EASI SMR

Deliverable 1.2 SMR-compatible waste management systems

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3.Summary

This report presents the results of Task 1.2 – Waste Management from LW SMRs, which is part of Work Package 1 (WP1): Transversal Topics for the Acceptability and Licensing of LW SMRs within the European EASI-SMR project. The output, designated as D1.2: SMR-compatible waste management systems, focuses on the review of existing radioactive waste (RW) management practices, including national case studies from the Czech Republic, Finland, and Ukraine for LW nuclear power plants and their applicability to LW SMRs in anticipation of their early commercial deployment across Europe.

The objective of task 1.2 is to assess whether current waste management systems, originally developed for large light water reactors (LWR), are technically and operationally suitable for LW SMR, especially given the modular design, smaller core inventories, higher activation of materials due to increased neutron leakage. The aim of the review is to identify potential areas for adaptation and innovation, particularly in regulatory frameworks, infrastructure, and stakeholder engagement that can increase the safety, efficiency, and acceptability of waste management throughout the entire life cycle of LW SMRs from operation mode to decommissioning. While the review focuses primarily on operational and decommissioning RW processing practices, it acknowledges that waste generation and environmental impacts must also be considered across the full life cycle of LW SMRs including manufacturing, fuel supply, and decommissioning in line with evolving European sustainability and resource efficiency frameworks.

The focus of output D1.2 is to compare existing waste treatment technologies and disposal practices used in countries such as Czech Republic, Finland and Ukraine with the anticipated needs of LW SMRs, based on a comparison with operating practices in large-scale commercial nuclear power plants. It assesses the availability and maturity of technologies that could be adapted or scaled up for use in LW SMRs, particularly in smaller or remote locations which are often the target deployment areas for SMRs and may lack waste processing capacity.

The report concludes that existing European waste management frameworks are suitable for LW SMRs, but technical and regulatory adjustments will be necessary to take into account the specific characteristics of LW SMRs. These include ensuring that waste acceptance criteria, repository configurations, and transport systems are compatible and that repository layouts can accommodate novel waste geometries or compact high-activity forms typical of LW SMRs.

4. Keywords

EASI SMR project, Light Water Small Modular Reactors (LW SMRs), Radioactive Waste Management, Low- and Intermediate-Level Waste (LILW), Intermediate-Level Waste (ILW), geological disposal, LW-SMR decommissioning

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5. Abbreviations and acronyms

Acronym	Description
ANS	American Nuclear Society
APR	Advanced Power Reactor
BWR	Boiling Water Reactor
C&D	Communication & Dissemination
CR	Cube Residue
CSFSF	Centralized Spent Fuel Storage Facility
DGR	Deep Geological Repository
DSNS	State Emergency Service of Ukraine
EPR	European Pressurised Reactor
EU	European Union
FA	Fuel Assembly
FP	Fuel Pin
GE	General Electric Company
HEPA	High Efficiency Particulate Air
HLW	High Level Waste
HTGR	High-temperature gas-cooled reactor
HVAC	Heating, Ventilation and Air Conditioning
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
INSC	Instrument for Nuclear Safety Cooperation
KhNPP	Khmelnytskyi NPP
LFR	Lead-cooled Fast Reactor
LILW	Low and Intermediate Level Waste
LLW	Low Level Waste
LW	Light Water
LWR	Light Water Reactor
MIT	Ministry of Industry and Trade
NEA (OECD)	Nuclear Energy Agency (Organisation for Economic Co-operation and Development)
NPP	Nuclear Power Plant
NNEGC	National nuclear energy generating company Energoatom
NRC	Nuclear Regulatory Commission (USA)
PWR	Pressurized Water Reactor
RNPP	Rivne NPP
RW	Radioactive Waste
RWM	Radioactive Waste Management
SF	Spent Fuel
SMR	Small Modular Reactor
SNRIU	State Nuclear Regulatory Inspectorate of Ukraine
SUJB	State Office for Nuclear Safety (Czech Republic)
SUNPP	South Ukraine NPP

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SURAO	Radioactive Waste Repository Authority (Czech Republic)
tHM	Tons of Heavy Metal
TVS	TVS (Toplivnaya Sborka) – Russian fuel assembly for VVER
US DOE	U.S. Department of Energy
VLLW	Very Low Level Waste
WP	Work Package
VVER	Water-Water Energetic Reactor
ZNPP	Zaporizhzhia NPP

Decommissioning
Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (IAEA 2022a).

Radioactive waste
For legal and regulatory purposes, material for which no further use is foreseen that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels as established by the regulatory body (IAEA 2022a).

Radioactive waste management
All administrative and operational activities involved in the handling, pretreatment, treatment, conditioning, transport, storage and disposal of radioactive waste (IAEA 2022a).

- ***Conditioning***. Those operations that produce a waste package suitable for handling, transport, storage and/or disposal.
- ***Pretreatment***. Any or all of the operations prior to waste treatment, such as collection, segregation, chemical adjustment and decontamination.
- ***Processing***. Any operation that changes the characteristics of waste, including pretreatment, treatment and conditioning.
- ***Treatment***. Operations intended to benefit safety and/or economy by changing the characteristics of the waste. Three basic treatment objectives are: (a) Volume reduction; (b) Removal of radionuclides from the waste; (c) Change of composition.
- ***Disposal***. Emplacement of waste in an appropriate facility without the intention of retrieval.

Small modular reactor (SMR)
According to the IAEA classification, an SMR is an advanced reactor with an output of below 300 MWe[1]. It is much smaller than a conventional reactor and allows for systems and components to be factory assembled and transported as one unit to the installation site.

Waste acceptance criteria
Quantitative or qualitative criteria specified by the regulatory body or specified by an operator and approved by the regulatory body, for the waste form and waste package to be accepted by the operator of a waste management facility (IAEA 2022a).

6.Introduction

Small Modular Reactors (SMRs) represent a transformative evolution in nuclear energy technology, offering enhanced safety, scalability, and adaptability compared to traditional large-scale reactors. Their modular design, lower capital requirements, and suitability for remote or decentralized deployment make them a highly attractive solution in the global pursuit of carbon

[1] Higher power reactors, also referred to as medium power reactors (between 300-700 MWe), are sometimes included in this category.

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neutrality and energy resilience. Given their technical and safety advantages, SMRs are increasingly being explored worldwide. However, their successful implementation will depend on proving their cost-effectiveness and regulatory viability compared to both large-scale nuclear reactors and alternative low-carbon energy sources.

The successful deployment of SMRs must consider the entire fuel cycle, particularly the "back end" processes related to the generation, handling, processing, storage, and disposal of radioactive waste (RW) and spent fuel (SF). This dimension becomes especially critical as emerging SMR designs may introduce novel waste forms, materials, and activity profiles, challenging the suitability of existing waste management frameworks.

This Report provides a comprehensive analysis of the systems for RW and SF management in Czech Republic, Finland, and Ukraine with a particular focus on the adaptation needs and challenges associated with future SMR deployment. It aims to:

- evaluate the existing RW and SF management infrastructures and regulatory environments,
- identify gaps, opportunities, and best practices related to the management of potentially new types of SMR waste,
- compare waste streams and management strategies between traditional NPPs and projected SMR systems,
- outline preliminary recommendations for ensuring responsible, sustainable, and harmonized waste management approaches across Europe.

The general observation is the lack of information regarding management of SF and RW. It is evident that not enough attention is paid to this area. The determining factor is the compliance/non-compliance of the SF and RW produced from a particular type of SMR with the SF and RW management policy in a particular country. Therefore, it was proposed to describe the situation and compare the management of SF and RW from large NPPs and SMRs in specific countries. Early attention to the back end of the SMR fuel cycle is essential to ensure a safe and sustainable transition to next-generation nuclear energy systems. The proposal was also supported by the fact that more information may be available for specific SMRs that are planned in specific countries. LW SMRs will be discussed in this report only.

The report has the following structure:

1. Introduction
2. Description of the SF and RW management in EU
3. Description of the current state of knowledge of SF and RW management for SMR
4. Description of the SF and RW management system and technology for existing and planned NPPs and SMRs for selected countries:
    - Czech Republic
    - Finland
    - Ukraine
5. Evaluation of expected differences between commercial LWRs and SMRs and applicability of current system and technologies
6. Conclusions.

6.1. Plans for the construction of the SMR

IAEA (2022b) lists 83 SMR projects currently under development (both Generation III+ and Generation IV). Most of them (38) are in the pre-conceptual or conceptual design phase. There are 20 projects in the basic design phase and 16 in the detailed design phase. In preparation, construction or operation of the SMR are:

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- KLT-40S (PWR, floating, Russia), 2 modules of 37 MWe each – in operation since 2020.
- HTR-PM (HTGR, China), 2 modules, 210 MWe – in operation since 2021.
- CAREM (integrated PWR, Argentina), 30 MWe – under construction, construction interrupted, date of commissioning unknown.
- ACP100 (integrated PWR, China), 125 MWe – under construction, expected commissioning 2026.
- BREST-OD-300 (LFR, Russia), 300 MWe – under construction, expected commissioning 2026.
- BWRX-300, GE-Hitachi (BWR), 300 MWe - component fabrication, Ontario Power Generation (OPG) site preparation in Darlington, Canada, targeting construction of 4 units by 2028. This SMR has also been selected for possible construction in the province of Saskatchewan. Construction of a NPP with this SMR is also underway in the USA (Oak Ridge). In Poland, a decision has been issued by the Ministry of the Environment for the construction of 24 BWRX-300 reactors at six sites. This SMR has also been selected for possible construction in Estonia (GE 2024).
- VOYGR, NuScale (integrated PWR, 4/6/12 modules, USA), 50 MWe per module – certified for the USA, production started, construction planned for a site near Idaho Falls (assumed to start construction 2025 and commissioning 2029), project cancelled at the end of 2023 (REUTERS 2024a). The project is being considered for the Doicesti site in Romania, investment decision expected in 2025 (REUTERS 2024b).
- Rolls Royce, Rolls-Royce SMR Limited (PWR, UK), 470 MWe – Rolls-Royce SMR Limited (Rolls-Royce SMR) and ČEZ Group (ČEZ) will join forces to bring their global capabilities and know-how to the deployment of Rolls-Royce SMR's small modular reactor (SMR) technology. This is enabled by an equity investment by ČEZ into Rolls-Royce SMR and a strategic partnership to deploy up to 3 GW of electricity in the Czech Republic using Rolls-Royce SMR power plants (ČEZ 2024). The pilot project in the Czech Republic should be an SMR reactor at the Temelin site with announced start-up in 2035.
- SMR-300, Holtec International (PWR, USA), 300 Mwe-Holtec International and Hyundai Engineering & Construction gathered at the Palisades site in western Michigan announce an "expanded cooperation agreement" to build a 10-GW fleet of Holtec-designed SMR-300s in North America. That fleet's first builds would be at Palisades, where Holtec is now focused on restarting the site's shuttered 777-MWe PWR. Holtec would then build a pair of SMR-300 PWRs at the Palisades site—targeting operation in 2030 (ANS 2025).
- XE-100, X-energy (HTGR, USA), 4x 80 MWe – is part of the US DOE Advanced Reactor Demonstration Projects (ARDS) programme, with about USD 1.23 billion to be provided by the US DOE for the construction of the SMR and TRISO fuel fabrication facility. The SMR is to be built at Seadrift, Texas (X-energy 2024).
- Natrium, TerraPower-GE Hitachi (SFR, USA), 345 MWe - 08/2023 land purchased to build SMR (Kemmerer, Wyoming), 03/2024 application submitted to NRC (USA), 04/2024 announced intention to build pilot facility to produce metallic HALEU in partnership with Framatom. US DOE Advanced Reactor Demonstration Projects (ARDS) program will provide $1.6 billion for the project (TerraPower 2024).

