be well positioned to establish a reprocessing capability to support its ambitious nuclear power roll-out plans, given a large investment into nuclear infrastructure will be required. However, reprocessing for FourLand's inventory alone is unlikely be economically justified and reprocessing for commercial purposes, e.g., offering these services to countries with similar SNF types, may be an option for providing income in the future.

However, reprocessing facilities are expensive as the experience in France, UK and Japan has shown. The French La Hague facility, including a fabrication facility for recycled fuel, was estimated to cost ~$18 billion in 2006 USD. The UK THORP facility was estimated to cost ~$6.7 billion in 2007 USD, although there appears to be more uncertainty over this value. The Japanese Rokkasho facility was estimated to cost a total of $21 billion in 2007 USD, but is yet to operate, having been subject to twenty-three delays by the end of 2017. [53, 54]

Consequently, establishing a reprocessing facility would be a highly strategic decision and would likely be driven by securing fuel supply and closing the fuel cycle rather than potential savings of the order < $1 billion in disposal costs by minimising disposal footprint through volume reduction of TRISO SNF.

5.6.5. Excavated DGR Volume

OneLand and TwoLand are likely to have mature DGR implementation programmes that can readily absorb the additional wastes from even relatively large power capacity increases. Hence, there are no strong drivers towards opting for an MNR rather than a national DGR that arise specifically from the inclusion of SMRs, where an exception exists should niche solutions be available for specific SMR wastes that a large DGR programme would rather not include in their inventory. The impact of SNF volume, etc., on excavated DGR volume is also unlikely to be a significant driver on the selection of an SMR design for deployment, certainly for OneLand. However, based on the basic deployment scenarios investigated, it is hard to conceive of ThreeLand (and potentially TwoLand) opting for a TRISO-fuelled reactor without particularly strong drivers, and/or a strong commitment to, and investment in, TRISO SNF pebble processing to reduce the SNF volume for disposal.

5.6.6. Alternatives to a National Mined Repository

In contrast to OneLand, volume generation rate would be a strong driver for Fiveland, e.g., to optimise storage and disposal efficiently. FiveLand would be strongly motivated to: opt for low-volume generation SMRs; actively work towards collaborative MNR development; explore the potential for deep borehole disposal; and/or be responsive to market-led solutions, such as SMR vendor SNF take-back offers. It is also reasonable to assume that FiveLand would be most likely to embark on a nuclear power programme through the use of SMRs, rather than by building a single large conventional power plant, due to the potential for an incremental introduction of nuclear power. For any non-nuclear nation, noting the significant R&D still required to demonstrate safety and feasibility of such a concept, deep borehole disposal could serve as a complementary solution to a mined MNR that would allow more programmatic flexibility, shorter intermediate storage periods and an earlier start and end point for disposal operations.

5.6.7. Thermal Dilution and Co-Packaging

From a decay heat perspective, the range of options across categories of countries is considerable. As stated above, the commonly cited figure for the KBS-3 disposal method limits the power output for each waste package ('disposal container') to 1.7 kW [52].

For our OneLand VOYGR Module scenario, the total SNF inventory – a result 44 GWe of electrical power generated by Reference PWRs, and 2 GWe generated by VOYGR PWRs – has an associated decay heat of 27 MW (at a point 100 years after removal from the reactors, greatly simplifying the scenario by assuming that each reactor operates for 60 years and all SNF is removed from all reactors at the same point in time). If the KBS-3 disposal concept was adopted, using the specific design referenced above, OneLand would require almost 15,900 disposal containers. This is over 1,000 times the 15 disposal containers that would be required for the FiveLand IMSR400 scenario (a total inventory decay heat of 25 kW resulting from 0.2 GWe of electrical power, generated exclusively by IMSR400 MSRs) using the same assumptions and simplifications.

However, we can contrast this with the constraint imposed by SNF volume, given that we have also identified representative data for this. A KBS-3 disposal container (one of various designs available in the open literature) is reported to have an internal free volume, i.e., space for SNF, of 1.2 m^3 [55].

Applying this disposal container volume constraint to the OneLand VOYGR Module scenario results in a need for over 22,100 containers to dispose of approximately 26,500 m^3 of SNF. This is more than 230 times the number of disposal containers that would be required in the FiveLand IMSR400 scenario (almost 114 m^3 of SNF packaged into 95 disposal containers), assuming the same boundary conditions and simplifications. It should also be noted that, in both cases, we do not account for SNF or disposal container geometry when filling this internal free volume.

Therefore, for the specific boundary conditions and simplified scenarios considered here, SNF volume is the greater constraining factor. Hence, there could be potential benefit in co-disposal of different wastes when the actual characteristics of an inventory for disposal in an MNR are considered, i.e., significant scope for optimisation during MNR development.

Given their existing deployment of Reference PWRs, and their relatively high decay heat values, nuclear nations may see a driver in DGR thermal ‘dilution’. DGR strategies already incorporate the potential for emplacing SNF waste packages such that packages with a higher heat load are interspersed with those with a lower heat load. The same approach could be adopted by nuclear nations with both conventional reactor and SMR SNF, alternating the emplacement of higher heat-emitting Reference PWR SNF packages with lower heat-emitting SMR SNF packages in a given disposal area.

Whilst the heat output of unprocessed TRISO SNF (i.e., from the Xe-100 and eVinci) is estimated to be lower than that of a Reference PWR, this would introduce large amounts of graphite, complicating a DGR safety case. Thermal dilution of Reference PWR SNF packages with MSR SNF would be ideal, given it has the lowest estimated heat output. However, less is understood about the potential SNF-coolant salt wasteform, leading to similar safety issues.

Assuming that the square and hexagonal fuel assemblies could be packaged together, a further step could be the co-packaging of Reference PWR and Natrium SMR SNF, i.e., one or more Reference PWR fuel assembly and one or more Natrium SMR fuel assembly could be packaged and encapsulated in the same disposal container. Potentially, this could also aid the resolution of fissile material management concerns. If co-packaging of Reference PWR and Natrium SMR SNF were to be considered as a means of thermal dilution, thus allowing closer spacing, this would have to be balanced by criticality considerations. The higher fissile content expected for this co-packaging could potentially alleviate criticality safety issues associated with Natrium-only SNF waste packages.

Whilst any potential benefits require far more detailed analysis in the context of a specific nuclear fleet, thermal dilution and co-packaging also have the potential to introduce additional logistical complexities. Most notably, the time management of SNF packaging and disposal could be of concern, owing to the different ages of the reactors involved, the periodicity with which they are refuelled and their estimated operational end dates.

6 SMR Impacts on Multinational Repository Planning

As previously noted, the most challenging RWM task technical, economically and socially is the implementation of geological disposal in a DGR. As a result, there is growing interest in shared disposal solutions, including a multinational approach to DGR development and realisation, i.e., an MNR.

An MNR, as with any DGR, must be constructed and operated in line with best international standards, respecting nuclear safety, security, safeguards and other requirements. Such a facility would require continuous support of all its users for integrated policy, strategic and technical planning across the RWM lifecycle.

By exploring SMR deployment in the context of MNR development, we aim to determine:

1. How would the existence of multiple national programmes with SMRs influence the probability that one or more MNR's are implemented?
2. What are the technical impacts on the design and operation of an MNR that accepts radioactive waste from countries operating a variety of reactors?

The answers to the technical questions will depend on existing national RWM plans (including waste types and the timing of their arising), the basic design of the MNR, the constellation of user countries delivering radioactive waste to the MNR (including waste types and the timing of their arising), and the organisational structures leading to implementation of the MNR.

6.1. Multinational Repository Requirements

In its final state, once it has been closed, an MNR will be no different from a national DGR – both result in radioactive waste emplaced deep underground in the geosphere to ensure the isolation of the waste from the biosphere and its long-term containment using an EBS. However, the path towards realisation of a DGR by a single country, sited within its own borders for the disposal of its own radioactive waste inventory will be significantly different from a DGR implemented through a multinational collaborative approach. These differences can, generally, be considered in terms MNR requirements covering:

1. **The waste requiring disposal.** A national RWM programme is likely to have a relatively clear understanding of the waste inventory for disposal and some degree of visibility regarding future nuclear power deployment plans at the point of DGR design initiation. Contrastingly, an MNR is not only more likely to be required to accept a variety of different waste types at initiation, but it may also need to be sufficiently flexible to enable the waste inventory for disposal to be expanded over time, e.g., as more countries become involved. The waste inventory for disposal drives disposal concepts and waste packaging, and may bring additional needs regarding upstream activities, e.g., additional processing and conditioning facilities. This will place primarily technical requirements on an MNR.
2. **The schedule of waste arisings.** A national RWM programme must integrate the operational schedules of different waste generating facilities and any post-operational processing and storage needs but, for an MNR, multiple national RWM programmes must be integrated. The schedule of waste arisings drives the duration for which underground openings must be maintained and is closely linked to the requirements for upstream aspects prior to disposal, e.g., the availability of storage facilities. This will place technical and non-technical 'internal stakeholder' requirements on an MNR, i.e., to either accommodate, or request amendments to, MNR user planning arrangements.
3. **The siting strategy.** A national RWM programme could follow one of various siting strategies, overseen by one or more of its national regulatory bodies. The trend in most active national programmes is towards attracting volunteer host communities, within a broad framework of technical siting preferences or requirements. An MNR siting strategy in any democratic country is certain to follow the same approach, with the additional need for potential host communities to be happy with the concept of the repository accepting wastes from outside their own country. The siting process will inevitably involve stakeholders from multiple countries and must satisfy

multiple regulators and requirements outlined within multiple regulatory frameworks. Together with the allocation of MNR responsibilities and liabilities across different national governmental bodies this will place primarily non-technical 'external stakeholder' requirements on an MNR.

6.2. Multinational Repository Models

Whilst interest has been registered in many countries and there is progress towards shared RWM activities or implementing joint projects in some countries, there is currently no MNR programme around the world at this time, nor has any group of countries committed to collaboration on a specific MNR project. As a result, rather than analysing the impact of SMR designs on any one specific approach to MNR development, we aim to carry out a high-level assessment of the impact of introducing SMRs into a range of models for potential MNR programmes.

In Appendix 6: Multinational Repository Scenarios, four MNR models are defined. These are designed to be representative of how potential collaboration would likely come to fruition:

A. An MNR through partnership of a few countries currently without nuclear power or previous RWM experience ('new nuclear nations') agree to share a DGR. For example, given their interest in the use of SMRs as a means to deploy their first nuclear power capacity it could be envisioned that Norway, Denmark and Estonia decide to align strategy and collaborate.

B. An MNR through partnership of a mix of nuclear and non-nuclear nations with some shared or aligned interest agree to share a DGR. More than half the Member States of the EU have shown some interest in this option and ERDO is committed to exploring it in detail. Although membership of ERDO does not involve any commitment to sharing an MNR, it is reasonable to expect that the ERDO member nations would be interested in such a solution.

C. Given the lack of available SNF disposal options, and the high barriers to initiating a DGR programme, a business opportunity is identified by a specific SMR vendor. This vendor decides to fill this gap in the market by developing a DGR (in collaboration with a host country, likely the country in which the vendor is based) to offer a 'cradle-to-grave' solution for its clients. This would involve the vendor offering to take back all the SNF from any of its clients and disposing of it in this DGR, which effectively becomes an MNR.

D. A similar opportunity is identified by the government of specific country, which decides to fill the gap in the market by developing a DGR and offering it to client countries as a commercial SNF MNR. The South Australian State government has considered this option in the recent past, as have small Pacific islands some decades ago.

The impact of SMR deployment is then explored through eleven scenarios, which are detailed in Appendix 6: Multinational Repository Scenarios and summarised in Table 9. Specific countries that might collaborate to develop a specific model of MNR are suggested in Table 9. However, these are generally linked to ERDO and are purely indicative groupings to provide examples and do not imply that there are any current MNR development plans by any of the countries named. To maintain a generic approach for purposes of discussion, they are represented by data for one of the hypothetical countries defined in Section 5.

It is recognised that the fuel lifetime and/or refuelling schedules for different SMRs varies considerably and an MNR accepting SNF from a range of technologies would need to manage this. However, for the purposes of this study, it is assumed that an MNR has an associated encapsulation plant for SNF and sufficient surface storage capacity to act as a holding area for all the SNF requiring disposal, thereby allowing all user countries to ship SNF for final packaging and disposal at a time of their choice.

Table 10 shows the number of each type of reactor assumed in each of the eleven scenarios considered and Table 11 shows the resulting total SNF inventory volume and decay heat in each scenario. The SNF volume is also shown graphically in Figure 12.

Each scenario discussion analyses the outlook by considering the following key issues that are expected to impact MNR implementation:

- SNF disposability parameters: volume, heat output, fissile content and waste packaging;

- Research, Development & Demonstration requirements; and
- Upstream impacts.

Table 9: MNR scenarios defined across four MNR models, based on analysis presented in Appendix 6: Multinational Repository Scenarios. The example countries are named purely to illustrate the size and scope of typical nuclear power capacities, etc., not as a result of any involvement in this study, where Croatia and Slovenia are combined due to their single shared nuclear power plant.