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NEA (2024) identifies 98 SMR projects; of these, publicly available information was found for 63 SMRs (56 SMRs were included with the consent of the development organizations in the publication); the remaining 35 SMRs include projects that are not currently in active development, may be without human or financial resources, or have been discontinued or cancelled.

The European Industrial Alliance on SMRs announced on 11 October 2024 the 9 SMR projects selected to be part of the first batch of its Projects Working Groups (PWGs) (Nucleareurope 2024). Out of the 22 applications received, the following projects have been selected to constitute the Alliance's first PWGs:

EU-SMR-LFR project (Ansaldo Nucleare, SCK-CEN, ENEA, RATEN); CityHeat project (Calogena, Steady Energy); Project Quantum (Last Energy); European LFR AS Project (newcleo); Nuward (EDF); European BWRX-300 SMR (OSGE); Rolls-Royce SMR (Rolls-Royce SMR Ltd); NuScale VOYGR™ SMR (RoPower Nuclear S.A) and Thorizon One project (Thorizon).

The PWGs will provide a framework for selected projects to gather interested stakeholders, and to potentially form project partnerships that will bring together technologically similar projects. Through its project development activities, the Alliance will aim at delivering concrete results, with the ultimate objective to facilitate and accelerate the development, demonstration, and deployment of first SMRs projects in Europe in the early 2030s.

Following this first selection, projects which have not been selected will have the opportunity to submit a new application in the next round of selection, set to take place in the second quarter of 2025.

ČEZ has selected Rolls-Royce SMR as its strategic partner for the deployment of small modular reactors in the Czech Republic, following a competitive evaluation of seven international SMR designs. The SMRs in Table 1 list the parameters and specifics of the SMR models (PWR and BWR) that were considered in the selection of SMRs in the Czech Republic (SMRs considered for early deployment).

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Table 1: Parameters of the considered SMR models for the Czech Republic (NEA 2021, 2023a,b)

Model	Type	Output (MWe/MWt)	Thermal efficiency (%)	Design lifetime (year)	Country	Company	Specifics
BWRX-300	BWR	300 / 870	32	60 (possible extension to 80)	USA	GE Hitachi	Natural circulation Reactor underground
VOYGR	PWR integrated	12 modules 600-924 / 2 000-3 000	30	60	USA	NuScale	Multi-module reactor Natural circulation Reactor v pool, underground
NUWARD[2]	PWR integrated	2x 170 / 2x 540	31	60	France	EDF	Multi-module reactor Boric acid free Reactor in pool, partly underground
SMART100[3]	PWR integrated	2x 107 / 2x 365	30	60	Korea	KHNP	
SMR-160[4]	PWR one-loop	1x 160 / 525	30	80 (possible extension to 100)	USA	Holtec	Natural circulation Reactor underground
Rolls-Royce SMR	PWR three-loop	470 / 1 276	35	60	UK	Rolls Royce SMR	Boric acid free
AP 300	PWR integrated	1x 300 / 900	-	80	USA	Westinghouse	Containment vessel with reactor in pool Reactor underground

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[2] In 2024, EDF announced optimisation of the Nuward design, focusing on existing and proven technologies with output of 400 MWe.
[3] From 2020, iSMR (4 modules of 170 MWe each) is being developed instead of SMART100.
[4] In 2023, Holtec renamed the reactor SMR-300 and increased its output to 300 MWe / 1000 MWt.

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7. Description of the SF and RW management in EU

The EU has long been at the forefront of nuclear energy utilization, with Light Water Reactors (LWRs) being the predominant technology. Consequently, the management of RW from these reactors has become a critical component of national energy policies. This section provides an in-depth analysis of the strategies employed by various EU member states in SF and RW management from LWRs, highlighting real-world implementations and country-specific approaches. Description of the situation in Ukraine, as a candidate for accession to the EU, is also included.

7.1. Management of SF

The EU approaches the SF management with a robust legal and operational framework. This framework combines stringent EU-wide regulations and directives with national strategies crafted by individual member states, tailored to their specific energy policies, technological capabilities, and geographic conditions.

The cornerstone of the EU's policy on SF management is the Council Directive 2011/70/Euratom (EC 2011). This directive establishes a legally binding framework to ensure responsible and safe management of SF and RW. It mandates that:

- Each member state is accountable for its SF and RW, irrespective of whether it is stored or disposed of domestically or abroad.
- Member states must develop and implement national programs detailing their strategies for managing SF and RW, including plans for the construction and operation of disposal facilities.
- Regular safety assessments and peer reviews are required to evaluate national programs, fostering transparency and compliance.

7.1.1. SF Management Lifecycle

After use in a reactor, nuclear fuel is considered spent or used and must be removed from the reactor for subsequent safe management, which includes first interim storage (in wet or dry storage) for a period depending on storage concepts and regulatory body requirements in different countries, followed by reprocessing or direct disposal.

Nearly all Member States have set out a policy of interim storage until a DGR will become available for direct disposal, while France and the Netherlands have continued to reprocess SF. Until a few years ago, a number of Member States used to reprocess SF too, however, they have mostly shifted to the direct disposal option. Nonetheless, a few Member States declared that they have not necessarily discarded reprocessing as an option for the future. (COM 2024)

The lifecycle of SF in the EU typically follows these key stages:

1. **On-site storage in cooling pools**. After being removed from nuclear reactors, SF is initially stored in cooling pools at the reactor site for a few years (commonly 5–10 years). This allows for both the decay of short-lived isotopes and a reduction in residual heat.
2. **Transfer to interim storage facilities.** According to specific country regulation requirements, SF is transferred to interim storage facilities. These facilities can be wet

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(water-cooled pools) or dry (casks and vaults) storage systems. Dry storage is increasingly favoured for its lower costs, enhanced safety, and longer storage potential.

3. **Reprocessing and recycling (optional)** Some EU countries, such as France, opt to reprocess SF to extract reusable materials like uranium and plutonium. These materials can be recycled into mixed oxide (MOX) fuel, reducing the volume of HLW.
4. **Disposal in DGR.** The ultimate solution for most SF is deep geological disposal. Significant progress has been made on the construction of a DGR in Finland. In Sweden, DGR started in 2025. In France, activities on a DGR are well under way. In 2023, the construction licence application for Cigéo DGR was submitted.

Looking ahead, advancements in nuclear technology, such as small modular reactors (SMRs) and advanced reprocessing methods, may influence SF management.

7.1.2. Current status of SF management in individual countries

Belgium

After removal from reactors, SF is stored in at-reactor pools. SF is then transferred to storage facilities on the power plant's site:

- wet storage in Tihange;
- dry storage in metal casks for storage and transport in Doel.

A part of SF from NPPs was reprocessed on the site of la Hague between 1980 and 2001. The reprocessing waste, conditioned at la Hague, has been repatriated to Belgium.
In 2022, the Belgian government took the decision in principle that the country's SF, HLW and long-lived ILW should be disposed of in a suitable DGR. Development of DGR has been going on in the country for more than 40 years. Start of operation of a DGR is supposed in 2050.

Bulgaria

SF is stored on the site of the Kozloduy NPP in a Spent Fuel Storage Facility (SFSF) and a Dry Spent Fuel Storage Facility (DSFSF). SF was also sent to Russia for reprocessing in the past.
Options for the management of HLW and SF are being considered, including the possible construction of a DGR, subject to appropriate conditions and resources (geological, technical, engineering, financial, etc.), as well as for the management of long-lived LILW.

Czech Republic

SF from the Dukovany and Temelin NPPs is after initial storage in at-reactor-pools stored in dry cask storage at these sites. SF will be disposed in the planned DGR. For details, see the chapter 9.1.4.1.

Finland

After removal from reactors, SF is stored in pool type interim storage facilities at the NPP sites. Two interim storages have been in operation in Loviisa and Olkiluoto. After a storage period of some tens of years, SF will be disposed of into a DGR.
Finland leads globally in SF disposal with its Onkalo Repository near Olkiluoto. Onkalo will become one the first operational DGR of its kind. In 2024, a trial operation of the DGR started. For details, see the chapter 9.2.4.1.

France

France has opted for a SF reprocessing-recycling strategy. SF is being stored pending reprocessing at different sites (NPP and reprocessing plant sites). Facilities in La Hague

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reprocess SF, extracting usable uranium and plutonium for reuse in MOX fuel. HLW from reprocessing is vitrified and stored in interim facilities while awaiting placement in DGR.
In 2023, the construction licence application for Cigéo DGR was submitted. Start of operation of the DGR is expected between 2035 and 2040.

Germany

SF from NPPs is stored in the SF pools and in dry storage on the NPPs sites. SF stored in the SF storage pools will be transferred to dry cask storage. Central dry fuel storage facilities are also available.
SF was also reprocessed abroad in the past. HLW from reprocessing is stored in casks. Following its nuclear phase-out decision, Germany prioritizes interim storage of SF in dry casks located at reactor sites. SF and HLW will be disposed in DGR, the site selection procedure was started in 2017.

Hungary

Hungary's Paks NPP stores SF onsite in wet pools before transferring it to dry storage. SF was reprocessed in Russia in the past. A programme on the disposal of SF and HLW in Hungary has been underway.

Italy

Almost all SF of NPPs has been transferred abroad for reprocessing and the resulting residual ILW and HLW is expected to be returned to Italy. Some minor quantities of SF, deriving from past research activities, are envisaged to be managed according to a dry cask storage strategy.
A dedicated program for the identification of a national deep geological disposal facility will be implemented in the near future.

Lithuania

Lithuania stores SF from its decommissioned Ignalina NPP in dry interim storage. Construction of a DGR for long-lived waste including SF is planned.

Netherlands

After removal from reactors, SF is stored in at-reactor pools and then removed to the COVRA facility for SF and HLW from SF reprocessing in Borssele (dry storage). SF is sent to France (and to UK in the past) for reprocessing, HLW from reprocessing is sent back to Belgium.
The centralized facility is designed to safely contain waste for over a century, allowing time for the development of geological disposal plans. A geological disposal facility is foreseen around 2130.

Romania

SF from Cernavoda NPP is stored onsite in interim facilities (pools and dry). SF will be disposed in a DGR which is planned to get an operational license in 2055. The concept of the DGR and a R&D plan to support implementing the repository are planned to start in 2025.

Slovakia

SF from NPPs is after initial storage in at-reactor-pools stored in Interim Spent Fuel Storage Facility (wet and dry storage). SF from the A-1 NPP has been reprocessed in Russia. DGR is under development in Slovakia.

Slovenia

Slovenia co-manages the Krško NPP with Croatia. SF is stored onsite in pools and then in a dry storage facility. Both countries are jointly planning a DGR.

Spain

SF is stored in the pools of NPPs, except for José Cabrera NPP, where SF is stored in an on-site dry store, and Trillo, Ascó, Almaraz, Cofrentes and Garona NPPs, which, due to insufficient capacity in their pools, have on-site dry stores. SF from Vandellós I NPP was reprocessed in France and RW from reprocessing will be sent to Spain.

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Spain is also assessing potential geological disposal options. DGR is planned to be put in operation in 2073.

Sweden

SF is stored in at-reactor storage pools and is then transferred to the central interim storage facility (Clab) (wet storage) pending disposal. Some amount of SF was shipped to UK and France between 1972 and 1982 for reprocessing.

In 2025, construction of DGR at Forsmark site started. DGR will be ready for disposal in the 2030s.

Ukraine

SF is initially stored in at-reactor pools at each of the operating NPPs (Zaporizhzhia, Rivne, Khmelnytskyi, and South Ukraine NPPs). After sufficient cooling, FAs are transferred to dry storage systems. Rivne, Khmelnytskyi, and South Ukraine NPPs currently use dry cask storage at the Centralized Spent Fuel Storage Facility (CSFSF) located in the Chornobyl Exclusion Zone. The CSFSF became operational in 2022 and is managed by Energoatom.

At the Zaporizhzhia NPP, a dry storage facility for SF has been in operation since 2001. It is used for long-term storage of VVER-1000 SF in specially designed concrete casks. However, the site has been under military occupation since March 4, 2022, raising significant risks about nuclear safety and security.

A long-term strategy for the final disposal of SF is still under development. Although Ukraine has no DGR currently under construction, national policy foresees the eventual disposal of SF in a national or multinational DGR. For details, see the chapter 9.3.4.1.

7.2. Management of RW

7.2.1. RW streams and classification at the sites of generation

In the EU, radioactive waste generated from NPPs, particularly those utilizing LWRs, is systematically categorized based on its origin, physical and chemical characteristics, and radiological properties (IAEA 2016). The primary RW streams at NPP sites include:

- operational waste: arising from routine reactor operations, such as contaminated equipment, filters, and resins,
- spent fuel: highly radioactive and thermally hot, SF is often considered a separate category due to its potential for reprocessing or direct disposal,
- decommissioning waste: generated during the dismantling of NPPs, including structural materials and components.

The classification systems employed across EU member states largely follow IAEA Safety Standards (GSG-1), which define RW categories based on radiological hazards, heat generation, and expected disposal pathways:

- Very Low-Level Waste (VLLW): suitable for surface or near-surface disposal; often includes construction debris, lightly contaminated materials, and decontaminated scrap,
- Low-Level Waste (LLW): requires minimal shielding and is suitable for near-surface disposal,
- Intermediate-Level Waste (ILW): requires more robust shielding but does not necessitate active cooling; disposal varies, with some countries already considering sub-surface or geological options,
- High-Level Waste (HLW): typically heat-generating and long-lived, often arising from spent fuel reprocessing; destined for deep geological disposal.

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Each EU country aligns its waste classification system to these core categories, though national schemes vary in detail based on waste inventory, historical policy, and long-term disposal strategies.

7.2.2. RW management at the sites of generation

At the operational level, the management of RW involves a structured sequence of actions from initial waste identification to interim storage or transport (IAEA 2018). In EU nuclear facilities, this chain includes:

- sorting and characterization: waste is segregated based on its radiological properties and physical form. Characterization includes determination of radionuclide content and activity levels to determine further processing and disposal options,
- processing and conditioning: processes such as compaction, incineration, and cementation are used to reduce the volume of waste and immobilize radionuclides,
- packaging: conditioned waste is encapsulated in containers designed to prevent the release of radionuclides during storage, transportation, and disposal,
- on-site storage: processed and packaged waste is stored on-site in specially equipped facilities until it is moved to off-site storage or disposal facilities.

For instance, Germany distinguishes waste streams based on residual heat output, while France applies detailed decay-based segregation that aligns with both radiotoxicity and disposal timelines. Across the EU, facilities incorporate on-site storage buildings for conditioned waste, employing shielded vaults or above-ground concrete casks pending transport to centralized repositories or interim facilities.

7.2.3. RW processing and storage (interim, long-term)

EU member states have implemented both interim storage facilities (ISF) and long-term storage strategies to accommodate RW pending final disposal. Interim facilities are usually situated on-site or in regional hubs and are designed for safe containment over decades, particularly for ILW and HLW.
A notable example includes the Zwilag facility in Switzerland, a technologically advanced ISF housing dedicated compartments for SF, HLW from reprocessing, and ILW from routine operations. Likewise, Belgoprocess in Belgium provides centralized storage for various waste forms including vitrified waste returned from France.
Long-term storage solutions have evolved in parallel, with some countries implementing reinforced surface buildings with extended design lifespans (e.g., 100+ years) and planning for geological repositories as the ultimate endpoint for HLW.

7.2.4. Disposal

Radioactive waste disposal facilities are engineered systems designed to isolate radioactive material from the biosphere for periods sufficient to ensure radiation levels do not pose a hazard to human health or the environment.
In the European Union, the final disposal of radioactive waste is implemented based on the classification of the waste: VLLW, LLW or ILW – which is determined by the radiological and physical-chemical characteristics of the waste streams. Unlike HLW and SF, which is managed through dedicated interim storage and future deep geological disposal, institutional, operational, and decommissioning RW is disposed of using engineered surface or subsurface facilities designed to safely isolate radioactive materials from the biosphere over appropriate timescales.
Disposal of radioactive waste across the EU follows a tiered approach based on waste classification and the corresponding radiological risk profile. Surface and near-surface

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disposal is widely used for VLLW and LLW, especially in facilities like CIRES (Centre Industriel de Regroupement, d'Entreposage et de Stockage) in France or El Cabril in Spain. These repositories employ engineered barriers and institutional controls to ensure isolation for periods aligned with the waste's decay profile. For ILW and HLW, countries are progressively transitioning toward DGRs. France is advancing its CIGÉO project in clay formations, while Sweden and Finland are global leaders in constructing granite-based DGRs like Onkalo, set to receive waste from 2025. Germany, Switzerland, and the Czech Republic are actively pursuing siting and licensing processes for future DGRs.
The document also underscores the increasing importance of waste form stability and engineered containment systems, which influence repository design and regulatory approval processes. For example, in the UK, LLW is compacted and grouted before burial in trench-type repositories in Drigg, while HLW is vitrified and stored in stainless steel canisters in Sellafield.

In the next, consideration of some specific cases.

Belgium

In Belgium, one of the most advanced projects for near-surface disposal is the cAt facility in Dessel, developed for the disposal of short-lived LILW. The concept involves conditioning the waste in concrete monoliths that are subsequently placed within engineered surface structures resembling tumuli. This design incorporates both natural and engineered barriers and is complemented by an active monitoring program designed to last for up to 300 years. The cAt project represents a long-term national solution for category A waste (short-lived LILW), and its implementation is being closely coordinated with the local community through partnership agreements.

France

France has a long-standing and comprehensive infrastructure for RW disposal. The Centre de l'Aube, operational since 1992, is a near-surface facility for LLW and ILW-SL (short-lived) waste. Waste is placed in reinforced concrete vaults and covered with multi-layer protective capping systems. Before the Centre de l'Aube, France operated the Centre de la Manche, which was closed in 1994 and has since entered a phase of post-closure monitoring. Additionally, France operates the Morvilliers site for VLLW, which typically originates from the decommissioning of nuclear installations. This facility uses engineered trenches and geosynthetic barriers to ensure containment of radionuclides over the required regulatory period.

Sweden

In Sweden, RW from nuclear operations is disposed of in the SFR facility (Final Repository for Short-lived Radioactive Waste) located near Forsmark. This facility is unique in that it is constructed in crystalline bedrock approximately 60 meters below the Baltic Sea. The SFR includes a series of engineered vaults, silos, and rock caverns specifically designed for the disposal of LLW and ILW. Operational since 1988, the SFR is currently undergoing expansion to accommodate additional waste from future decommissioning activities.

Germany

In Germany, the primary national facility for the final disposal of LILW is the Konrad repository, located in a former iron ore mine near Salzgitter. This deep geological disposal facility has been licensed since 2002 and is currently under construction. Unlike facilities designed for SF or HLW, Konrad is authorized only for non-heat-generating RW. It will dispose of waste at depths of between 800 and 1,300 meters, using the mine's geological stability as the main containment mechanism. The facility is expected to become operational in the latter part of the 2020s.