<table>
<tr><th colspan="2">MNR Model</th><th>Example Countries (Representative Hypothetical Country)</th><th colspan="2">SMR Deployment Scenarios</th></tr>
<tr><td rowspan="2">A</td><td rowspan="2">New-nuclear Partner MNR Model</td><td rowspan="2">• Denmark (FiveLand)
• Norway (FiveLand)
• Estonia (FiveLand)</td><td>1</td><td>• All deploy Reference PWRs.</td></tr>
<tr><td>2</td><td>• All deploy VOYGR Modules.</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">ERDO Partner MNR Model</td><td rowspan="2">• Netherlands (TwoLand)
• Slovenia and Croatia combined (ThreeLand)
• Denmark (FiveLand)
• Norway (FiveLand)
• Italy (ThreeLand)
• Poland (FourLand)</td><td>3</td><td>• All deploy VOYGR Modules.</td></tr>
<tr><td>4</td><td>• TwoLand deploys Xe-100s.
• ThreeLand deploys Natrium SMRs.
• FourLand deploys IMSR400s
• FiveLand deploys eVincis.</td></tr>
<tr><td rowspan="5">C</td><td rowspan="5">Commercial Vendor Take-back MNR Model</td><td rowspan="5">• Host: SMR-dependent (OneLand, given SMR Vendor)
• Netherlands (TwofLand)
• Slovenia and Croatia combined (ThreeLand)
• Denmark (FiveLand)
• Norway (FiveLand)
• Italy (ThreeLand)
• Poland (FourLand)</td><td>5</td><td>• All deploy VOYGR Modules.</td></tr>
<tr><td>6</td><td>• All deploy Xe-100s.</td></tr>
<tr><td>7</td><td>• All deploy Natrium SMRs.</td></tr>
<tr><td>8</td><td>• All deploy IMSR400s.</td></tr>
<tr><td>9</td><td>• All deploy eVincis.</td></tr>
<tr><td rowspan="2">D</td><td rowspan="2">Commercial Disposal Service MNR Model</td><td rowspan="2">• Host: Dependent on interest (assume OneLand)
• Netherlands (TwoLand)
• Slovenia and Croatia combined (ThreeLand)
• Denmark (FiveLand)
• Norway (FiveLand)
• Italy (ThreeLand)
• Poland (FourLand)</td><td>10</td><td>• All deploy Reference PWRs.</td></tr>
<tr><td>11</td><td>• OneLand deploys VOYGR Module.
• TwoLand deploys Xe-100s.
• ThreeLand deploys Natrium SMRs.
• FourLand deploys IMSR400s.
• FiveLand deploys eVincis</td></tr>
</table>

Table 10: Number of each reactor design in each scenario in Table 9 (rounded up, so becomes less accurate for low nuclear capacity scenarios), with the total power contribution of that reactor design using Table 7 data (assuming that, although this is not the case for the example countries in Table 9, all current installed nuclear capacity is provided by conventional, large PWRs, represented by a Reference PWR).

MNR Model	MNR Scenario	Total (Installed + Required) Nuclear Generation Capacity (and Estimated Number of Reactors) by Reactor Type						
		Reference PWR	VOYGR PWR	Xe-100 HTGR	Natrium SFR	IMSR400 MSR	eVinci HPR	Total
A	1	0.6 GWe (1 Reactors)	-	-	-	-	-	0.6 GWe (1)
	2	-	0.6 GWe (8 Reactors)	-	-	-	-	0.6 GWe (8)
B	3	15 GWe (13 Reactors)	4.9 GWe (64 Reactors)	-	-	-	-	19.9 GWe (77)
	4	15 GWe (13 Reactors)	-	1 GWe (13 Reactors)	1 GWe (3 Reactors)	2.5 GWe (13 Reactors)	0.4 GWe (115 Reactors)	19.9 GWe (157)
C	5	59 GWe (51 Reactors)	6.9 GWe (90 Reactors)	-	-	-	-	65.9 GWe (141)
	6	59 GWe (51 Reactors)	-	6.9 GWe (84 Reactors)	-	-	-	65.9 GWe (135)
	7	59 GWe (51 Reactors)	-	-	6.9 GWe (20 Reactors)	-	-	65.9 GWe (71)
	8	59 GWe (51 Reactors)	-	-	-	6.9 GWe (36 Reactors)	-	65.9 GWe (87)
	9	59 GWe (51 Reactors)	-	-	-	-	6.9 GWe (1972 Reactors)	65.9 GWe (2023)
D	10	65.9 GWe (57 Reactors)	-	-	-	-	-	65.9 GWe (57)
	11	59 GWe (51 Reactors)	2 GWe (26 Reactors)	1 GWe (13 Reactors)	1 GWe (3 Reactors)	2.5 GWe (13 Reactors)	0.4 GWe (115 Reactors)	65.9 GWe (221)

Table 11: Total SNF volume generated and SNF Decay Heat at 10 and 100 years after discharge from the reactor for each MNR scenario in Table 9, assuming a reactor lifetime of 60 years for all reactors for normalisation purposes.

MNR Model	MNR Scenario	Total SNF Volume (m^3)	Total SNF Decay Heat @ 10 Years (kW)	Total SNF Decay Heat @ 100 Years (kW)
A	1	345	1,462	351
	2	374	1,519	371
B	3	11,680	48,947	11,812
	4	23,412	41,342	9,911
C	5	38,219	161,195	38,815
	6	82,765	157,055	37,183
	7	36,215	153,867	36,476
	8	43,315	145,455	35,416
	9	102,401	157,055	37,183
D	10	37,879	160,532	38,591
	11	49,952	153,590	36,913

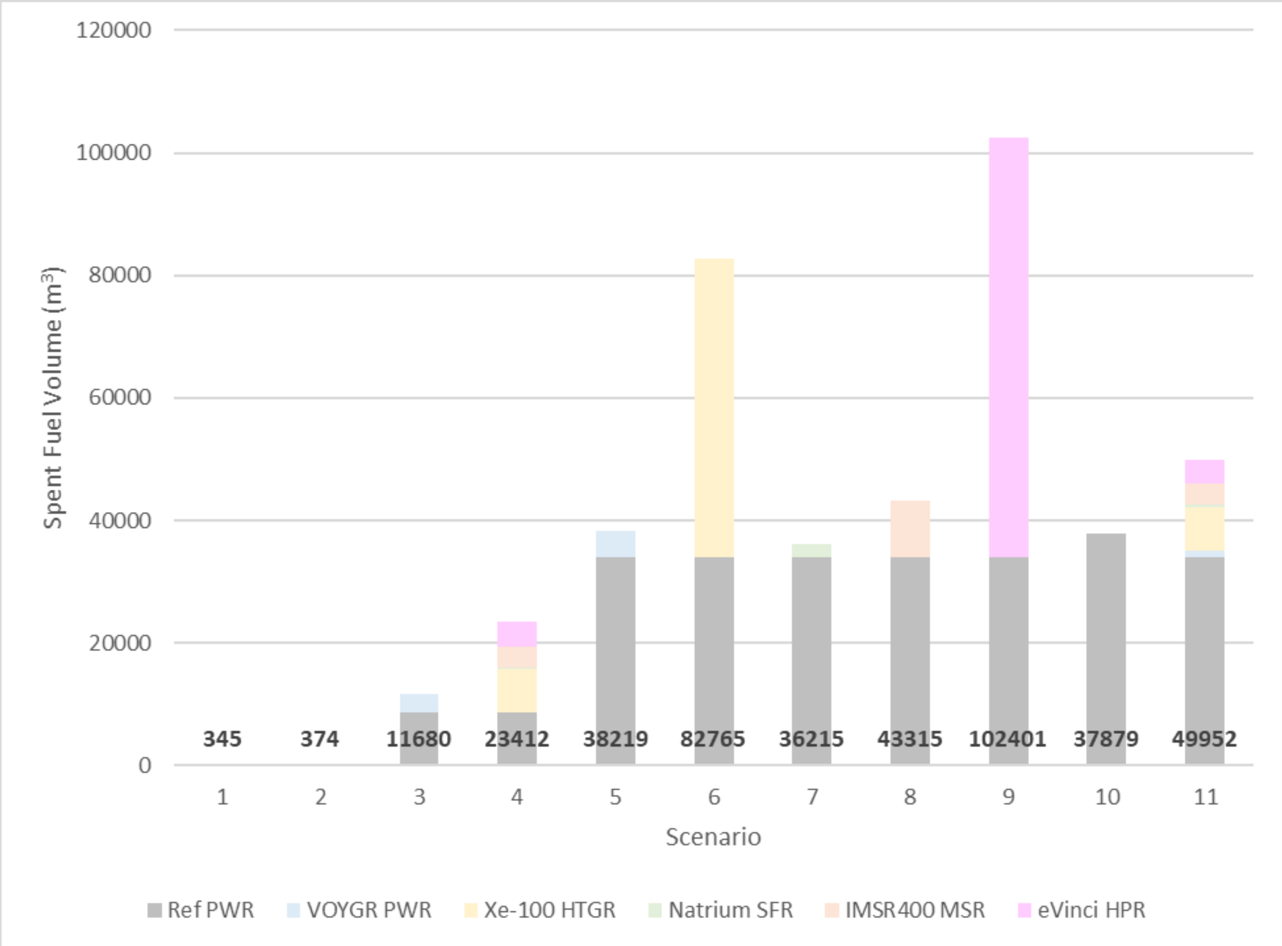

Figure 12: SNF volume generated in each scenario, where the value on each column shows the total SNF and the colours represent the Reference PWR and five SMR designs.

6.3. SMR Deployment for a New-nuclear Partner MNR (Model A)

In this MNR model, three countries currently without nuclear power, and with smaller power requirements, agree to share a repository:

- Denmark (represented by the profile and data of FiveLand)
- Norway (represented by the profile and data of FiveLand)
- Estonia (represented by the profile and data of FiveLand)

The scenarios for this model and the resulting technology mix are presented in Table 12.

Table 12: Technology mix for each scenario considered for MNR Model A.

Scenario for MNR Model A	**Reactor mix**, i.e., number of reactors and contribution to total scenario power capacity by SMR design according to following colour co-ordination:					
	Reference PWR	VOYGR PWR	Natrium SMR	Xe-100 HTGR	IMSR400 MSR	eVinci HPR
1	0.6 GWe from 1 Reactor					
2		0.6 GWe 8 Reactors				

6.3.1. Disposability

An MNR for the disposal of SNF generated in countries that are currently without nuclear capacity but are interested in a small amount of nuclear energy generation capacity, will inevitably be small in nature. Figure 13 shows that there is no significant difference between Scenarios A1 and A2, with the latter generating less than 10% more SNF volume than the former. For comparison, the higher figure is ~6% of the estimated 5,900 m^3 (conditioned, but unpackaged volume) of SNF expected to be disposed of in a UK DGR as a result of generation through 16 GWe of nuclear new build [56].

Figure 14 shows that there is little difference between the two scenarios in terms of heat output following irradiation, given a difference of 58 kW (4%) for the total SNF inventory of the Model A MNR at 10 years, with a difference of 19 kW (5%) at 100 years. As a result, the impact on pre-disposal management following extraction from the reactor through to the difference in heat generation after emplacement between the two scenarios is unlikely to be significant enough to impact technology choice for this MNR model.

The VOYGR Module fuel and SNF have enrichments and burnup that is very similar to the Reference PWR, so no additional precautions are likely to be required outside those currently in place and/or planned for storage, transport, packaging and disposal of the SNF in either scenario. No significant differences in the excavated volume of an MNR would therefore be expected to be required to account for either scenario.

The packaging options and EBS designs developed in existing national disposal concepts for conventional PWR SNF would be equally applicable to VOYGR Module SNF, although the length of disposal containers could be smaller. Smaller containers could readily be accommodated in existing DGR concepts with little impact on space or volume compared to disposing of conventional PWR SNF. Consequently, there are unlikely to be major differences in design or dimensions of an MNR between the scenarios.

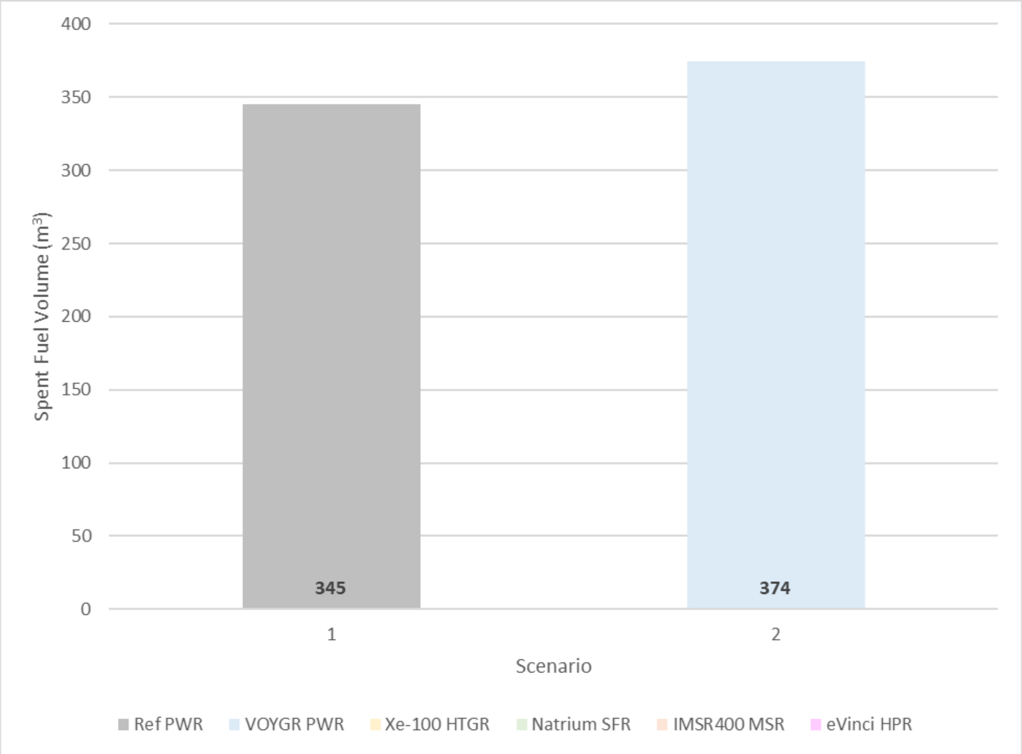

Figure 13: SNF volume generated in scenarios A1 and A2, where the value on each column shows the total SNF and the colours represent the Reference PWR and five SMR designs.

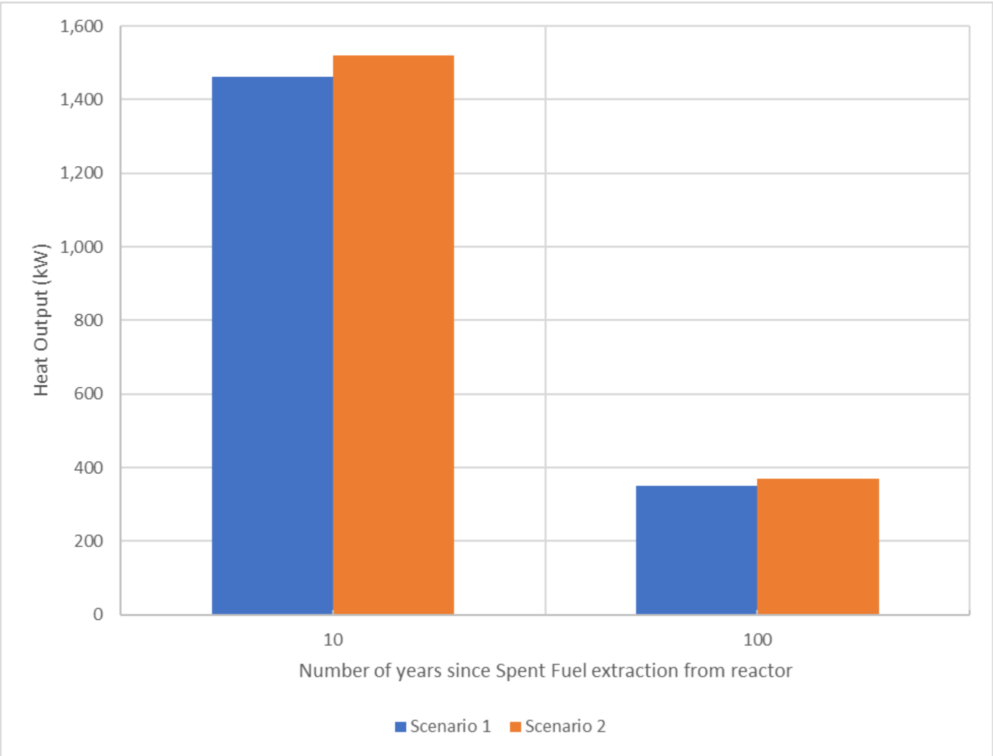

Figure 14: Total heat output of total SNF inventory volume generated in scenarios A1 and A2, assuming the same deployment options over a 60-year period (where heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment).

6.3.2. Research, Development and Demonstration

This is unlikely to be a major concern. For scenario A2, evaluations would be required of the different container dimensions, fission product inventories, thermal characteristics and contents of fissionable material and their impacts on repository design. Overall, it is expected that there would be only limited requirement for DGR concept and design adaptations or safety case development, beyond what is already required for PWR SNF disposal.

6.3.3. Upstream

Both scenarios involve similar technologies – PWRs – one involves a conventional PWR and the other involves eight SMRs. Therefore, the MNR partners open up the potential for much wider collaboration than only MNR development. It is feasible that the countries involved could work together on every upstream activity, sharing various facilities. With a well thought out strategy, this could be done in such a way that skills and expertise in different areas were built by each of the countries, sharing them with one another in an efficient approach.

The key difference between scenario A2 and A1 is the eight-fold increase in reactor units required to generate the same amount of power. A greater number of reactors – in this case eight, would likely involve a significantly larger, likely more complex and potentially less efficient transport network to service the MNR, with more waste packages being transported per GWe-year than for the single Reference PWR required for scenario A1.

A greater number of reactors also likely means a less efficient approach to the decommissioning of any given reactor or plant and its associated facilities. This is due to a need for either much more decommissioning equipment for parallel decommissioning operations or much more frequent transport of decommissioning equipment should SMRs be decommissioned in series. A parallel decommissioning approach could be hindered by the availability of expertise. Decommissioning several reactors one after another could have benefits through the application of learning from experience. However, it would increase decommissioning timescales significantly, possibly adding to RWM costs or increasing the time over which a DGR had to remain open for emplacement operations.

Overall, less efficient decommissioning will potentially increase the costs of labour, the costs of decommissioning technologies and the volumes of many of the lower-level waste streams associated with decommissioning.

However, it should be noted that NuScale propose to implement their VOYGR Modules as part of a larger VOYGR plant, using either four, six or twelve modules per plant. [57] In this case, the detrimental upstream aspects may be less of an issue, with more efficient decommissioning and potentially reduced operational challenges, given the eight VOYGR modules for scenario A2 could result in just two VOYGR plants. Such a solution would only be valid for specific use cases, i.e., where geographical distribution of the full power capacity is not required, and a series of energy generation hubs is acceptable.

6.4. SMR Deployment for an ERDO Partner MNR (Model B)

In this MNR model, the ERDO member countries collaborate to host a single MNR in one of their territories:

- Netherlands (represented by the profile and data of TwoLand)
- Slovenia and Croatia combined, with a single shared nuclear power plant (represented by the profile and data of ThreeLand)
- Denmark (represented by the profile and data of FiveLand)
- Norway (represented by the profile and data of FiveLand)
- Italy (represented by the profile and data of ThreeLand)
- Poland (represented by the profile and data of FourLand)

The scenarios for this model and the resulting technology mix are presented in Table 13.

Table 13: Technology mix for each scenario considered for MNR Model B.

Scenario for MNR Model B	**Reactor mix**, i.e., number of reactors and contribution to total scenario power capacity by SMR design according to following colour co-ordination:					
	Reference PWR	VOYGR PWR	Natrium SMR	Xe-100 HTGR	IMSR400 MSR	eVinci HPR
3	15 GWe from 13 Reactors	4.9 GWe from 64 Reactors				
4	15 GWe from 13 Reactors		1 GWe from 13 Reactors	1 GWe from 3 Reactors	2.5 GWe from 13 Reactors	0.4 GWe from 115 Reactors

6.4.1. Disposability

It can be seen from the Scenario B3 data in Figure 15 that a small amount of SMR SNF could be incorporated into an MNR inventory without a prohibitive impact on total SNF volume – the VOYGR Module deployment in question increasing the SNF volume by 35%, from 8,622 to 11,680 m^3. However, the deployment of mixed SMR designs in Scenario B4 results in almost an exact doubling in total SNF volume. In fact, the 2.5 GWe of IMSR400 power and 0.4 GWe of eVinci power in Scenario B4 each contribute more SNF volume than the 4.9 GWe of VOYGR Module power in Scenario B3.

Not shown in Figure 16 is the heat output of the committed SNF from the Reference PWRs alone; this is 36,540 kW at 10 years. Hence, raising the total heat output by 34% to 48,947 kW through the deployment of sixty-four VOYGR Modules is also unlikely to have a prohibitively significant impact on the required excavated MNR volume. In Scenario B4, the lower heat output of all the non-PWR SMR designs implies that the total Scenario B3 inventory generates 18% more thermal power than the total Scenario B4 inventory 10 years after extraction from the reactors, increasing to 19% at 100 years.

As noted above, VOYGR fuel and SNF enrichment and burnup are close to those of the Reference PWR, so only limited additional precautions are likely to be required in Scenario B3 apart from those currently in place and/or planned for storage, transport, packaging and disposal of the SNF. Accordingly, no significant differences in the footprint of an MNR would be expected to be required.

For scenario B4, however, the inclusion of the non-PWR SMRs must be considered carefully – especially the Natrium SFRs, given the higher fissile content of the SNF. Given the scale of commitment to the Natrium SFR, with three reactors providing only 1 GWe of capacity, the additional fissile material is, in the wider context, not likely to be significant when considered as a portion of the overall SNF inventory for disposal. However, the loading of SNF assemblies into individual disposal canisters could be an issue, as the sensitivity analysis performed in [34] found that none of the canister loadings of SFR SNF assemblies that were studied was likely to be acceptable from a criticality safety perspective. This is because the ~fifteen-fold increase in fissile concentration over the acceptable limit means that SFR SNF packaging assemblies would involve splitting one fuel assembly across up to four disposal canisters (conservatively assuming a loading of four Reference PWR fuel assemblies per disposal canister, in line with the Posiva approach [58]), resulting in up to a quadrupling in the Natrium SFR SNF contribution to packaged volume. In Scenario B4, this four-fold increase in Natrium SFR SNF volume would only increase the total SNF packaged volume by 1,000 m^3 – a large amount, but at only 4%, a value unlikely to be of significant impact.

As for Scenarios A1 and A2, packaging options and EBS designs developed in existing national disposal concepts for conventional PWR fuels would be equally applicable to VOYGR Module SNF and, for Scenario B3, there are unlikely to be major differences in design or dimensions of an MNR.

However, for Scenario B4, all of the complexities associated with unconventional SNF noted in Section 5 and Appendix 4: Down-selected SMR Design Waste Data & Information apply. Each of the issues noted, e.g., the lack of an established TRISO SNF processing solution, the lack of molten salt fuel-coolant waste packaging precedent, would need to be addressed by the country deploying the exotic SMR design in question.

A key difficulty from a disposability perspective is the disposal of many types of SNF in one single facility, for which significant RD&D would be required.

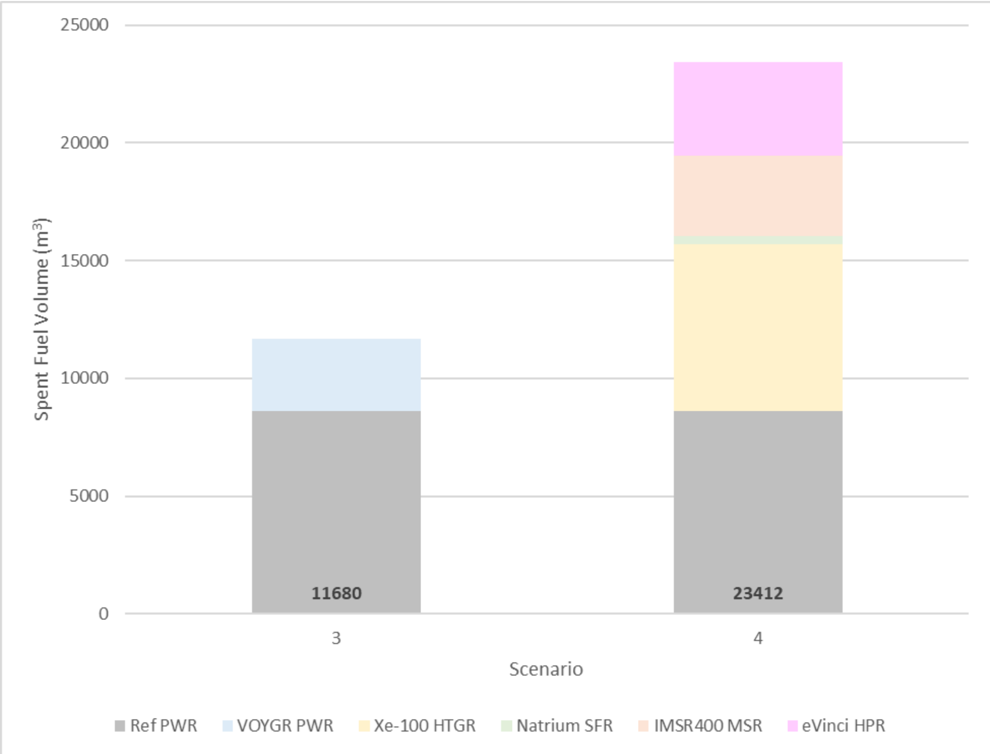

Figure 15: SNF volume generated in scenarios B3 and B4, where the value on each column shows the total SNF and the colours represent the Reference PWR and five SMR designs.

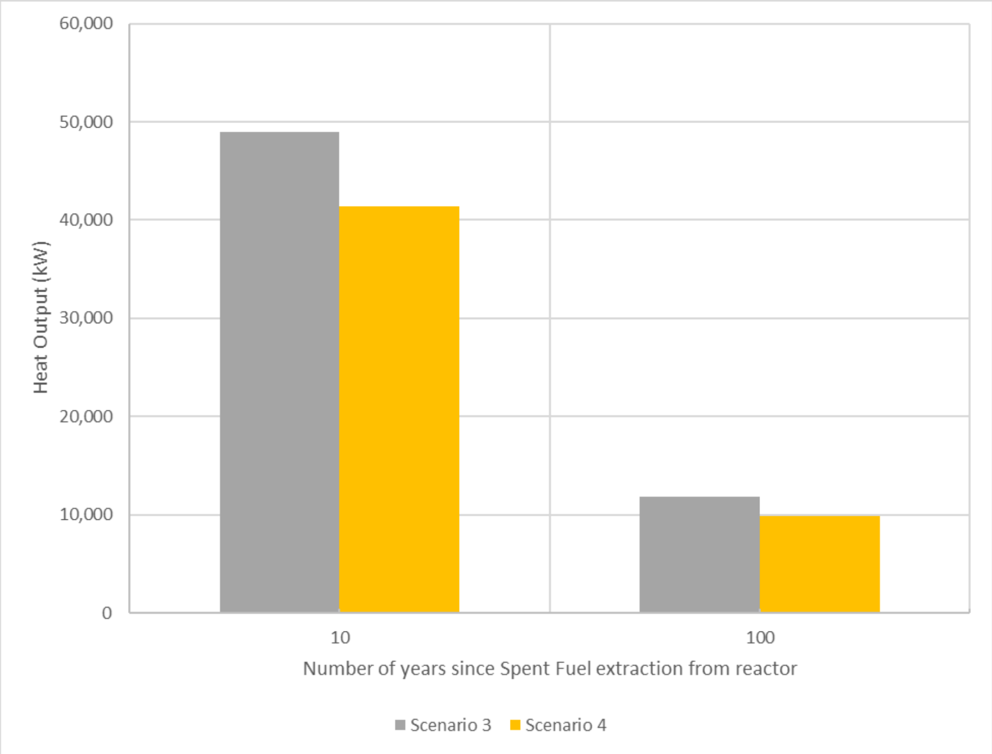

Figure 16: Total heat output of total SNF inventory volume generated in scenarios B3 and B4, assuming the same deployment options over a 60-year period (where heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment).