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Slovenia
Slovenia is in the process of constructing a national repository for LILW near the town of Vrbina, adjacent to the Krško NPP. The repository will consist of reinforced concrete silos designed to accommodate conditioned waste from nuclear operations and decommissioning. The siting of the repository was the result of a national consensus and community agreement, and it represents a key step toward meeting Slovenia's long-term obligations under the EU waste directive.

Ukraine
In Ukraine, which is a prospective member of the European Union, significant progress has been made in developing infrastructure for the disposal of RW, especially legacy waste from the Chernobyl disaster and institutional sources. The Vector Industrial Complex, located within the Chernobyl Exclusion Zone, includes multiple near-surface and interim storage facilities. It consists of disposal cells for solid LLW, long-term storage modules for ILW, and treatment plants. Ukraine's RW management system is undergoing modernization with extensive support from the EU and international partners, aiming to align national practices with European standards and directives.

RW disposal in the EU is implemented through a combination of near-surface and subsurface facilities, each tailored to the type and longevity of the waste involved. Across the EU, there is a strong emphasis on engineered safety barriers, geological stability, and public engagement. While some countries like Finland, Sweden, and France lead with fully operational national systems, others like Slovenia and Belgium are advancing new projects with long-term visions. Ukraine, though not yet a full EU member, demonstrates substantial progress in aligning its disposal strategies with European norms. Overall, EU Member States follow a multi-faceted and evolving approach to RW disposal, guided by common safety principles and EURATOM directives, while implementing national strategies tailored to their specific geological and institutional contexts.

8. Description of the current state of knowledge of SF and RW management for SMR

8.1. Management of SF from SMR

For most LW SMRs, it is planned to use low enriched fuel (3-5%) in the same form as is currently commercially available (oxide pellet fuel). Longer fuel campaigns (3-7 years, sometimes longer) are envisaged (NEA 2023a).
The project "SMR Waste Management in Finland" (Keto et al. 2022) investigated the effect of SMR SF characteristics on the final disposal and applicability of the currently used management methods. SF characteristics studied in the project with Serpent 2D numerical modelling for LDR 50 district heating reactor (VTT design) and for older version of the NuScale Power Module TM reactor with following conclusions:

- The lower discharge burnups in the SMRs lead to lower decay heat and ionizing radiation at the assembly level.
- Concentrations of mobile nuclides in the SMR SF are lower.
- The lower average burnups in combination with high enrichment variations may contribute to higher post irradiation reactivities (criticality safety).

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- Considering similar discharge burnups, the 2D model gives SF inventories that are very similar to EPR fuel.

The applicability of the currently used methods for the SF management is as follows:

- Waste form / EPR type SF should be compatible with current encapsulation methods using shorter canisters.
- Differences in fuel dimensions, configuration, fission product inventory, decay heat generation, physical and chemical characteristics and fissionable material content would need to be taken into account in repository design (SF mass per canister, canister spacing, etc.).
- Some studies suggest that SMR use may lead to more SF and LILW being generated per GWe year (Krall et al. (2022), Brown et al. 2017, Glaser et al. 2013) than in large NPPs, but these results need to be verified.

The above project was followed by another project "SMRSiMa: SMR Siting and Waste Management" (Keto et al. 2023). The SMRs VOYGR, Rolls-Royce, BWRX-300, NUWARD, SMART and LDR-50 (50 MWt) were compared. The SF characteristics were studied using Serpent Ants 3D calculations.
Further information on the plans to modify the current strategy for the SF management in Finland with respect to SF from SMRs is provided in Keto et al. (2024). Storage of SF can be both decentralised (on-site) and centralised. At present, SF is stored in a centralised (wet) storage facility. Some SMR concepts include dry storage, so dry storage could also be on-site. SF disposal is also discussed. In addition to disposal in DGR, deep borehole disposal is mentioned as another possible solution, which could also be located on the SMR site. However, this is an option that still requires extensive research and development, especially in crystalline rock environments. The influence of SMR SF characteristics on disposal (cover material, burn-up, radionuclide composition, etc.) is also discussed. It is concluded that the properties of SMRs need to be verified, which is still difficult due to the lack of data and operational experience. However, the existing Finnish strategy for disposal of SF in DGR is generally applicable also for SMRs based on LWR technology.
Krall et al. (2022) estimated the amount and characterized the nature of SF from SMRs and existing PWRs (3,400 MWth). VOYGR (from NuScale Power) was also assessed. From the specifications given in the NuScale reactor certification application, basic principles of reactor physics relevant to estimating the volumes and composition of integrated PWR waste were analysed.
In SMRs, there is a higher neutron leakage from the core (due to the smaller core), therefore there will be a higher activation of materials around the SMR core. For a PWR (3,400 MWt) the thermal neutron leakage is <3%; for a SMR VOYGR (160 MWt) it can be >7%. Higher neutron leakage will also affect reactivity and power, leading to lower burnup, hence lower fuel efficiency, i.e. higher SF production, unless compensated by higher fuel enrichment, use of a neutron reflector or a more efficient moderator.
The burnup for the standard PWR was assumed to be 57 MWd/kg, for the VOYGR the burnup calculation was 34 MWd/kg. Then, on a heavy metal mass basis, 1.7 times more SF is produced by the VOYGR. In IAEA (2022b), a higher burnup (≥45 MWd/kg) is mentioned, which would correspond to a lower amount of SF from the operation of the VOYGR – about 1.3 times more than from the standard PWR. To calculate the volume of SF, o ther matrix materials have to be included.
Kim et al. (2022) evaluated the nuclear waste attributes of SMRs scheduled for deployment within this decade using available data and established nuclear waste metrics, with the results

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compared to a reference large PWR. VOYGR (from NuScale Power) was also assed. The information on reactor design and performance parameters of the SMRs were obtained from open literature. Missing data needed for evaluating waste metrics were calculated in this work or obtained from a reactor with a similar power rating and design features.
Parameters used for evaluation for the LW NPP and SMR:

- PWR (3,500 MWt, 1,175 MWe, thermal efficiency 34 %, burnup 50 GWd/t),
- VOYGR (PWR, generation III+, 160 MWt/77 MWe, thermal efficiency 31 %, burnup 49.5 GWd/t).

For evaluation of SF, the following factors were used:

- SF mass and volume,
- SF activity from 10 to 100,000 years after discharge, decay heat of SF at 10 and 100 years,
- radiotoxicity of SF at 10,000 and 100,000 years

Conclusions for SF for VOYGR were:

- VOYGR generates 1.1 times the SF mass and 1.1 times the SF volume of the reference large PWR due to relatively lower burnup and thermal efficiency,
- VOYGR SF has slightly higher activity, decay heat and radiotoxicity.

Krall et al. (2022) and Kim et al. (2022) agree on the higher SF production from VOYGR, however, they differ in their estimate of the amount of SF (1.7 or 1.1 times more than from PWR per mass of heavy metal). Considering the difference likely caused by using different burnup values (34 / 49.5 GWd/t for VOYGR and 57 / 50 GWd/t for PWR), the results are close to each other (1.3 or 1.1x more for higher VOYGR burnup and lower PWR burnup). These are estimates based on calculations that will need to be verified.
The following areas will need to be addressed for the management of SF from SMR operation:

- SF transport and storage capacities,
- the need for new casks,
- the impact on the storage concept and the capacity of the DGR,
- international cooperation in the case of a fleet approach.

So far, only limited information is available on the fuel used in the SMR. In the framework of the selection of suitable SMRs in the Czech Republic, information on selected SMRs considered for early deployment was collected (see Table 2).

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Table 2: SMR models considered for the Czech Republic – fuel cycle parameters (NEA 2023a,b, 2024; IAEA 2022b)

Model	Fuel	FA length (m)	FA weight (kg)	Enrichment / FA number in active zone	Campaign duration (month)	Burnup (GWd/t)
BWRX-300	Standard fuel, UO_2 pellets (10x10) GNF2, 92 rods in FA (Hitachi 2023)		299 (Hitachi 2023)	av. 3.81%, max. 4.95% 240	12-24 (32-72 FAs)	49.6
VOYGR	Standard fuel, UO_2 pellets (square 17x17) 264 rods in FA (NuScale 2019) Possible uses of MOX	2.44 (NuScale 2020) 2 (active length)		< 4.95% 37	18 (1/3 of core)	≥ 45
NUWARD[2]	Standard fuel, UO_2 pellets (square 17x17)			< 5% 76	24 (1/2 of core)	-
SMART100[3]	Standard fuel, UO_2 pellets (square 17x17)			< 5% 57	30	< 54
SMR-160[4]	Standard fuel, UO_2 pellets (square 17x17)	3.7 (active length) (SMR 2023)		Average 4% 57	19 (1/3 of core)	45 (basic design)
Rolls-Royce SMR	Standard fuel, UO_2 pellets (square 17x17) Total production of 1 708 FAs (60 years of operation) (Rolls-Royce 2024)	2.8 (active length)		< 4.95% 121	18 (1/3 of core)	50-60
AP 300	Standard fuel, UO_2 or MOX pellets (square 17x17) Later advanced nitride fuel.	2.44 (active length)		< 5% 89	24	> 62

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8.2. Management of RW from SMR

In the case of LW reactors, RW produced will be of the same nature as those from LW reactors in operation today and no specific problematic RW are expected. For some SMRs it is expected that boric acid will not be used in the coolant, which will simplify the RW management system [5]. On the other side, higher amount of HLW may be expected. Innovations in SMR technology will require innovations in RW management.

One of the findings of the "SMR Waste Management in Finland" project (Keto et al. 2022) is that some studies suggest that SMR use may lead to more LILW being generated per GWe year than in large NPPs, but these results need to be verified. It is very likely that RW management methods from existing NPPs will also be applicable to the management of RW from SMRs.

Keto et al. (2024) discusses both centralized and decentralized RWM (LLW, LILW; storage, processing and disposal). Centralised RW management is described as preferable. Decentralised RW management could be more advantageous for sites with multiple SMRs (which is not very likely), as it would reduce the number of RW shipments. A mixed (or hybrid) management approach (some activities would be carried out at the sites and some at a central site) has been identified as an interim option.