6.4.2. Research, Development and Demonstration

As for Scenarios A1 and A2, RD&D is unlikely to be a major concern for Scenario B3. Evaluations would be required on the different container dimensions, fission product inventories, thermal characteristics and contents of fissionable material (different burnups) and their impacts on repository design. Overall, it is expected that there would be only limited requirement for MNR concept and design adaptations or safety case development beyond what is already required for disposal of PWR SNF.

A mixed SNF repository, as assumed in Scenario B4 would have distinct requirements from a safety case perspective, which would require significant research. However, it is not unfeasible that this could be carried out, as current DGR programmes assume the disposal of various waste types, including different SNFs. Hence, a major area of RD&D for Scenario B4 would almost certainly be a multi-purpose disposal container that could be used to dispose of all the types of SNF in question. The use of a variety of disposal containers would require versatile equipment capable of handling different types of waste package, which would inevitably become expensive to construct and more challenging to operate. Alternatively, the use of different disposal 'fields' within a single MNR could be explored. There is precedent for this in the way that many geological disposal programmes generally assume that ILW and SNF will be disposed of in different parts of a repository, but with shared common equipment.

The requirement for disposal of such a wide variety of types of SNF in Scenario B4 opens the potential for further RD&D in terms of disposing of other components. The dimensions of the removeable IMSR400 and eVinci cores are not known. However, they appear to be similar in size to existing PWR SNF disposal containers or small fuel transport casks. Hence, RD&D could be conducted by the countries deploying these SMRs to determine the feasibility of using a similar EBS configuration as is widely envisioned for PWR SNF canister disposal, e.g., emplacement in a disposal hole in the floor of an MNR disposal tunnel, for the disposal of removeable SMR cores.

6.4.3. Upstream

The strategic benefits available to countries working towards an MNR in a partnership approach noted in Section 6.3.3 apply equally for Scenario B3. However, the exact opposite is true for Scenario B4, where the use of very different technologies means that the possibility for upstream collaboration is minimal and upstream challenges will likely be addressed on a country-by-country basis. This is further compounded by the number of reactors involved. Managing the SNF from 77 VOYGR Modules of a common design will be challenging, but Scenario B4 assumes that there will be 144 SMRs – across four different designs, in addition to 13 Reference PWRs.

Due to the lack of upstream alignment potential, the different SMR design refuelling patterns would be a concern to be addressed by each country individually. Clear boundary conditions for the MNR programme would need to be defined early on. This would ensure that the problems that would, and would not, be solved through the MNR programme are established so as to provide each country's RWM programme with a common end point towards which it would need to work (e.g., the surface infrastructure required for storage of waste packages at the MNR site whilst awaiting emplacement). The need for RWM programmes across the MNR partner countries to be fully integrated could become a significant challenge, given the different licensing regimes and regulatory requirements, along with other difficulties such as language and terminology.

6.5. SMR Deployment for a Commercial Vendor Take-back MNR (Model C)

In this MNR model, an SMR vendor develops a DGR for waste from its host-nation, in addition to any waste from users of its SMR design (here, assumed to be the ERDO member countries):

- **Host:** SMR-dependent (represented by the profile and data of OneLand)
- Netherlands (represented by the profile and data of TwoLand)
- Slovenia and Croatia combined, with a single shared nuclear power plant (represented by the profile and data of ThreeLand)
- Denmark (represented by the profile and data of FiveLand)
- Norway (represented by the profile and data of FiveLand)
- Italy (represented by the profile and data of ThreeLand)
- Poland (represented by the profile and data of FourLand)

The scenarios for this model and the resulting technology mix are presented in Table 14.

Table 14: Technology mix for each scenario considered for MNR Model C.

Scenario for MNR Model C	**Reactor mix**, i.e., number of reactors and contribution to total scenario power capacity by SMR design according to following colour co-ordination:					
	Reference PWR	VOYGR PWR	Natrium SMR	Xe-100 HTGR	IMSR400 MSR	eVinci HPR
5	59 GWe from 51 Reactors	6.9 GWe from 90 Reactors				
6	59 GWe from 51 Reactors		6.9 GWe from 84 Reactors			
7	59 GWe from 51 Reactors			6.9 GWe from 20 Reactors		
8	59 GWe from 51 Reactors				6.9 GWe from 36 Reactors	
9	59 GWe from 51 Reactors					6.9 GWe from 1972 Reactors

6.5.1. Disposability

Given the use of a single reactor type in each case, the discussion around disposability mirrors that in Section 5.4.1 entirely. The only difference here is that Section 5.4.1 considered one country deploying each reactor type and disposing of SNF in a national DGR, whereas here we have various countries each deploying the same reactor type and disposing of SNF in an MNR.

Hence, given that the contribution of the host, with its large existing nuclear power capacity, dominates the other MNR users, Figure 17 and Figure 18 are very similar to the charts in Figure 7, differing primarily in scale.

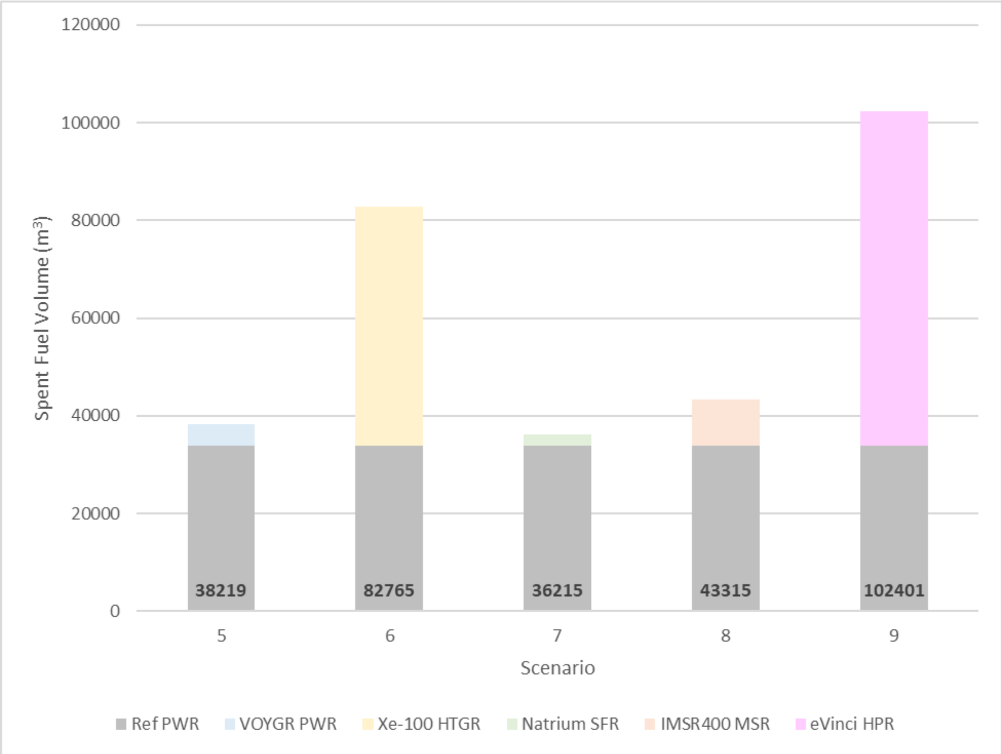

Figure 17: SNF volume generated in scenarios C5, C6, C7, C8 and C9, where the value on each column shows the total SNF and the colours represent the Reference PWR and five SMR designs.

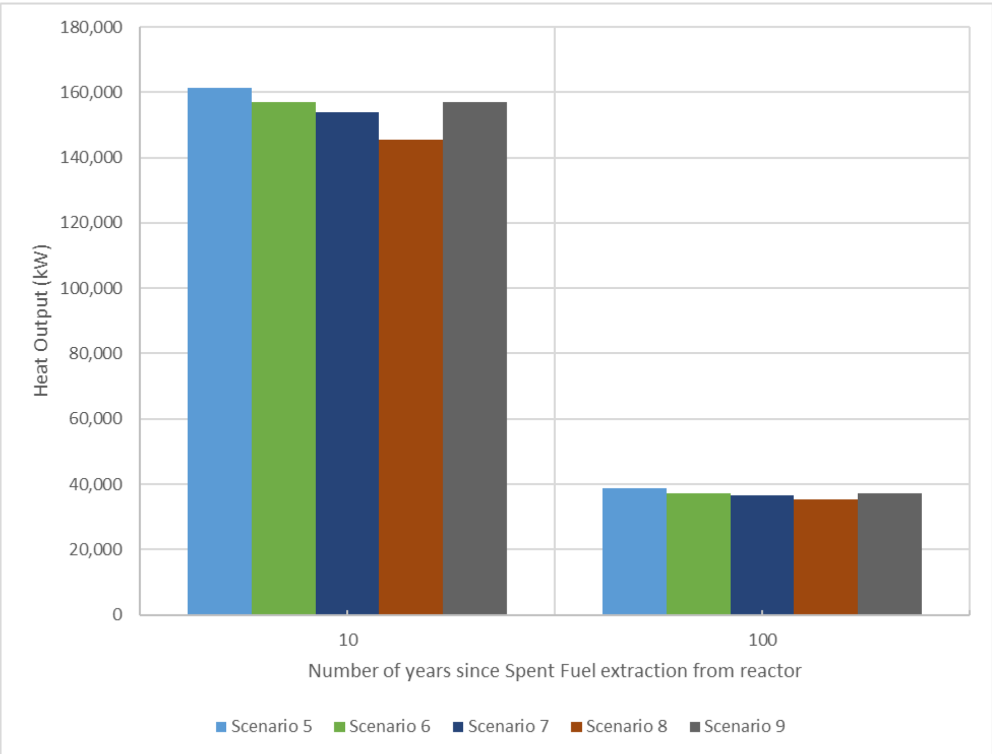

Figure 18: Total heat output of total SNF inventory volume generated in scenarios C5, C6, C7, C8 and C9, assuming the same deployment options over a 60-year period (where heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment).

6.5.2. Research, Development and Demonstration

The discussion in Section 5 and Appendix 4: Down-selected SMR Design Waste Data & Information establishes the need for significant RD&D on the packaging for Xe-100, IMSR400 and eVinci SNF and on the implications for MNR design, safety case and operations.

Each scenario represents an opportunity for research associated with bespoke post-operational processing, transport and disposal requirements related to each of the specific SMR technologies. This opportunity for shared research is a benefit of any MNR Model where user nations adopt the same SMR technology. The model outlined in this document assumes non-vendor MNR user nations operating in alignment with an identical technology and disposal in a single location. This will result in identical boundary conditions for multiple countries at the same time – a unique situation which may provide potential cost savings and efficiency benefits that are not always accessible even with only slight variations in boundary conditions.

In these scenarios, where non-vendor MNR user nations are adopting technology from a vendor, it would also be expected that those nations would benefit from research initiated by the vendor nation as MNR host. However, any nation-specific RD&D which is not required by the lead nation (e.g., due to differences in policy and/or regulatory requirements) would have to be carried out within the bounds of the vendor technology, potentially causing issues around capability and expertise, depending on the commercial arrangements in place.

6.5.3. Upstream

The commitment to a single SMR technology in each of the scenarios would be beneficial from an upstream perspective, as optimisation efforts would be focused on a single SNF form. However, this would be true for any scenario with commonality across new nuclear power generation plants, even the simple case for MNR Model A in Section 6.3.

The efficiency of decommissioning associated with a large number of reactor units is complicated in Scenarios C6 and C7, given the potential requirement for on-site stabilisation of activated graphite (Xe-100 in Scenario C6) and conditioning of sodium contaminated wastes (Natrium SMR in Scenario C7) prior to their transport to a central management facility if required.

Remote reactors will not have processing facilities, which either means the transport of unprocessed waste (which may mean maintaining the unprocessed waste in a liquid form in the case of the IMSR400). Alternatively, the inclusion of on-site processing facilities may increase the cost and bulk of a given SMR station, making it much less attractive. However, the latter is considered out of scope for this study.

Westinghouse plans to transport eVinci canisters back to a central factory prior to any decommissioning efforts. The complexities of such a transport mechanism are discussed in Section 5.4.2. However, this is complicated further in the MNR case, given that almost 2,000 units would need to be deployed to generate the 6.9 GWe required by the MNR partner countries. This scenario is unlikely, but highlights the potential challenge associated with the commercialisation of such a reactor type.

Even for more realistic scenarios, such as C6, C7 and C8, the management of SNF from 71 to 141 different reactors would be challenging. Beyond the supply chain and human resource difficulties, such a large number of reactors would pose difficulties for processing, packaging and transporting waste from reactors during operations and at the end of their life. Extra processing and packaging facilities would likely be required to handle the increased throughputs. This would be further complicated when the different life cycles of some SMRs are considered, e.g., the requirement for IMSR400 core replacement after ~7 years, the requirement for eVinci factory refurbishment after ~8 years.

As noted in Section 5.4.1, the large volume contribution of the TRISO-fuelled SMRs is due to the form factor of the TRISO pebbles, whereby reprocessing is a potential option that would result in a volume reduction of the SNF inventory for disposal. Whilst reprocessing is challenging and expensive, and unlikely to be implemented for repository footprint minimisation only (as noted in Section 5.6.4), OneLand's fuel cycle facilities and expertise would make it better placed than other nuclear nations in this regard. This could potentially open up the possibility of upstream synergies for the SMR vendor host nation, e.g., by extending the commercial MNR to upstream aspects, including use of a central reprocessing facility and potentially offering reprocessing services as part of the MNR package.

In this example, it might be assumed that the USA could act as MNR host, given many SMR vendors are US-based. In this hypothetical case, current US policy against SNF reprocessing could mean that the construction of a central reprocessing facility in the host nation would be problematic. However, this is considered further in the discussion around MNR Model D in Section 6.4.

In such a case, a shared benefit of this model could be the increased nuclear capability and expertise in an MNR user country such as FourLand – characterised by a current lack of nuclear power programme but with ambitions for a large nuclear power programme, e.g., through the hosting of reprocessing operations. With close partnership, the reprocessing-to-packaging-to-disposal lifecycle could be shared between MNR host and user nations, building up nuclear skills and expertise outside the host country. Such an approach would be more feasible through Scenario C5 – where a transport and reprocessing solution would need to account for only two closely-related forms of SNF.

6.6. SMR Deployment for a Commercial Disposal Service MNR (Model D)

In this MNR model, a specific country, represented by the profile and data of OneLand decides to fill a gap in the market by developing an MNR offering for potential client countries (here, assumed to be the ERDO member countries) as a commercial disposal service:

- **Host:** Dependent on interest (represented by the profile and data of OneLand)
- Netherlands (represented by the profile and data of TwoLand)
- Slovenia and Croatia combined, with a single shared nuclear power plant (represented by the profile and data of ThreeLand)
- Denmark (represented by the profile and data of FiveLand)
- Norway (represented by the profile and data of FiveLand)
- Italy (represented by the profile and data of ThreeLand)
- Poland (represented by the profile and data of FourLand)

The scenarios for this model and the resulting technology mix are presented in Table 15.

Table 15: Technology mix for each scenario considered for MNR Model D.

Scenario for MNR Model D	**Reactor mix**, i.e., number of reactors and contribution to total scenario power capacity by SMR design according to following colour co-ordination:					
	Reference PWR	VOYGR PWR	Natrium SMR	Xe-100 HTGR	IMSR400 MSR	eVinci HPR
10	65.9 GWe from 57 Reactors					
11	65.9 GWe from 57 Reactors	2 GWe from 26 Reactors	1 GWe from 13 Reactors	1 GWe from 3 Reactors	2.5 GWe from 13 Reactors	0.4 GWe from 115 Reactors

6.6.1. Disposability

Besides the addition of the more conventional SMR (the VOYGR Module), Scenario D11 is similar to Scenario B4, given the variety of technologies deployed, although Figure 19 and Figure 20 do show that Scenario D11 is dominated more by the host country's existing Reference PWR SNF commitment than in Scenario B4. The key difference here is that MNR Model B assumes partnership – ERDO member countries collaborating together on all aspects of a MNR, whereas MNR Model D assumes a host country providing a commercial service, an aspect which does not apply to disposability.

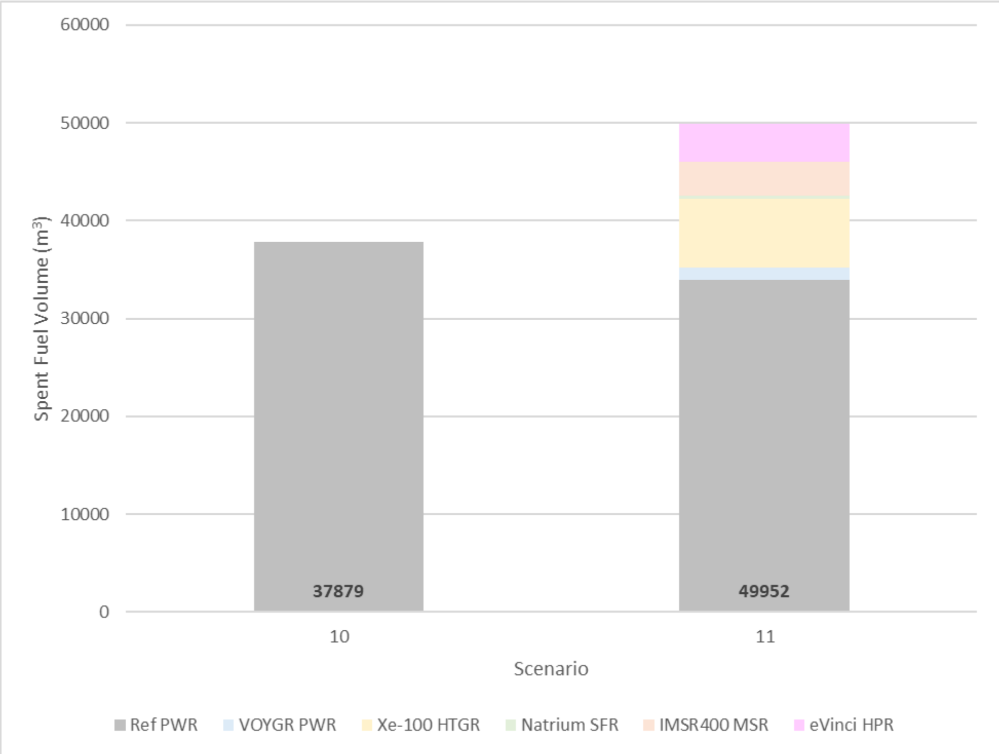

Figure 19: SNF volume generated in scenarios D10 and D11, where the value on each column shows the total SNF and the colours represent the Reference PWR and five SMR designs.

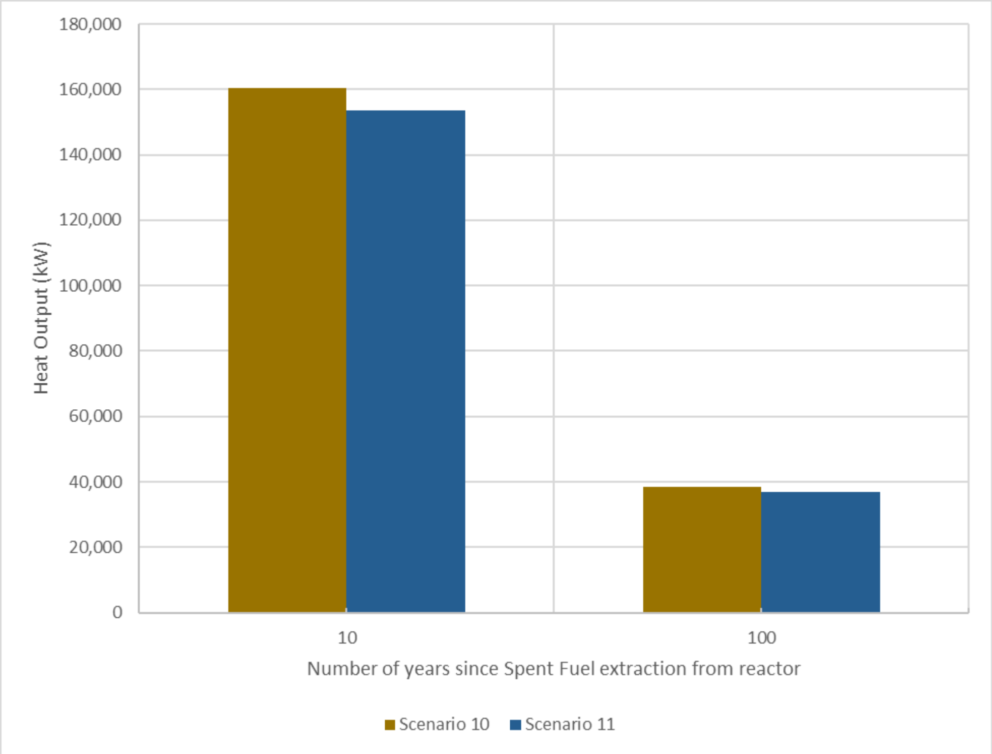

Figure 20: Total heat output of total SNF inventory volume generated in scenarios D10 and D11, assuming the same deployment options over a 60-year period (where heat output assumes that all nuclear capacity is deployed at the same time, and all of the SNF is generated at the same time, 60 years from the point of deployment).

6.6.2. Research, Development and Demonstration

By providing an MNR, the host country is able to determine whether it will accept all SNF (i.e., Scenario D11), or limit acceptance to only Reference PWR SNF (i.e., Scenario D10). The latter case means that no RD&D beyond that currently required for the various ongoing DGR programmes underway worldwide. The former case means that the same considerations as for Scenario B4 apply.

6.6.3. Upstream

From a technical perspective, the same challenges apply to Scenario D11 as for Scenario B4, where the potential synergies are focused instead on the commercial model at play.

As with MNR Model C, the degree of upstream flexibility depends on the precise boundary conditions of the commercial offering. Given that the host nation is not linked to any SMR design development, it is less likely that there would be a commercial benefit in offering upstream solutions. The host is more likely to offer an the MNR in isolation. Hence, RD&D is likely to be focused on disposal, as co-ordinated by the host country, rather than any other upstream aspects.

However, the option for further services would likely exist, given that many user countries would likely be willing to pay for the convenience of a host country-providing a cradle-to-grave solution. This level of interest is likely to be determined by each user countries' desire for native nuclear skills and expertise.

6.7. Technical Implications

As noted in Section 6.1, the additional MNR technical requirements (beyond those for a national DGR) are likely to be dominated by the potentially wide range of waste types requiring disposal and the schedule of waste arisings, both of which may also place additional boundary conditions on upstream activities. Reflecting on the eleven MNR scenarios in the context of the MNR requirements covered in Section 6.1, the following technical requirements and schedule management considerations can be considered. The key overarching question, however, is whether inclusion of

SMR wastes makes the implementation of an MNR significantly more difficult to manage technically and thus more difficult to achieve.

6.7.1. Expanded Technical Requirements

As discussed in Sections 4.8.1 and 5.6.1, the primary technical concern is disposal of SNF, rather than of operational and decommissioning wastes. For SNF, no disposability topic is necessarily worth consideration in isolation, and technical implications are likely to require a holistic approach.

Whilst heat output is unlikely to present an issue for disposal when considered alone, the 18% increase (Scenario B3 from Scenario B4) and 11% increase (Scenario C5 from Scenario C8) in total SNF heat output at 10 years could pose upstream waste management challenges. However, each scenario with a higher heat output involves PWR SNF, the more conventional technology. Hence, the lower heat output in exotic SMR deployment scenarios potentially presents an opportunity, rather than the deployment of PWR technologies presenting an issue: i.e., this does not present a barrier to MNR development.

The SNF volume generated in scenarios C5, C6, C7, C8 and C9 varies significantly, ranging from approximately 36,000 m^3 to 102,400 m^3, although the respective thermal powers are relatively close. The lowest estimated volume involves the widespread deployment of an SFR design (a reactor type not already deployed by any of the participant countries), reinforcing the general need for a holistic consideration of disposability topics and upstream considerations. However, there are two outliers in terms of SNF volume: Scenario C6 and Scenario C9, both of which involve the widespread deployment of TRISO-fuelled SMRs.

The disposal of unprocessed TRISO SNF pebbles could lead to a spatially constrained MNR footprint being exhausted quickly, particularly for the high SNF volumes arising in Scenario C9. Were the MNR programme to be small, e.g., a partnership of only a few countries with small inventories, accepting TRISO wastes from even a moderate user of TRISO-fuelled SMRs could become a major issue, causing a single disposability topic, SNF volume, to have an outsized impact. Should TRISO-fuelled SMRs be deployed in large numbers by MNR participants, upstream collaboration towards a solution for processing TRISO pebbles to separate SNF from other wastes (along with potential reprocessing), could become a very attractive option in order to minimise the volume of the inventory for disposal. This is also true of the MSR fuel-coolant salt, where a commercial processing and waste packaging solution could lead to comparatively lower SNF volumes, heat outputs and fissile material concerns (compared to conventional PWRs, TRISO-fuelled reactors and SFRs respectively). Hence, the alignment of designs across MNR participants, rather than alignment of designs with existing operational reactor types, is more conducive for MNR optimisation. Considering holistic upstream opportunities could therefore increase the feasibility of MNR development.

However, the alignment of technology could still pose a problem if the specific technology has undesirable characteristics. SNF disposability has been covered, but a key quantitative difference across scenarios is immediately visible from Table 10 – the number of reactors required. For the same power generation capacity, Scenario A2 sees an eight-fold increase in reactor units over Scenario A1; Scenario B4 would result in just over double the number of total reactors as for Scenario B5; and Scenario C9, albeit a theoretical rather than realistic deployment case, would involve an order of magnitude increase in reactor numbers over any other commercial MNR scenario. This has no direct technical implication for the design of an MNR (at least none not already covered by SNF volume) but could introduce a need for technical improvements and/or upscaling where upstream activities are concerned, e.g., as a result of challenges involving transport of reactors and SNF.

Given the large numbers of eVinci HPRs that would be required to achieve even a modest energy capacity, an MNR programme may look to dispose of the eVinci cores themselves, together with the generated SNF. It would seem feasible that a moderate adaptation of Reference PWR SNF packaging and associated DGR designs could potentially be used for direct disposal of eVinci cores. If only a few microreactors contribute to the MNR inventory, major technical issues would be unlikely.

An MNR with a range of different wastes is likely to be the most complex and costly when considering upstream, implementation and post-closure safety challenges. Complexity arises through the nature of managing a range of waste types and costs from the RD&D necessary to develop and demonstrate processes and equipment for everything from post-operational handling through to EBS design. Two scenarios explore this: Scenario B4 assumes disposal of SNF from a broad mix of SMRs through a partnered approach to MNR development, with Scenario D11 doing the same, but from a commercial MNR perspective. MNR Model D, a purely commercial venture, may have to handle a greater variety of wastes requiring disposal, because a core requirement of its likely business model is the ability to provide a disposal solution for a variety of clients, who may or may not be using a variety of technologies. This potential uncertainty highlights the importance of versatility for a commercial MNR design. Without an initial agreement with potential SMR users, and a vision for providing a disposal solution for many potential users, it would be useful for such an MNR developer to design a system that can handle a wide range of SMR wastes. This will involve additional up-front costs when compared to the adoption of an existing DGR design (and associated safety case, operational procedures etc.) from a DGR programme that has already undergone national licensing. The wider the range of SNF containers (with different dimensions, thermal characteristics and fissile material content), the longer it could take to complete the necessary RD&D and licensing procedures for MNR operation. Potential users of an MNR that intends to cater for a wide range of materials will need to consider whether it would be more cost-effective to concentrate on a national DGR than to wait for an MNR to be fully operational, or to have to contribute to technology development costs that they might otherwise not have to bear. This will depend on the MNR financing, and cost-sharing arrangements made.