The nature of the SMR (compactness, integration, modularity) will simplify decommissioning (less technology). The compactness and modular design of the SMR will allow for easier disassembly of technology units. However, the disassembly of the technology units may be more challenging in the case of integrated reactors; in some cases, the disposal of entire technology units could be considered. For a few types, the transport of the entire reactor module (small size) is considered, sometimes including SF, to the production plant for dismantling using special equipment. This would reduce the radiation protection requirements during decommissioning on site. The modules would also be easier to store until the activity declines, simplifying their further handling.

Formally, there should be less RW from SMR decommissioning due to the smaller amount of technology and components, but on the other hand, in the case of integrated reactors, the amount of activated components may be larger (relative to the power), as parts that are not activated in conventional reactors (steam generator, volume compensator, pumps) will also be activated.

Krall et al. (2022) estimated the amount of RW from the decommissioning of SMR VOYGR and standard PWR (3,400 MWt) (see the chapter 8.1 for more information about the study). These were activated materials (the reactor itself and its surroundings) and materials contaminated by contact with the primary coolant. The higher volume of RW from decommissioning is due to the more extensive activation by the higher neutron flux and the use of neutron reflectors. The VOYGR reactor has a stainless steel reflector around the core which will be highly activated; the total neutron flux at the periphery of the VOYGR SMR core should be comparable to a standard PWR. The thermal neutron flux at the VOYGR reactor vessel should exceed the thermal flux at the pressure vessel of a PWR by a factor of 4.5, so that part of the reactor vessel may also be destined for disposal in the DGR. The VOYGR pressure vessel is located in a containment vessel

[5] The presence of boric acid salts (borates) significantly affects management of RW and the quantity of conditioned RW for disposal.
One option to reduce the amount of RW to be disposed of is to use methods that allow a higher portion of concentrates in conditioned RW. This requires a higher concentrate concentration. The concentration of concentrates with high borates content is significantly affected by their pH-dependent crystallisation. Higher concentrate concentration is problematic at normal operating temperature, as crystallisation is a risk at higher concentrations and the re-dissolution of crystals is quite problematic. In order to avoid borate crystallisation, the whole concentrate treatment process has to be carried out at a higher temperature, which is operationally demanding and standard methods do not allow it.
It is also possible to reduce the amount of RW by removing the borates from the concentrate, for which appropriate technologies are required to achieve a sufficiently low activity of the recovered boric acid for its release as inactive material. The removal of borates from the concentrate would lead to a reduction in its salinity of about 35 to 40 % by weight and thus a reduction of the amount of conditioned waste.

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that will be contaminated and partially activated (LILW), no activated concrete is assumed (the vessel is located in a pool). Compared with a PWR, the NuScale integrated PWR would increase the energy-equivalent volume of long-lived decommissioning LILW in need of geologic disposal by a factor of 9 to 17. Per energy equivalent, a 160-MWth integrated PWR will generate at least a twofold larger volume of short-lived decommissioning LILW than a 3,400-MWth PWR.
Kim et al. (2022) evaluates the nuclear waste attributes of SMRs with the results compared to a reference large PWR. VOYGR (from NuScale Power) was also assessed (see the chapter 8.1 for more information about the study).
For evaluation of RW from decommissioning the following factors were used:

- LLW volume (for near surface repository).
- ILW (for DGR).

Operational RW was not included.
Conclusions for RW from decommissioning for VOYGR were:

- The decommissioning volume of LLW for VOYGR is 10% smaller than that of the reference PWR.
- Compared to the reference PWR, the normalized ILW volume for VOYGR is a factor of six larger (attributed to the reflector blocks added to the core to reduce neutron leakage).

A detailed comparison of the results of the two studies by Krall et al. (2022) and Kim et al. (2022) would only be possible through complex validation of calculations and source information, which would be beyond the scope of this report.
The following areas will need to be addressed for RW management from SMR operation:

- technologies for RW management: possibly a centralised facility for more sites or use of existing NPP sites,
- technologies for decommissioning,
- impact on the disposal concept,
- DGR capacity for HLW/ILW,
- storage capacity for RW (LLW, HLW/ILW),
- International cooperation in case of fleet approach.

Limited information was found in publicly available sources on the anticipated management of SF and RW from SMR operation. It is clear that this area has not yet received the necessary attention in the planning of a SMR project. It is assumed that in the case of the SMR project, already available technologies for RW management will be used or adapted, which is acceptable in the case of LW reactors.

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9. Description of the SF and RW management system and technology for existing and planned NPPs and SMRs for selected European countries

9.1. Czech Republic

9.1.1. Introduction

In Czechia, two NPPs are in operation:

- NPP Dukovany, 4 x VVER 440/213 (output of 4 x 510 MWe), in operation since 1985-1987, planned operation until 2045-2047.
- NPP Temelin, 2 x VVER 1000/320 (output of 2 x 1,125 MWe), in operation since 2002-2003 planned operation until 2061-2062.

The construction of up to four APR1000 type NPPs (generation III+, output of 1,055 MWe) with a minimum lifetime of 60 years is planned:

- Dukovany 5,6 (planned start of operation 2038-2039),
- Temelin 3,4 (planned start of operation 2041-2042).

Construction of SMR is also being considered (details below). At least 60 years of operation of the NPP and SMR is assumed.
In addition to those directly cited, information from the following sources was used in this chapter: Trtílek and Podlaha et al. (2024), Czech Policy (2025), Czech National Report (2024).

9.1.2. Legislation

9.1.2.1. Legislation concerned

The legislation for the peaceful uses of nuclear energy in Czechia has been fully harmonised with the EU legislation. The fundamental legal regulations governing the licensing and approval process for nuclear installations and workplaces of category IV, or for workplaces with sources of ionizing radiation, are the Atomic Act No. 263/2016 Coll. (Act 263), Building Act No. 283/2021 Coll. (Act 283). The Act No. 500/2004 Coll., Code on Administrative Procedure (Act 500), Act No. 100/2001 Coll., on environmental impact assessment and amendments to some related acts (Act 100), and the Act No. 106/1999 Coll., on free access to information, are other important parts of the legislative framework in this area as amended (Act 106). The acts are further linked to regulations of lower legal force.
RW and SF management fully complies with the Policy of Radioactive Waste Management and Spent Fuel Management. The requirements for RW management are defined in the Part IV of the Atomic Act (No. 263/2016 Coll.) (Act 263) and in Decree No. 377/2016 Coll. (Decree 377).

9.1.2.2. Legislative changes

An amendment to the Atomic Act will be effective from 1 July 2025. With regard to SMRs, the amendment responds to the need to adapt licensing processes and regulatory requirements to the advent of new technologies, in particular SMRs, which are being considered for wider deployment in the near future.
In particular, the amendment introduces the possibility of shorter and simpler permitting processes for new NPPs and SMRs, which should speed up the overall process of their introduction in the Czech Republic. It also introduces more precise conditions for the application of the so-called graded approach and the possibility of specific exemptions from regulatory

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requirements, which is intended to allow for a more flexible response to technological innovations and authoritative assessment and state approval of activities with facilities that is currently under development and whose exact parameters will only be known within a few years.
In the case of the thermal energy tariff, the amendment to the Atomic Act will provide not only for research reactors, but also for nuclear facilities whose main purpose is the production of thermal energy (for the prospective heating use of SMRs in the future). A substantial part of the payments to the nuclear account is to cover the costs of activities that will take place in the future. The methodology for setting the level of charges is based on current price relations and takes into account known cost estimates, risks and other relevant factors (e.g. expected development of the national economy, interest rates, inflation, envisaged scenarios for the construction of NPPs in the State Energy Policy) and respects the Policy for RW and SF Management and will be periodically adapted to the published plans of potential investors planning to build NPPs and prospectively for SMRs in the future. The formation of the nuclear account resources is compared with expected future expenditures at reasonable intervals, not exceeding five years, and in the event of significant deviations, the relevant government regulation will be adjusted or an amendment to the relevant provision of the Atomic Act will be initiated.
A completely new institute, following the example of foreign good practices and also Act No. 283/2021 Coll., the Construction Act, is the preliminary information, which should offer clients of the state administration a higher level of legal certainty regarding regulatory requirements and their interpretation by the regulator. Also, the advance information should help to facilitate the process of deployment of new technologies, whether traditional nuclear sources or SMRs.

9.1.3. Policy of the RW and SF management in the Czech Republic

The updated Policy (MIT 2025) is a default document that formulates the principles, procedures and objectives of the state in the management of RW and SF for the period up to approximately 2035 with a view to a longer period (after 2050). An evaluation of how the objectives and targets of the Policy are being met and subsequent updating or refinement is expected after 2035.
The Policy enables organisations that produce or handle RW and SF to develop strategies and plans in line with these principles, objectives and recommendations and to implement them in their activities. The Policy, which is regularly evaluated and updated, recommends effective solutions that ensure the disposal of waste in accordance with the requirements for the protection of human health and the environment, without disproportionately passing on the present consequences of the use of nuclear energy and ionising radiation to future generations.
The aim of the Policy is:

- to establish and specify strategically justified, scientifically, technologically, environmentally, financially and socially acceptable principles and objectives for the management of RW and SF in the Czech Republic,
- to maintain a systematic framework for decision-making by the authorities and organisations responsible for RW and SF management in the Czech Republic,
- to communicate information on the long-term solution for the management of RW and SF in an understandable way to all concerned entities and the wider public, while enabling the concerned public to participate effectively in the implementation of the objectives of the Policy,
- and to provide a framework for the assessment of progress in the management of RW and SF and for the preparation of relevant reports in the framework of the Joint Convention on the Management of RW and SF and Council Directive 2011/70/Euratom.

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New recommendations have been proposed or updated by the update of the policy concerning management of RW and SF from SMRs.

9.1.4. Management of SF and RW at NPPs

9.1.4.1. SF Management

After removal from the reactors, SF is stored for several years in the pools of the main production units and then transferred to dry storage where it is placed in the storage casks.
These storage facilities are located on the premises of the respective NPP:

- Interim store Dukovany with a capacity of 60 casks (600 tHM), the store is full.
- Interim store Dukovany with a capacity of 133 casks (1,340 tHM), with 57 casks of SF in storage as of 31.12.2023.
- Temelin SF with a capacity of 152 OS (1,370 tHM), 65 casks with SF were in storage as of 31.12.2023.

Until the operation of the DGR, SF from NPPs will be stored in transport and storage casks located in SF stores.
Estimation of amount of SF produced is in the chapter 9.1.7.1.