The need for flexibility is not as essential for a the more constrained MNR Model C, as the SMR vendor is able to maintain a level of control, offering the disposal service only to users of the same SMR design. However, scheduling will still be a concern.

6.7.2. Schedule Management

To avoid a high degree of complexity, the MNR scenarios do not consider the rate at which MNR user countries might begin to deploy SMRs, the times at which those SMRs might start operations, or the fuel cycle requirements (e.g., refuelling), all of which would influence SNF disposal implementation timelines. However, the probable bounding cases affecting MNR design and development are likely to be (from most readily managed to most challenging):

1. All MNR users have a clear programme for SMR introduction, along with the timescale over which they will begin operations and have selected the specific designs they will use.
2. An MNR is close to operation (for committed wastes from the existing national nuclear power programmes of the users) before any SMR wastes are considered. Users then decide in a piecemeal fashion on SMR numbers, technologies, and construction and operation timescales.

The former case is most likely to occur for a shared MNR developed progressively by a long-standing partnership of users (e.g., the ERDO Association). The latter case is most likely to arise for a commercially developed MNR, but it does imply that the implementation of an operational commercial MNR would outpace the rate at which SMRs come online, which seems improbable, given the multidecade lead-times for a DGR project. Nevertheless, were the scenario to arise, any commercial MNR project would need to be prepared for the problems or additional work and resource-needs that could arise. Given the significant additional work that will be required, along with the uncertainties involved, the latter case is one that any MNR developer would wish to avoid.

In any case, it is likely that countries working together on MNR development will be motivated to use a small number of SMR technologies and attempt to optimise their SMR deployment scheduling, although this motivation will not necessarily be strong enough to override other factors in SMR choice. Strategic, commercial, and even political factors affecting choice are likely to be of primary concern. Common interests could, however, motivate the formation of an 'SMR user club' among

MNR participant countries. This would likely be influenced by multiple factors, an important one of which will be waste disposal. There is an opportunity here for:

a) SMR vendors to take a lead; and
b) SMR operators to address technical uncertainties jointly, pool resources and take full advantage of the potential benefits of MNR implementation.

6.8. Strategic Implications

Work by organisations such as the NEA implies that there is indeed an upsurge in interest regarding new nuclear power. As explored in Appendix 2: Global Interest in SMR Vendors & Designs, many countries are taking real steps towards SMR deployment, e.g., the recent down-selection of six SMR designs in the UK's 'Great British Nuclear' competition [59].

As shown in the MNR scenarios explored in this study (and the preceding representative national scenarios in Section 5), SMR deployment could lead to a situation in which there are hundreds of SMRs operating worldwide, in which case:

- Countries with a large nuclear programme could have a diverse portfolio of many tens of SMRs in addition to large, conventional reactors – each deployed to address specific use cases. Other countries might commit solely to SMRs, e.g., SMR-leaders, i.e., the first adopters of SMR technologies who plan to commit significantly.
- Within the global SMR user base, there are likely to be many nuclear newcomer nations – with little or no experience in managing radioactive wastes, and nations interested in only a small number of SMRs – generating insufficient resources for implementing a state-of-the-art DGR. Crossover between these specific groups is also likely.

In such a future global situation, many drivers towards the use of an MNR will be present, where the following are fertile contexts for MNR exploration:

- Countries with a substantial existing nuclear power capacity may have tailored their waste disposal programmes towards the specific types of reactors in operation. A requirement to include novel types of waste from some of the more 'exotic' SMR designs could create problems for the design and/or licensing of a national DGR. If the possibility of diverting these wastes to a state-of-the-art MNR is available, this could be a simpler and more cost-effective solution than DGR re-design efforts and/or regulatory re-engagement regarding an existing DGR design.
- Nuclear newcomer countries, i.e., those currently without nuclear power, especially those with limited requirements, are more likely to purchase SMRs if an MNR solution for disposal is available, either by the vendor country offering to take back waste (or at least requiring geological disposal) generated by the SMR fleet, or by the availability of an MNR elsewhere.
- Nuclear newcomer countries planning to deploy SMRs may, in addition, consider hosting an MNR to defray the costs of their planned nuclear power programme.
- Countries that back their own national vendors of SMRs (e.g., USA, UK, France) may consider adopting a national policy allowing the takeback of SMR-generated wastes to greatly enhance the commercial opportunities of these vendors.
- SMR vendors themselves, identifying the availability of an MNR as a route for attracting customers, might lobby their governments to adopt a 'waste takeback' policy, or might also encourage, or even directly help, a third country to offer an MNR solution.
- The widespread deployment of large numbers of SMRs in many countries across the world may be seen by competent commercial organisations as a major market opportunity for the provision of disposal services.

- Such a global distribution of SMRs might motivate international organisations concerned with nuclear security and safeguards to encourage initiatives to ensure that all SMR users have access to a state-of-the-art MNR, alleviating such concerns.

Whether genuine or perceived, the lack of a solution to '*the waste disposal problem*' has been an obstacle to the consolidation and expansion of the nuclear industry. If SMRs are successfully commercialised, their widespread deployment will further highlight the issue. Hence, SMR commercialisation offers a new opportunity for both SMR vendors and SMR users to solve this problem, providing a context for innovation and a new framework within which MNRs might be initiated.

Returning to the MNR models presented in Section 6.2, their definition emerged from the consideration of two overall frameworks for MNR development, driven by either vendor interests or the requirements of users of SMRs:

- An MNR may be implemented through partnership between various nations, e.g., a shared DGR, potentially including upstream facilities distributed between partner nations.
- An MNR may be implemented as a commercial endeavour, where one DGR is made available to multiple nations through contracting, where the specific boundary conditions regarding the commercial solution could extend upstream, or not.

6.8.1. Partnering Approach to MNR Implementation

This option is well documented, being first explicitly defined in the seminal 2004 IAEA report on Developing Multinational Radioactive Waste Repositories [60]. In the two decades since then, extensive work has been done on this option, including by the Arius and ERDO Associations. Implementing multinational repositories through partnering by smaller countries has also been supported indirectly by the European Union (EU) through its promotion of the potential benefits of regional solutions, i.e., facilities shared by contiguous or adjacent European Union (EU) Member States. The growing interest in SMRs may have direct impacts on this approach by, for example:

- expanding membership in ERDO, as further countries consider introducing nuclear power by deploying SMRs;
- encouraging the establishment of analogous organisations to ERDO in other global regions;
- incentivising potential MNR partners to coordinate their choice of SMR design(s);
- diversifying MNR concepts to include deep borehole solutions, which may be a disposal solution applicable for countries with only a few SMRs.

Collaboration with regard to a final disposal facility (i.e., an MNR, but also including every link in the chain of necessary upstream activities) will require some level of regulatory harmonisation. Regional collaboration in many other industries is carried out routinely, but the highly regulated nature of the nuclear sector means that work may be required up front to ensure that viable technical solutions are acceptable from a social and legal perspective. However, this is being discussed increasingly at the international level, and the need for harmonisation is a view shared by the IAEA, NEA and World Nuclear Association (WNA), with a recent publication noting that "increased international co-operation and global harmonisation of nuclear regulations is imperative" in order to benefit from the development and deployment of innovative technologies such as SMRs. [61]

6.8.2. Commercial Approach to MNR Implementation

Within the commercial MNR approach, two different contexts were explored through MNR Model definition in Section 6.2:

- An MNR where development is led by an SMR vendor that offers a 'cradle-to-grave' solution for its clients, including the vendor offering to take back all the SNF from any of its clients and disposing of it in its MNR, i.e., a Commercial Vendor Take-back MNR Model.

- An MNR where development is led by an organisation or country de-coupled from a nuclear power vendor as a commercial disposal service provider, i.e., a Commercial Disposal Service MNR Model.

Commercial Vendor Take-back MNR Model

In this model, an SMR vendor (or a group of SMR vendors) are attracted to being involved in MNR development from the potential marketing advantage of providing a solution for disposal of waste generated by their SMR design(s). Hence, the offer to take SNF back from customers periodically, and potentially any other wastes requiring geological disposal, either periodically or as they arise through decommissioning, would likely be central to the business model.

Historically, nuclear power plant vendors have had little interest in addressing waste disposal. Besides ensuring that upstream waste management for the materials used in their designs is at least feasible, RWM has not been part of the business models of nuclear power vendors. The short-sightedness of this approach has been recognised by, for example, Oak Ridge National Laboratory (ORNL) administrator Alvin Weinberg, who reflected that he "paid too little attention to the waste problem" and, if he could do things differently, he would "elevate waste disposal to the very top of ORNL's agenda". [62] This is a powerful and direct message for countries considering their first steps into nuclear power generation.

At the same time as reactor developers avoided the waste disposal issue, reactor users tended to concentrate on the immediate benefits of nuclear power, deferring the inevitable requirement for a permanent disposal solution. This has created the present situation, where almost every country with nuclear power is still struggling to convince its public of the feasibility of safe disposal, especially in the context of the justification for new nuclear power. Without a national or multinational solution, additional wastes and SNF generated by the operation and decommissioning of SMRs in these countries are likely to make this situation worse. Again, new nuclear countries should be aware of this and consider pressing for vendor SMR waste take-back as part of their SMR introduction package, even as only one option, e.g., using a 'dual track' approach recommended by ERDO [63].

Whilst there are certainly many challenges, SMR vendors may regard offering SMR waste take-back as an enormous opportunity. It is likely that offering waste take-back would be of great interest to many potential customers looking to expand their nuclear power portfolio with relative ease — simplifying political discussions, accelerating the achievement of strategic energy goals and relieving longer-term economic pressures. However, the step change would be the opening of a potentially large new market — countries that have not yet deployed nuclear power. For example, a recent survey by the African Nuclear Business Platform noted an emerging acceptance by the majority of African countries to considering the adoption of SMRs, but RWM was considered the second most critical factor concerning SMR deployment concerns (with safety in first place). [64] The provision of waste take-back would be of significant interest for new nuclear countries, as neither a national geological disposal programme, nor active involvement in MNR development would be required.

The problem for SMR vendors of course, is MNR development, and the potentially much more complicated upstream requirements when compared to development of a national DGR. The SMR vendor as MNR developer would need to find commercially attractive disposal solutions (with or without reprocessing) that it could offer to potential MNR users (those that do not already have their own disposal programme, facilities, etc., in addition to those following a dual track approach).

In a context where the country of SMR vendor origin, or potentially a customer country, has an effective disposal programme of its own, waste take-back within the national RWM and DGR programme(s) could be of interest, but there are several factors that would need to be dealt with, including:

1. the national policy and legislation of the country of SMR vendor origin must allow for, or be amended for, import of radioactive waste for disposal;

2. the legal and commercial mechanisms must be established allowing the SMR vendor to be either a partner in the national DGR or an additional user in what might be a state-owned facility; and
3. the socio-political and legal issues of accepting returned (and thus perceived as foreign) wastes into a national DGR.

If take-back were restricted to SNF, then the socio-political aspect might be more readily overcome, especially if the vendor country were also offering fuel recycling services. For example, France offers SNF recycling, where Orano has an interest in developing SMR SNF processing options, and the country will soon have an operational DGR. France is also entering the market as an SMR developer and possible SMR vendor with the EDF NUWARD PWR.

A plausible model might be found in the well-established solutions for research reactor SNF in research reactor vendor countries (e.g., USA, Russia). As of this time, no major issues regarding take-back procedures, transport or safety have been reported. However, today, it is hard to envisage any WMO that is developing a national DGR programme choosing to complicate its mission through the introduction of foreign wastes to its waste inventory. Nevertheless, it is conceivable that requests to accept returned wastes might come from above. Governments may wish to support their native reactor vendors, judge that their involvement could substantially reduce disposal costs for their native reactor operators or may have other motives such as minimising nuclear security and proliferation risks (both the USA and Russia have accepted the return of SNF from research reactors for this reason).

In the absence of governmental direction, a take-back solution would need to be a commercial venture driven and led by one or more SMR vendors. To be successful, an SMR vendor would need to be prepared to 'champion' MNR development, i.e., raise the concept in the public consciousness, present solutions to perceived objectors, work with regulators etc. Any SMR vendor taking on this role then risks tying their own SMR business to the realisation of an MNR and, should the latter be received poorly, the same is likely for the former. The country of origin for many SMR vendors at present is the USA. It is unlikely that a USA-based SMR vendor would be willing to take the issue forward themselves due to a lack of any existing reactor-to-centralised storage or reactor-to-DGR solutions for the existing USA waste inventory. If SMR vendors in the USA are interested in the take-back context, they would need to form relationships with other countries to manage SNF, again pointing towards SMR vendor collaboration.

Looking beyond the government of the country of SMR vendor origin, an SMR vendor may wish to collaborate with other MNR initiatives, or approach one of its customers to initiate an MNR programme for the purposes of SMR waste take-back and disposal.

Currently, there are no MNR programmes under development with which an SMR vendor could team for this purpose. However, if the current enthusiasm and activity in SMR development had been in place at the time of the 2016 South Australian MNR initiative [65], a context could be envisaged where SMR vendors would have been proactively supporting or informing the state government's option assessment. At the time, there was no potential end-user involvement in the MNR feasibility study. The situation today in Australia is evolving rapidly, with interest not only in introducing nuclear power generation with SMRs, but also in reassessing Australia's role in the whole nuclear fuel cycle.

In business and commercial terms, becoming involved as the prime developer of an MNR would be a major commitment for an SMR vendor company, taking it into technical areas with which it may not be familiar. Deciding whether this context is likely to result in a major expansion of business, or act simply as a distraction from the mainline business, will be difficult. The risks to an SMR vendor could be much reduced were MNR programme to exist already, even in an early state. For example, if the ERDO member nations had decided to develop an MNR in one of their territories, then the involvement of SMR vendors in design, financing and licensing could be attractive to the project participants and would have considerable attractions for the SMR vendor(s) themselves. However, the involvement of multiple SMR vendors would represent a shift from MNR Scenarios C5, C6, C7, C8 and C9 defined in Section 6.2 (SNF from one SMR design per MNR) towards Scenario C11 (SNF from multiple SMRs in one MNR), introducing the different technical challenges associated with such a mixed inventory for disposal, as outlined in Section 6.7.

As a first step towards a collaborative MNR programme, one or more SMR vendors – especially those with novel fuel cycles – may see benefit in building multinational user groups, i.e., customer organisations and/or governments. An initial goal might be for several SMR customers using the same design to cooperate on developing SNF conditioning and packaging approaches for disposal.

An SMR exporter with a variety of clients could team with another country or organisation with advanced disposal experience (e.g., Canada, Finland, Sweden, Switzerland) and offer to help its user group in developing a shared MNR in one of their countries. For example, the SMR vendor could partner with the commercial wing of a national WMO to offer an international service.

One way in which such a partnership could develop is for an SMR vendor to work with an established disposal company to offer highly localised solutions to a user country (e.g., for a remote off-grid SMR user) that could be uncoupled from a mainstream national RWM and/or DGR programme. If deep borehole disposal proves to be an appropriate solution for some types of SMR SNF, then this could be an attractive package, provided that on-site disposal approvals could be obtained.

The potential upsides for take-back and disposal services are clear, and the economic attractions of a commercial MNR alone could be sufficient to elicit interest in the initiation of a purely commercial disposal service, de-coupled from SMR vendors and designs.

Commercial Disposal Service MNR Model

A scenario can be conceived where a competent organisation sees a marketing opportunity for providing a global radioactive waste disposal service. A major study in Australia examined this option over 20 years ago and the South Australian state government took the analyses further in 2016, attempting to determine whether a feasible business case could be developed for such an MNR. [65] This is also an active area of work at the IAEA. In each case the focus is on large reactor wastes, but SMR-specific considerations include:

a) The potential customer base: *Is there a sufficient number of potential customer countries that seek solutions for waste that would require geological disposal?*

More than half of the countries with nuclear power have small programmes and equivalently small inventories of waste for disposal. Given the high cost of implementing a DGR in comparison to the lower cost of expanding a DGR, countries with small inventories would, proportionally, benefit most from an MNR. Should SMRs see wide deployment, it is likely that the number of countries interested in a modest fleet, generating relatively small inventories, would potentially grow significantly, given the versatility of SMRs. Hence, an increased interest in MNRs as an economic alternative to a small national DGR would be likely to emerge.

b) MNR interest: *Is there tangible evidence of countries expressing interest in an MNR solution?*

Global interest in MNRs was clear prior to the upsurge in SMR interest based on the number of countries that have been involved in MNR studies, initiatives, and proposals over many years. In Europe, around half of the national reports submitted to the European Commission under the EU Waste Directive [66] make some reference to multinational disposal or to 'dual track' approaches. The potential MNR user base would be expected to increase following any large-scale deployment of SMRs.

c) The potential MNR inventory size: *Would the current and future inventories for geological disposal in potential customer countries be sufficient to justify development of a common facility?*

The size of the market for a disposal service depends not only on the number of countries that might use the service, but also on the inventories of waste that might be require disposal. The most recent assessment of this was conducted by the South Australian Royal Commission. [67] The Royal

Commission excluded from its analysis potential clients that are major nuclear power users that will be constrained by national policies, laws to develop national solutions, or that have structured programmes leading to a national DGR (e.g., USA, France, UK). Despite these assumptions, the conclusion was that, were a disposal service to be available, then there could be an adequate inventory to justify the development of an MNR. These estimates included only plans for large reactors and, therefore, based on the analysis in the current study, it is assumed that widespread deployment of SMRs will result in the growth of the potential inventory for disposal.

d) The potential profitability: *What price might a customer country be willing to pay for the service provided?*

After establishing that there will be a sufficient number of countries with a sufficiently large, combined inventory to justify the feasibility of a disposal service, any service provider would also need to consider the economics, i.e., the provider must assess the price that the customer countries might be willing to pay. This is likely to vary based on many country-specific drivers and conditions which would require a full life cycle analysis, using a range of scenarios and assumptions. However, a key upstream component would likely be the estimated cost of storage prior to disposal, based on current management options and available technologies. A sub-component of this would be the costs avoided by delaying a decision around national DGR development, and the implementation of other interim management approaches. For countries with existing RWM and/or GDR programmes, the committed costs of existing facilities and/or long-term contracts with supply chain organisations would need to be factored in. Ultimately, however, market economics will be central, with the importance for any country depending on the price and schedule. Technical, societal, financial and political aspects all play a part here. The economic report in the South Australian study [67] looked in some depth at 'willingness to pay' for an MNR disposal service. One of its conclusions was that, for SNF and HLW, "the estimates derived when taking all these factors into account range from around USD1 million / tHM up to tens of millions of USD / tHM for countries which face steep cost penalties from a lack of credible waste management options for existing nuclear power plants."

The last consideration listed here, cost, is the most complex and most difficult to quantify. For existing power stations, if an operating nuclear power plant is in danger of being shut down because there is a lack of storage space for SNF in existing facilities, and political blockages prevent new stores being built, then the operator might be willing to pay a premium to ensure that its reactor can remain operational. If an MNR provides a credible disposal solution that allows a fleet of nuclear reactors to continue operation or is a requirement before new reactor construction is allowed, then this adds value to the service. For SMRs in newcomer countries, all four points – customer base, MNR interest, inventory size and potential profitability – will influence the economic case for interest in an MNR solution.

The broad conclusion to be drawn from these issues is that, even without the expected large-scale deployment of SMRs, there is a potential market opportunity for a provider of an MNR (and potential upstream activities and facilities), and this market opportunity may grow significantly, based on a shifting picture of global SMR deployment expectations.

Path Forward for a Commercial MNR

A commercial MNR model will be stimulated by either expansion by one or more SMR vendors, or by a market opportunity identified by one party, likely as a result of the potential expansion in global nuclear power capacity requirements. Offering an MNR solution to customers solves the most significant problem associated with an SMR vendor's business primary offering. For an independent MNR developer, linking with SMR vendors will likely provide access to skills, expertise and customers. How can such situations be encouraged?

Table 16 shows the strengths, weaknesses, opportunities and threats from the perspective of an SMR vendor considering offering a SNF take-back and disposal service, with disposal either in the country of SMR vendor origin or a customer country. Table 17 does the same from the perspective of a commercial MNR provider considering working together with one or more SMR vendors to tailor or extend its MNR concept to accommodate SMR SNF.

One promising path forward may be through encouraging SMR vendors to develop relationships with potential MNR providers, such as ERDO, and/or with WMOs offering DGR development services that could be transferred to other countries. This is a two-way process, and organisations such as ERDO should also be promoting discussions with SMR vendors. The overarching issue is that of MNR credibility: SMR vendors are only likely to expend resources on pursuing this approach should concrete MNR commitments surface.

In the current absence of any commercial MNR programme, there is no obvious opportunity for realising the advantages identified in Table 16 and Table 17. However, recognition that these advantages exist could be a further stimulus for SMR vendors to survey the international landscape for potential programmes, and raise the potential opportunities offered in their discussions with potential SMR user countries, at a national level.

Table 16: SWOT analysis for MNR development by SMR vendors.

Strengths	Weaknesses
• Highly marketable to both customers and international organisations concerned with nuclear safety. • Enhances global security. • Enhances corporate reputation, both at home and internationally.	• Requires acquisition of entirely new skill sets to enter geological disposal arena: this can be mitigated by an SMR-MNR partnership arrangement. • MNR host country likely to be difficult to identify in the next decade. • Dependent on success of national DGR programme.
Opportunities	**Threats**
• Attract clients by providing a full lifecycle service. • Develop business relationship with a fuel provider organisation. • Encourages development of ‘disposable’ designs for reactor components. • Potential business area in fuel cycle services if SNF reprocessing partner found. • Working with a potential MNR host country WMO.	• MNR development becomes too costly and threatens corporate finances. • Failure to find MNR solution damages corporate reputation.

Table 17: SWOT analysis for MNR development by potential commercial MNR providers.

Strengths	Weaknesses
• Extends the potential global inventory available to the operator, thus improving the commercial viability of the MNR. • Assisting with global security for the new global SMR regime will enhance corporate reputation at home and internationally.	• Some SMR waste types will require new or significantly adapted DGR concepts and designs. • Diversification across SNF types could negatively impact on unit costs of disposal.
Opportunities	**Threats**
• Working together with an SMR vendor will improve the marketability of both organisations. • For an MNR with national support (such as was intended for the South Australian initiative) links with SMR developers could become part of a comprehensive national fuel cycle services strategy.	• No significant threats identified.

7 Conclusions

7.1. Which SMR designs and reactor types are attracting most interest?

The growing interest in SMRs is manifesting into action, with strategic and medium- to long-term agreements being signed between developers and/or vendors of SMR technologies and potential customers. Based on these agreements and strategic partnerships, it appears likely that multiple different SMR types, through different SMR designs, will be deployed globally. This is a result of various drivers, many of which are country-specific.

Whilst this study identifies twenty-two particularly credible SMR designs, there are over 80 listed in the latest IAEA SMR Book and over 40 in the NEA SMR Dashboard, noting significant crossover between these sources. In general, there appears to be a greater interest in PWR technologies — for reasons explored in this study. However, there remains significant interest in many different SMR designs, ranging across a wide variety of generic reactor types, with a correspondingly wide range in potential SNF, operational wastes and decommissioning wastes.

It is extremely unlikely that even the most optimistic SMR deployment scenarios will be able to sustain the implementation of such a range of different SMR designs, even without consideration of the upscaling in factory production and supply chain support that would be required. However, even though most of these SMR designs will not be realised on a commercial level, no specific reactor type can be definitively ruled out at this time.

7.2. How will the management of radioactive wastes differ for the deployment of SMRs in comparison to more conventional, large reactors?

The waste streams from SMRs and conventional reactors currently operating are likely to be highly variable, including a high degree of variance between SMR designs. Some countries will have experience in managing these wastes, but others will not. No countries have industrial-level experience of handling molten salt fuel-coolant wastes generated by MSRs or activated sodium coolants from SFRs on a commercial scale and, for these wastes, experience with research reactors would need to be applied and existing facilities scaled up.

The activities required to manage waste from the point of extraction from the SMR systems discussed here (during refuelling, other operational activities, or during decommissioning) through to permanent disposal are well established for most wastes, although some problematic waste streams exist for which solutions are not currently in place. In some cases, consideration has been given to upstream activities by SMR vendors. However, these considerations are generally not detailed. Where they exist, there are a wide variety of upstream implementation assumptions made by SMR vendors, either as a requirement of the specific technology involved (e.g., SNF sodium cleansing), or as a selling point of the technology (e.g., the transport of the reactor unit to a central facility to avoid on-site refuelling and decommissioning).

The greater number and geographical distribution of reactors and/or power plants and/or sites involved with SMR deployment is likely to introduce new logistical challenges for any country (noting that in some cases SMRs may be used exclusively in a power plant arrangement requiring the same number of sites as conventional reactors, but this is unlikely to be the case for application by most countries). Similarly, the wider distribution and greater throughput required of an RWM transport infrastructure will present security and safeguards concerns. A key benefit of SMRs is the ability to generate nuclear power in off-grid areas without the need for a large team of highly skilled staff. However, the more an SMR user utilises these benefits, the more concern there is likely to be around securing the SMR units (and associated transport) and safeguarding the nuclear material contained at the sites (and during associated transport shipments).

Overall, a given SMR design may require the removal, addition, or adaptation of one or more upstream activities. Hence, this would need to be supported by relevant RD&D, development of skills and expertise, construction of facilities and regulatory engagement to arrange licensing. There are potential opportunities for simplifying the RWM landscape, through a move towards a more standardised approach to RWM, mirroring the modular nature of SMRs. However, existing concerns around security and safeguards will be heightened as a result of a required expansion of the RWM infrastructure.

7.3. What impact could SMR deployment have on a national RWM and/or DGR programme?

The implications of accepting SMR operational and decommissioning waste into a national RWM programme are likely to be small. New nuclear programmes may have some problems with these wastes, but none that they would not have to overcome if introducing certain conventional, large reactors. The exception here is a known problematic waste in the form of activated graphite, generated by certain reactors (including some conventional large reactors). Hence, the management and disposal of SNF from SMRs is the most differentiating in terms of potential impacts.

Different SMR designs which use different reactor types will have different benefits and drawbacks for waste disposal. Waste volume (and mass), thermal load, fissile material content and waste packaging feasibility will all require consideration holistically. The most challenging aspects are expected to be the establishment of a stable molten salt fuel-coolant wasteform suitable for disposal, and the potential volume of TRISO fuels, which have a high volume per mass ratio and contain graphite, for which no processing solution currently exists. These challenges are likely to require significantly more RD&D investment to develop suitable, safe solutions.

Countries with large- to medium-sized nuclear power programmes are likely to have mature DGR programmes that can readily absorb the additional wastes from even relatively large power capacity increases as a result of the deployment of multiple SMRs. For these nations, there are no SMR-specific drivers towards opting for an MNR, rather than a national DGR. For these countries it is likely to be more cost-efficient for SMR technologies to align closely with existing national nuclear technologies. However, if the SMR design(s) chosen for deployment were to generate more exotic wastes, for which an operational MNR solution existed, exporting those wastes to an MNR could still be an attractive option. Noting potential security challenges and societal, political and regulatory barriers, a country hosting an SMR vendor that has a medium to large nuclear power programme may see benefit in offering SNF take-back to one or more countries that do not currently use, but are interested in some level of deployment of, nuclear power. This would effectively make the national DGR an MNR. For the former, this would provide market advantage and, for the latter, a solution to SNF back end issues, simplifying their path(s) toward nuclear power deployment.