Dukovany NPP
FA contains 126 FPs and 1 central tube. Spacer grids, which are placed along the height of the FA, define the correct position of the FP. On the outside, the FA are completely surrounded by the shroud. A characteristic feature of the FA at the Dukovany NPP is the division into a standard FA and a FA connected to the control organ (so-called control assembly).

SF Pools
The SF pool is constructed next to each reactor unit where SF is stored for a period of time necessary to reduce the residual heat output. In the pools, SF is stored in a compact rack with the capacity of 682 positions. SF pool also contains 17 positions for hermetically sealed containers for damaged SF storage. Damaged SF will be managed during the decommissioning of the NPP. Depending on the number of removed FAs in the annual reactor cycle, the pools enable to store SF for a period of at least 7 to 9 years.

Figure 1: SF pool and transfer cask shaft during reactor refuelling

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As of 31 December 2023, 2,180 FAs with a total weight of approximately 265.2 tHM were stored in all four pools of NPP Dukovany. The removal of damaged FAs from the SF pool is only considered after the end of power production, prior to the start of the NPP's decommissioning.

ISFSF Dukovany

ISFSF Dukovany is designed for dry storage of SF using CASTOR-440/84 casks. The central building of ISFSF Dukovany is a ground-level hall with a combined structural system consisting of fixed reinforced concrete poles and steel roof structure.
The total capacity of ISFSF Dukovany is 60 casks. ISFSF Dukovany contained 60 casks CASTOR-440/84 with the total number of 5040 FAs as of 31 December 2023.

SFSF Dukovany

SFSF Dukovany, connected with ISFSF Dukovany, is used for dry storage of undamaged SF using CASTOR-440/84M and ŠKODA 440/84 casks. The storage capacity of SFSF Dukovany is sufficient to cover all SF production of NPP Dukovany.

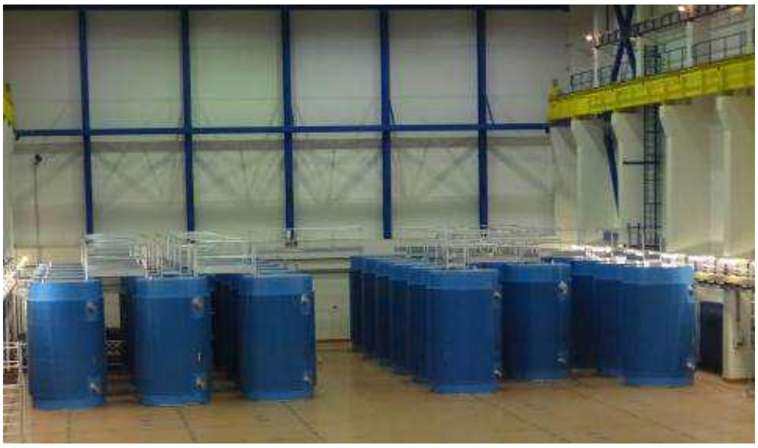

Figure 2: Storage hall in SFSF Dukovany

The storage capacity of SFSF Dukovany is 1,340 tHM in 133 casks. As of 31 December 2023, there were 52 CASTOR 440/84M and 5 ŠKODA 440/84 casks with a total of 4788 pcs of FAs in SFSF Dukovany.

Temelin NPP

FA contains 312 FP, 18 guide tubes and 1 central tube. Spacer grids, which are placed along the height of the FA, define the correct position of the FP. On the outside, the FA is surrounded by stiffening plates in assembly corners to improve mechanical stability. The historical development of the fuel includes the transition from US fuel (VVANTAGE) to Russian fuel (TVSA-T). From 2024 onwards, fuel is again supplied by the Westinghouse company.

SF Pools

The main production building of NPP Temelin provides a storage pool for SF removed from the reactor, immediately next to the reactor cavity. The removed SF is stored in the storage pool for a period up to 12 years (during NPP operation), or for at least 5 years (after NPP decommissioning).
The entire SF pool enables to store 678 FAs, 25 FAs in hermetically sealed containers (10 positions occupied) and 2 cluster cases (one position occupied).
As of 31 December 2023 the SF pool at unit 1 of NPP Temelin contained 397 FAs and 25 individual FPs and the SF pool at unit 2 contained 369 FAs and 24 individual FPs with a total weight of approximately 342.5 tHM.

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Figure 3: Uncovered SF pool at NPP Temelin

SFSF Temelin

The Spent Fuel Storage Facility is used for dry storage of undamaged SF assemblies using CASTOR-1000/19, ŠKODA 1000/19 and ŠKODA 1000/19M casks. The storage capacity of SFSF Temelin is sufficient to cover all SF production of two NPP Temelin units at least till the end of 2037. The capacity will be doubled by the addition of two mirror-oriented storage halls.

Figure 4: Storage hall in SFSF Temelin

The storage capacity of SFSF Temelin is 1370 tHM in 152 casks. As of 31 December 2023 SFSF Temelin contained 48 CASTOR 1000/19 casks with 912 FAs, 5 ŠKODA 1000/19 casks with 95 FAs and 12 ŠKODA 1000/19M casks with 228 FAs.

Nuclear new-build

In the case of the new NPPs Dukovany 5,6 and Temelin 3,4, the procedure will be similar to that for the existing NPPs. After the first SF is removed from the NPP, the fuel will be cooled in pools and stored dry in appropriate storage facilities with a delay of about 5-8 years (assumed to be the same approach as for the current NPPs). A separate storage facility (or a common one for several NPPs) will be located at the NPP site and will be built with a delay compared to the NPP construction. The possibility of central storage is not excluded.

9.1.4.2. RW management

Types and quantity of RW

IAEA RW classification system is applied in Czechia. On the Figure 5 there is a scheme of sorting of RW produced at Czech NPPs.

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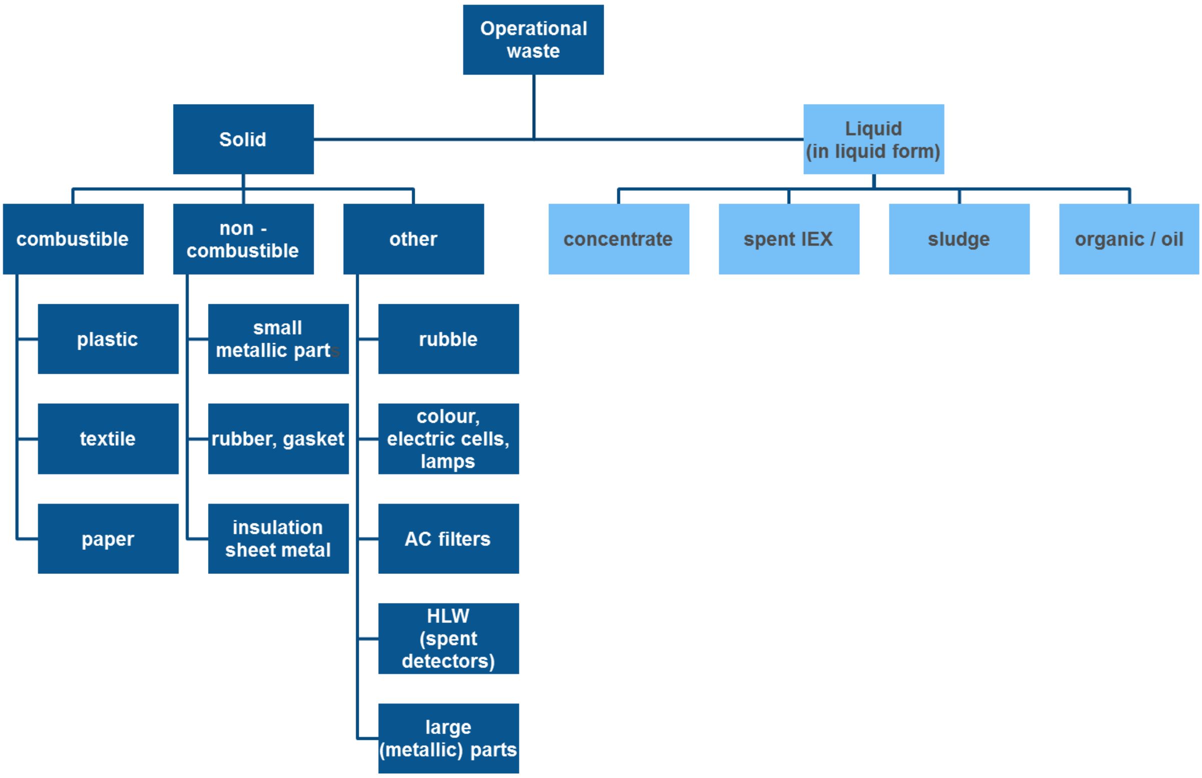

Figure 5: Classification of RW at Czech NPPs

Approximately 200 or 60 m^3 of conditioned RW is produced yearly from operation of the Dukovany or Temelin NPP.

During operation of the NPP, activated items are generated which are stored for the whole period of operation of the NPP and will be disposed of during decommissioning of the NPP (e.g. activated measuring sensors, thermocouples, embedded rods, surveillance specimen cartridges, absorbers). Approximately 60 t is expected for Dukovany 1-4 and 10 t is expected for Temelin 1-2 for a 60-year operation.

Estimation of total amount of conditioned RW for disposal is in the chapter 9.1.7.2.

Gaseous RW

The philosophy of processing of gaseous RW is rather simple and it consists in separation of radioactive materials from contaminated air in the ventilation system by filtration. Gaseous RW is removed using venting technology systems (piping, tanks) and ventilation systems (premises). Gaseous RW is processed in the venting process systems – gaseous RW is either treated or held-up. The treatment includes filtration of radioactive aerosols, including radioactive iodine in the aerosol form. Hold-up means that gas flow is decelerated which causes the activity of short-term radionuclides to drop. Processing of gaseous RW produces solid RW and gas that complies with the requirements for clearance of radioactive substances from a workplace.

Solid RW

Management of solid RW

- Solid LLW

  The management of solid LLW consists of the following steps:
  - Controlled collection and primary segregation of solid RW by the type is performed at stable assigned places, the collected waste is transported from collection points to processing.
  - Measuring and segregation of solid RW.