For countries with small, or no, nuclear power programmes, the implementation of SMRs of the same, or similar, designs being deployed in other similar countries could be an incentive for enhancing cooperation on pre-disposal and disposal activities. This would provide unique resource-pooling and economy of scale opportunities.

Non-nuclear nations interested in only a small nuclear power capacity would be strongly motivated to seek MNR solutions and are the most likely to be responsive to market-led solutions, such as SNF take-back offers. It is also reasonable to assume that such countries would be most likely to embark on a nuclear power programme through the use of SMRs, rather than by building a single large conventional nuclear power plant. It is these nations that would likely benefit most from implementing geological disposal by using a deep borehole concept (noting that significant R&D is still required to demonstrate safety and feasibility of deep borehole disposal), as this might be achieved more flexibly than through scheduling and strategy alignment with a MNR facility. As with SNF take-back, security challenges remain a key complexity.

Conversely, countries that do not have nuclear power, but have ambitious plans, may be the most likely to have drivers towards being new technology leaders for SMR implementation and the disposal of SMR SNF. With large-scale ambitions to deploy many SMRs for multiple purposes, it is more likely that these countries would include more than one SMR design (and reactor type) in their

SMR portfolios. Here, the ambitious approach may make less-conventional technologies more viable, given an appropriate, and significant, level of investment, should the case for that specific technology be particularly attractive. Given the need for a DGR programme to support their ambitious plans, such countries would also be better placed to investigate the option of hosting a commercial MNR, potentially offsetting the significant investment into nuclear power that would be required.

7.4. What impact could SMR deployment have on multinational RWM collaboration?

There are various models for implementing an MNR, each of which has its own specific drivers and may be more or less attractive to different countries, based on their commitment to nuclear power, i.e., those with an established nuclear power programme, newcomer nuclear power nations, and variants within these categories.

The various MNR models can generally be considered as either: an MNR through partnership between various nations, potentially including upstream facilities distributed between partner nations; or an MNR as a commercial endeavour, where the specific boundary conditions regarding the commercial solution could extend upstream, or not.

For both, the likelihood that more nations with small inventories of waste requiring geological disposal will arise through the widespread deployment of SMRs makes MNR interest more likely. As has been demonstrated over the past decades, national DGR programmes are difficult to implement and costly, hence an opportunity to avoid, or share, this burden would be a welcome one to any organisation responsible for such waste.

The technical implications of accepting SMR SNF into an existing disposal programme are mostly the same for either a national DGR or an MNR. Whilst SMR SNF will affect the design and management of an MNR project, no additional concerns beyond that for a national RWM and/or DGR programme exist, as its inclusion along with other committed wastes from national nuclear power programmes seems unlikely to introduce difficulties that are significant enough to discourage MNR development. Should multiple potential MNR users be interested in a particular SMR technology, it might ease the decision to deploy SMRs if a common solution is being investigated, rather than a country going it alone. In this case, involvement in an MNR project could be attractive.

An MNR is more likely to require the disposal of multiple different types of SNF, which will be more complex and costly than an MNR (or DGR) in which only one type of SNF is disposed of. Any commercial MNR will therefore likely need to design a system that can handle a wide range of SMR wastes. Additional up-front costs can be expected when compared to adopting an existing DGR design, safety case and operational procedures. As a result, countries involved in MNR development through partnership (e.g., ERDO Association) are likely to be motivated to align their selection of SMR technology and attempt to optimise their SMR deployment scheduling. Alternatively, complexities around a scenario where the disposal of different types of SNF is required may be sufficient to make the establishment of reprocessing of interest, despite the cost, given the potential for producing a standardised wasteform.

Depending on the approach to MNR development (either a partnered or commercial approach), the varied nature of waste arisings could necessitate a significant storage facility accompanying the MNR or could otherwise place significant constraints on the upstream activities and facilities. Scheduling of waste arrivals at an MNR will require careful management and planning and would be more easily controlled if the MNR participants extended their collaboration upstream.

An MNR will utilise an expanded transport network when compared with a national DGR, extending across countries, potentially throughout a region, or even globally. The level of transportation would be compounded should upstream collaboration be included.

The widespread nature of SMR deployment and the necessary transport infrastructure for an MNR heighten the security and safeguards concerns outlined for a national DGR. Each aspect would become more pronounced, with the added complexity of cross-national regulatory and legal compliance: potentially, significantly so, if the MNR involved shared upstream activities.

Overall, SMR deployment is likely to make MNR development efforts more likely and could help with public engagement and acceptance. The technical, security and safeguards concerns should not be seen as significant from an MNR implementation perspective, as they will need to be dealt with in some degree, should SMR deployment be widespread. The alignment of upstream activities and scheduling of waste transports, along with varied regulatory regimes and the legal status of exporting radioactive waste for disposal are likely to be the most challenging aspects for potential MNR projects which accept waste from SMRs for geological disposal.

8 Outlook and Recommendations

The SMR industry is moving fast, with positive advances published regularly. In an equally positive direction, interest in multinational solutions at the back end of the fuel cycle appears to be higher than ever, given the huge costs and challenges in developing a national DGR programme. However, there are significant hurdles to be negotiated before SMR deployment becomes ubiquitous, and there remain many open issues around MNR implementation. Common challenges include:

- Technical detail associated with the specific amount and nature of SMR waste arisings;
- Technical solutions and licensing arrangements for disposal solutions and associated upstream activities, e.g., waste packaging and transport;
- The upscaling of supporting infrastructure required for a multinational collaboration with regard to radioactive waste disposal;
- Establishing working partnerships aimed at initiating multinational disposal-focused projects; and
- The application of standard DGR-related considerations such as siting, cost, programme, safety, security and safeguards, to the more complex context of an MNR project.

There are various ongoing projects and activities that could help to address some of these challenges:

- The NEA WISARD project [68] was approaching initiation at the time of original drafting. Focused primarily on the nature of waste arisings from SMRs, the project scope is expected to cover more technical detail than this report or its appendices.
- The NEA-ERDO joint Multinational Infrastructure for Radioactive Waste (MIRA) project [69] was being discussed at the time of original drafting. The project scope is expected to focus on exploring how a multinational infrastructure (e.g., access to shared waste processing facilities) can contribute to the safe, timely and efficient handling of radioactive waste and avoid unnecessary duplication.
- The DG-ENER pilot project - focused on a joint European approach towards radioactive waste [70] - is currently underway, initiated by a direct request from the European Parliament. The pilot project has drawn together EU member state representatives in discussions around the feasibility of shared waste management activities in Europe. Conclusions from the current phase are due to be considered in 2026, which could lead to the establishment of an EU policy-level forum focused on joint approaches to RWM.
- SMRs wastes are a subject of interest to be covered by the European Partnership on Radioactive Waste Management (EURAD-2). The focus of efforts is summarised in a recent document that covers SMR implementation and deployment needs from the back end of the fuel cycle [71].

There is further potential for additional projects to cover other challenges raised in this document, which are not known to be under active consideration in detail elsewhere. Examples include:

1. Establishing global communities for progressing regional collaboration around RWM and/or MNR development. See Section 8.1.
2. Aiding countries that are potentially interested in collaboration over the entire back end through a systematic assessment of the upstream implications for MNRs. See Section 8.2.
3. Exploring the degree to which existing European legal, political and financial mechanisms and organisational structures could be applied, adapted or extended to support a multinational implementation organisation in MNR realisation. See Section 8.3.
4. Encouraging collaboration between SMR vendors and potential multinational implementation organisations to facilitate engagement around MNR project initiation. See Section 8.4.

8.1. Establishing Global Communities

The ERDO Association is currently the only organisation where countries have come together under their own direction and dedicated themselves to working together to address the common challenges of safely managing the long-lived radioactive wastes in their countries.

Other countries with nascent programmes have an opportunity to avoid the nuclear acceptance problems that have been encountered in other parts of the world by many nuclear power programmes that delayed consideration of, or simply ignored, back end RWM. Working together, even at the conceptual stage of RWM planning, could lead to more effective, cost-efficient RWM and safe disposal solutions. Working together with prospective SMR vendors on the management of SMR wastes would encourage suppliers of these technologies to assist national RWM programmes at the inception stages of their nuclear power projects.

Potential regions that could benefit from this are parts of Africa and the Association of Southeast Asian Nations (ASEAN). The scoping review presented in Appendix 2: Global Interest in SMR Vendors & Designs shows increasing interest in nuclear power deployment (including SMRs) for countries in these areas.

8.2. Assessment of Upstream Implications for MNRs

Given that it is likely that an MNR would need to be able to dispose of various radioactive wastes generated in many countries, disposal packaging versatility, from the perspective of its suitability for different types of waste, would be highly beneficial. A versatile disposal container able to accept different SMR wastes could potentially be a significant component in MNR collaboration. Furthermore, when considering the upstream activities, the movement of radioactive wastes through various facilities, some of which may already exist, could result in significant re-packaging, e.g., packaging for transport, unpackaging for treatment, re-packaging for interim storage, re-packaging for further transport to a disposal facility and final re-packaging into a container suitable for disposal. Hence, versatility of waste packaging from the perspective of its suitability for different upstream activities is also likely to be highly beneficial. A standardised multi-purpose container (MPC) minimising loading and unloading throughout the fuel cycle could also potentially be a significant element of MNR collaboration, especially if the MPC and its proposed contents were assessed as disposable in a DGR. Here, thermal considerations are particularly relevant. One of the benefits of MPCs from a storage and transport perspective – their large volume, with a capacity of tens of fuel assemblies [72, 73] – could be problematic from a disposal perspective. This is because of the potential for a much increased thermal load per container, as compared with other containers designed for disposal, e.g., the previously discussed KBS-3 disposal container, with a capacity of up to only four fuel assemblies [52].

In this study, the upstream context has not been investigated in detail. Furthermore, to ensure a high-level generic approach, the timing of waste arisings has been essentially discounted as a variable. However, these two aspects, especially when combined, could have a significant impact on the likelihood of widespread MNR development. A Life Cycle Assessment (LCA) for different scenarios could highlight unique challenges associated with a collaborative RWM approach. The scenarios could consider various numbers of participant countries, scales of nuclear power deployment, types of nuclear technology, geographical span of in-scope waste generating facilities, etc. These challenges would need to be addressed through optimisation of an MNR programme. This would also be useful in determining precisely how beneficial a versatile, standardised MPC could be.

Hence, potential collaborators in multinational RWM activities and/or MNR development would benefit from:

- An analysis on how the adoption of a standardised MPC, compatible with various radioactive wastes (including SMR SNF), could beneficially affect the development of an MNR and associated upstream facilities in terms of cost, safety, disposability, and implementation.
- A generic LCA methodology which could be applied to determine opportunities and challenges that exist for those potential collaborators in their specific scenarios.

8.3. Assessment of potential mechanisms to bring forward an MNR

The realisation of an MNR requires further work to define organisational structures, financing models, and legal frameworks. Some work has been done on both, but it is now dated and requires updating. Advancing progress here would be more achievable for a central, dedicated organisation that is willing, and prepared, to apply a sustained effort in resolving such challenges on behalf of a wider group of interested parties: a multinational implementation organisation.

There is no directly applicable case study for a multinational implementation organisation. No directly applicable roadmap exists. No recent work to explore which legal, political and financial structures could support its establishment is known. Examples of such structures in Europe include the Euratom treaty, International Projects of Common European Interest (IPCEIs), and the nuclear fusion projects Jet and ITER. A formal and systematic assessment of these structures, along with others inside and outside of Europe, could be beneficial in understanding their potential application, adaptation or extension to support the realisation of a multinational implementation organisation.

8.4. Encouraging SMR Vendors to Engage & Promote MNR Solutions

Final conclusions and recommendations relate to our analysis of how both SMR vendors and SMR users could benefit by collaborating on the promotion of common multinational solutions for upstream and disposal RWM activities. One of the main findings of this study is that there are clear marketing, cost, technical and programme management benefits for vendors and users to work together, and this is something that could be encouraged to start in the near future. Specific suggestions, reiterated from Section 6, are:

- As a first step towards a collaborative MNR programme, one or more SMR vendors — especially those with novel fuel cycles — may see benefit in building multinational user groups, i.e., customer organisations and/or governments. An initial goal might be for several SMR customers using the same design to cooperate on developing SNF conditioning and packaging approaches for disposal.
- An SMR exporter with a variety of clients could team with another country or organisation with advanced disposal experience (e.g., Canada, Finland, Sweden, Switzerland) and offer to help its user group in developing a shared MNR in one of their countries. For example, the SMR vendor could partner with the commercial wing of a national WMO to offer an international service.
- One way in which such a partnership could develop is for an SMR vendor to work with an established disposal company to offer highly localised solutions to a user country (e.g., for a remote off-grid SMR user) that could be uncoupled from a mainstream national RWM and/or DGR programme. If deep borehole disposal proves to be an appropriate solution for some types of SMR SNF, then this could be an attractive package, provided that on-site disposal approvals could be obtained.
- The path forward would seem to be through encouraging SMR vendors to develop relationships with MNR providers, such as ERDO, and/or with WMOs offering DGR development services that could be transferred to other countries. This is a two-way process, and organisations such as ERDO should also be promoting discussions with SMR vendors. The overarching issue is that of MNR credibility: SMR vendors are only likely to expend resources on pursuing this approach should concrete MNR commitments surface.

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Appendix 1: Potential Global SMR Deployment

See separate appendices document.

Appendix 2: Global Interest in SMR Vendors & Designs

See separate appendices document.

Appendix 3: Disposability of SNF

See separate appendices document.

Appendix 4: Down-selected SMR Design Waste Data & Information

See separate appendices document.

Appendix 5: National Radioactive Waste Management Programme Scenarios

See separate appendices document.

Appendix 6: Multinational Repository Scenarios

See separate appendices document.

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