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  - Clearance of solid waste into the environment – the waste meeting clearance criteria is after measurement cleared from a workplace or disposed of on the dump for solid municipal waste.
  - Storage of solid RW – solid waste which cannot be cleared from a workplace is classified as solid RW and stored in an organized manner in box pallets with the volume 0.4 m^3 and 0.8 m^3 or, after low-pressure compacting (15 t), in 200-liter drums in storage vaults.
  - The part of the solid RW intended for decay storage or for incineration is kept loose in the storage premises in polyethylene bags.
- Solid ILW (waste failing to meet the waste acceptance criteria for disposal in RW disposal facility, non-generating heat)
  If RW cannot be disposed in a RW disposal facility due to its high specific activity, it is stored in an organized manner in a storage area for radioactive items while their final processing and disposal will be addressed within the NPP decommissioning process.

Facilities for processing of solid RW

- Solid LLW
  The part of solid LLW that cannot be cleared from a workplace is processed or treated (incineration, high-pressure compacting, remelting) in external technological facilities and deposited in RW disposal facilities. Non-treated solid LLW is stored in the storage facility.
- Solid ILW
  Solid ILW is not treated but only fragmented (if practicable) and stored under controlled conditions in the storage facility for RW.

Facilities for storage of solid RW

- Solid LLW
  Solid LLW storage system consists of concrete rooms. The rooms are covered with in-situ concrete blocks or closed with hermetic closures. A steel hall is constructed above the storage area to shelter the whole area above the rooms.
- Solid ILW
  Solid ILW is kept in the storage facility for active items in the reactor hall. The anticipated storage time is until NPP decommissioning.

Liquid RW

Management of liquid RW

Liquid RW generated in the process of radioactive liquid media treatment (concentrate, sludge, sorbents) are collected and placed in storage tanks where is stored before processing (bituminization, fixation).

Facilities for processing of liquid RW

The bituminization technology is used for radioactive concentrate conditioning into a form acceptable for RW Disposal Facility Dukovany. The bitumen-based product is than disposed in RW Disposal Facility Dukovany using 200 l drums.
Radioactive sludge and used resins are removed from the tanks, after dewatering are conditioned by fixation into a geopolymer matrix. The mixing of the radioactive sludge and resins with the individual components of the solidifier takes place in a 200 l drum.

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Facilities for storage of liquid RW

The system for storage of liquid RW consists of:

- storage tanks for radioactive concentrate,
- backup or emergency tanks,
- tanks for active sorbents,
- pumps and auxiliary technology equipment.

Liquid RW of the organic origin (oils) are stored in 200 l metallic drums. There are safety sumps under them to accommodate the whole volume of the stored drums.

Nuclear new-build

The estimate of LLW production from the NPP is based on the general requirement for advanced Generation III+ reactors to produce less than 50 m^3 of processed RW per year suitable for disposal per 1 000 MWe of installed capacity (EUR 2021). The reduction of RW volume will be based on commonly available and proven technologies for centrifugation, evaporation, operationally proven membrane processes and selective sorbents, solidification, compacting, incineration, etc. For the conditioning of liquid RW, e.g. the technology of solidification with inorganic solidifiers (cement, geopolymer matrix) or drying can be used. The requirements to minimise the resulting volume of conditioned RW will also be consistently applied to newly built NPPs.

9.1.4.3. RW disposal

RW Disposal Facility Dukovany has been developed in the site of NPP Dukovany to dispose of conditioned LLW from the NPPs (and limited amount of institutional RW).

The disposal facility has been in operation since 1995. The total volume for waste disposal is 55 000 m^3 (about 180 000 of 200 l drums) is sufficient to accommodate all RW from NPP Dukovany and NPP Temelin.

Table 3: Summary data on RW Disposal Facility Dukovany (as on 31 December 2023)

Beginning of operation	1995
Scheduled end of operation	2090
Total volume adapted for the disposal facility	55 000 m^3
Filled volume	13 931 m^3
Free volume	41 069 m^3

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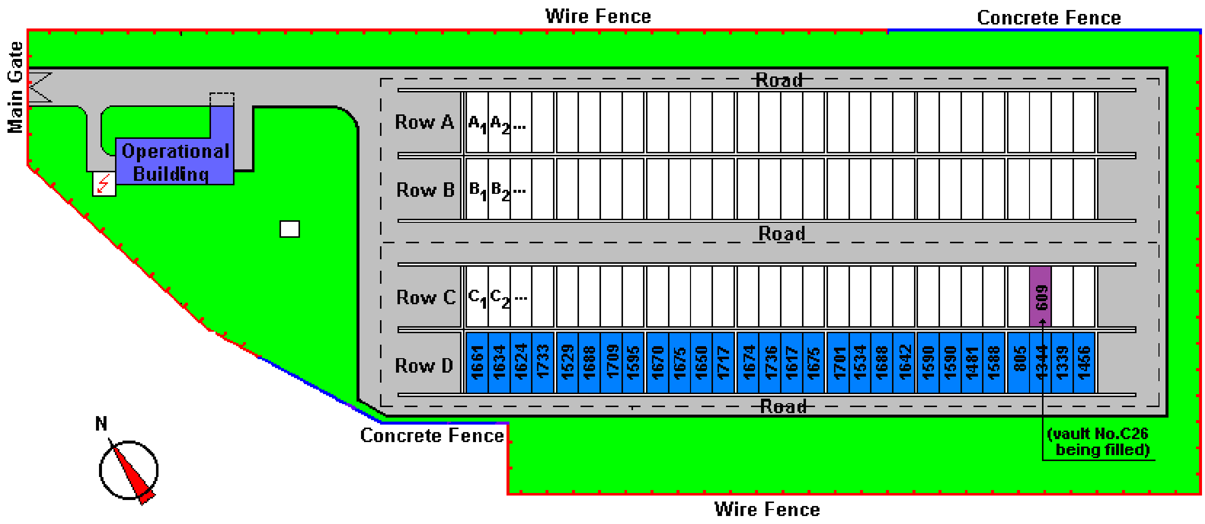

Figure 6: Ground plan and current filling of the disposal units in RW Disposal Facility Dukovany with packages as of 31 December 2023

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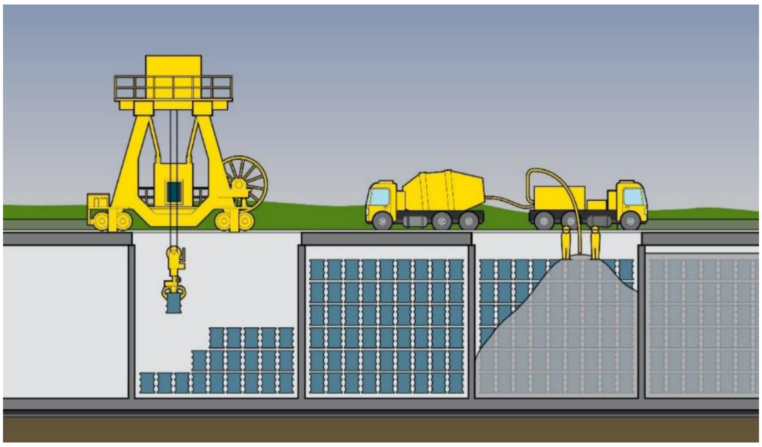

Figure 7: General view of the Dukovany repository, placement of barrels into the box, schematic section of the box during RW placement and concrete filling[6]

9.1.4.4. Decommissioning of NPPs

Decommissioning plans for Dukovany and Temelin NPPs are prepared in accordance with legal requirements in accordance with the Policy of RW and SF Management in the Czech Republic and the operator's intentions. These documents include, inter alia, detailed descriptions of RWM and balance data on RW generated during decommissioning, including the expected timing of their generation.
The decommissioning plan is regularly updated every 5 years on the basis of new experience from the operation of the NPP, new knowledge on the development of technological procedures and activities carried out during decommissioning, as well as with regard to the development of state supervision requirements and legislation, and according to the course of the NPP operation itself. The NPP decommissioning plans allow the operator to formulate a decommissioning approach based on detailed analyses and, on this basis, to gradually secure the necessary technical and financial resources for the development of the decommissioning project and to ensure the implementation of the decommissioning of the NPP.
The relevant Decree sets out the scope and method of decommissioning. The decommissioning methods (options) are:

- immediate decommissioning, where decommissioning activities must be carried out in a continuous sequence from the time decommissioning starts until its completion,
- deferred decommissioning, where the decommissioning activities are divided into a number of successive phases with a time lag between them.

Two basic decommissioning options are considered for existing NPPs - immediate decommissioning and deferred decommissioning. Table 4 shows the most important baseline limits considered.

Table 4: NPP life cycle time data (current NPPs

NPP	Termination of energy operation	Termination of operation	Start of decommissioning	Termination of decommissioning – immediate (deferred)
Dukovany 1-4	2047	2055	2056	2076 (2091)
Temelin 1,2	2062	2067	2068	2083 (2101)

[6] Figures from SURAO promotional materials.

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SF is stored for 7-10 years in a pool, then 40-70 years in a dry way, i.e. an average of about 65 years is considered.
For new NPPs, immediate decommissioning is preferred, but deferred decommissioning is not excluded. It is the responsibility of the contractor/operator to prepare a decommissioning plan that compares the two options (immediate and deferred decommissioning) and proposes a schedule. The operator will decide which of the decommissioning options it prefers.
Table 5 shows the most important baseline limits considered for new NPPs.

Table 5: NPP life cycle time data (new NPPs)

NPP	Termination of energy operation	Termination of operation	Start of decommissioning	Termination of decommissioning – immediate
Dukovany 5,6	2038	2099	2104	2105
Temelin 3,4	2041	2102	2107	2108

9.1.5. Plans for the construction of SMRs

On 1 November 2023, the Government of the Czech Republic approved the MIT material "Czech SMR Roadmap – Applicability and Contribution to Economy" (MIT 2023). Small and medium-sized reactors are understood in the roadmap as reactors with a capacity of up to 700 MWe. On the basis of this document, the area of small and medium-sized reactors will be included in the State Energy Policy and taken into account in the Czech Spatial Development Policy. The aim is for small and medium modular reactors to become complementary to large ones in the 30-40s. The paper summarises the existing knowledge in the SMR sector and the recommendations of the working group. It describes the framework for the possible application of SMR technology in the Czech Republic, including information on Czech projects and offers from foreign manufacturers. The Government Resolution sets out tasks for the preparation of a suitable investment environment in relation to the EU Taxonomy. The material recommends accelerating the process of site selection and preparation so that sites are ready for construction in the first half of the 2030s.
According to MIT (2023), the electricity grid of the Czech Republic will have a power deficit of approximately 2.8 GWe in 2050, which would correspond to about 5-15 SMR units connected to the grid continuously in the 2030s and 2040s. According to its analyses, ČEZ, a. s. also confirms the level of the required power supply of up to 3 GWe. The material lists 45 potential sites for SMRs (existing sites with conventional power plants, heating plants, other significant heat sources); other potential sites are existing NPPs and the potential nuclear site Blahutovice. Locations outside the above sites are also possible.
The material also contains recommendations for the management of SF and RW:

- Ensure the disposal capacity for new nuclear sources (including SMRs) or examine the options of building a new facility in a new location or disposal on the site of the deep repository for SF and RW under preparation.
- Ensure adequate capacity for SF storage in the deep repository project.
- Update estimates of operational RW produced and the inventory of SF.
- Prepare estimates of the expected inventory and economics of SF and RW and storage capacity of RW from SMR reactors and incorporate them into the update of the RW and SF Management Policy.
- Consider SF as a possible source of fissile material for fuel for Generation IV reactors and take this into account in plans for its disposal in a deep repository.

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In terms of quantities of SF and operational RW, predictions for storage capacity requirements from SMRs will need to be continuously refined and updated once the technology supplier is known.
Rolls-Royce SMR Limited (Rolls-Royce SMR) and ČEZ Group (ČEZ) will join forces to bring their global capabilities and know-how to the deployment of Rolls-Royce SMR's small modular reactor (SMR) technology. This is enabled by an equity investment by ČEZ into Rolls-Royce SMR and a strategic partnership to deploy up to 3GW of electricity in the Czech Republic using Rolls-Royce SMR power plants (ČEZ 2024).
The pilot project in the Czech Republic should be an SMR reactor at Temelin with an installed capacity of 470 MWe and announced start-up in 2035. ČEZ plans to apply for a siting permit at the end of 2025. Application for a construction license is planned at the end of 2026. There are plans for the construction of up to 5 additional SMR reactors also at the so far non-nuclear sites. In addition to ČEZ Group, ORLEN Unipetrol RPA s.r.o. and Sokolovska uhelna, a. s., SUAS Group a.s. are evaluating the possibility of using SMR technology at their sites without a binding indication of the number of units and schedule at present.

9.1.6. Expected management of SF and RW from SMR

9.1.6.1. SF management

So far, only limited information is available on the assumed SF. The starting points for the SF and the back end of the SMR fuel cycle are as follows:

- UO_2-based fuel with a maximum enrichment of up to 5%, square grid (type 17 x 17), FA length of about 2.8 – 3 m, number of FAs in the core 121 (Rolls Royce SMR),
- length of fuel cycles 18 to 24 months,
- after removal of SF from the reactor core, storage in the storage pool for 4 to 5.5 years is envisaged,
- open fuel cycle,
- SF stored in type-approved casks of type B(U)F and S,
- the possibility of a central storage facility for storage of SFs from SMR operation is being considered,
- the use of MOX fuel is not considered.

The method of management of SMR SF will be similar to SF from operating NPPs.

9.1.6.2. RW management

Limited information on the assumed management of RW from SMRs was found in publicly available sources. The generation of problematic RW is not foreseen; already available technologies can be used for the RWM. It is assumed that the operation of LW SMRs should produce more RW per unit power than large reactors.
The Rolls-Royce SMR will not use boric acid in the coolant, which would simplify the RW management system. Information is provided in Rolls-Royce (2024) regarding the management of RW from the Rolls-Royce SMR, 470 MWe.
Processing of gaseous RW consists of:

- collection, drying and recombination of gaseous effluents or filtration on HEPA filters,
- passing through charcoal (activated carbon)-based beds to abate radioactivity via adsorption hold-up delay to permit decay,
- discharging to the environment via the stack (where monitoring is provided).

The delay beds in these systems will consist of activated charcoal that may require replacement, though operating experience indicates that these beds might be able to operate for the full 60-year operational life. If replacement is required, it is anticipated that this material will be LLW,

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but could potentially (though it is unlikely, due to the short half-lives of relevant radionuclides) comprise ILW (e.g. in the event of a fault).
Processing of liquid RW consists of:

- prefiltration by backwashable filters,
- reverse osmosis process using membrane separation to separate a purified permeate from a concentrated retentate,
- ion exchange polishing in resin beds to demineralise permeate from upstream reverse osmosis process,
- vacuum evaporation for volume reduction of retentate from upstream reverse osmosis process.

Processing of solid RW consists of:

- LLW
    - Wet waste processing system is currently assumed to take the form of a cementitious grouting plant.
    - Processing of dry waste involves a variety of activities, such as loading soft waste into 200 litre waste drums and compacting them in the in-drum compactor, size reducing pieces of equipment where practicable in the fume cupboard, loading pieces of waste into waste packages (such as soft-sided packages).
- ILW
    - Cementitious grouting was selected as the preferred option for conditioning wet ILW (resins, filter solids, concentrates).
    - There is no treatment system for dry ILW.
    - Decay storage before disposal into LLW repository
- Higher Activity Waste (Non-Fuel Core Components, ILW)
    - Long-term storage before disposal into DGR

The classification and quantity of solid RW per year is:

- dry HLW – neutron measurement sensors,
- dry ILW – miscellaneous operational RW, activated metal objects (0.3-0.7 m^3),
- wet ILW – resins (2.22 m^3), concentrates (1.46 m^3), suspended filter solids (0.8 m^3); total of 12 drums (probably 500 l volume) for disposal,
- dry LLW – HVAC filters (4.0 m^3), membranes (0.8 m^3), dry active waste (25.0 m^3), metallic waste (3.0 m^3), other operational (quantity undefined); total of 361 drums for disposal,
- Wet LLW – resins (quantity undefined), concentrates (quantity undefined), sludges (0.25 m^3), oils and solvents (1 m^3); total 33 drums for disposal.

The total expected quantity of drums is 406 per year, i.e. about 85 m^3/year of conditioned operational RW for disposal. It would correspond to approx. 180 m^3/year/1000 MWe that is much more than 50 m^3 according to requirements of EUR (2021). The amount of RW produced and processed will have to be estimated with respect to expected RWM in Czechia.

9.1.6.3. Decommissioning of SMRs

For SMRs, a minimum lifetime of 60 years is assumed. An immediate decommissioning option is assumed; a deferred decommissioning option will also be evaluated in the context of the

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development of the decommissioning plans. Cooling of the SF is considered for 5 years after all FAs have been removed from the reactor core.
Rolls-Royce (2024) provides general information regarding the decommissioning of the Rolls-Royce 470 MWe SMR.
The proposed decommissioning phases include:

- Phase 1 (5 years): Pre-closure preparatory work: This work will commence approximately five years prior to final cessation of generation to avoid delays in the transition to decommissioning. Key regulatory submissions in support of this phase include (but are not limited to) the final core safety case, the detailed decommissioning plan / near-term work plan, and revisions to the licence compliance arrangements.
- Phase 2 (5-20 years): Defueling and post operational cleanout (POCO): Defueling (involving initial cooling of SF in the SF pool and transfer to the intermediate SF store) will be carried out using the operational fuel handling equipment, procedures, and safety case. Retrieval, processing and packaging of operational wastes (for example, filters, in line with operational procedures), along with decontamination of the primary circuit, will take place in the early stages of decommissioning. Turbine island decommissioning will take place after the completion of defueling. Various systems will need to remain operational to support the above tasks (for example the SF pool and associated systems), but any that become redundant at shutdown will be removed as soon as practicable.
- Phase 3 (5-20 years): Reactor de-commissioning: All remaining plant, equipment and buildings (including the reactor and primary circuit but excluding the ILW and SF stores) will be decommissioned, and the associated waste managed, at this stage. A decommissioning waste management facility will be required for decontamination and dismantling operations, noting that there is the potential for re-use of the turbine island area to site this facility. Radiological surveys, excavation of structures and delicensing activities will also occur during this stage.
- Phase 4 (70 years): ILW and SF Storage: The volumes of operational and decommissioning waste to be managed at this stage are uncertain, and the required stores are in the preliminary stages of design. Therefore, the nature of the storage is not yet finalised, but this phase is planned to be largely quiescent with primarily non-routine activities (including maintenance, inspections, and recladding of buildings) taking place. There is potential for some site clearance to occur during this phase if benefit could be provided by reducing the area of land covered under the site license.
- Phase 5 (2 years): Remobilisation for waste disposal: This phase will align in terms of timing with the DGR becoming available for the acceptance of ILW. Personnel will be mobilised to the site to retrieve ILW packages and transfer them offsite (for DGR disposal), and the ILW store will be demolished once this is complete (leaving only the SF store / hot cell buildings on site).
- Phase 6 (5-10 years): ILW and SF disposal: This phase will commence with the refurbishment of the Hot Cell building (for repackaging), after which the SF casks will be retrieved from the SF store, and the SF repackaged into the DGR-compliant casks in the hot cell for offsite transfer (DGR disposal). All remaining materials and wastes will be managed in accordance with the waste hierarchy.
- Phase 7 (6 years): Final site clearance and delicensing of site for re-use: This final stage will involve the removal and clearance of all remaining structures and materials followed

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by monitoring, remediation and landscaping activities such that decommissioning can be completed, and environmental permits and the nuclear site license rescinded.

It is noted that depending on site specific requirements, these phases may be flexible and can be done in parallel as they may not need to be done at the plant site itself. There is potential for the timescales to be reduced, especially if the DGR becomes available during this time.
An estimate of the amount of RW from decommissioning is not available.

9.1.7. Comparison of RW and SF management between SMR and existing and planned NPPs

9.1.7.1. SF management

So far, only limited information is available on the assumed SF from LW SMR operation. It is expected to be a shortened standard fuel for LW reactors, with similar enrichment. The burnup will be similar or lower than the fuel for standard NPPs. The method of management of SF from SMR will be similar to SF from operating NPPs.
An assessment of the quantities of SF is included in the update of the Policy for RW and SF Management in the Czech Republic.

Table 6: Predicted inventory of SF (in DGR) updated in (MIT 2025)

Origin of SF	SF inventory (tHM)
Dukovany 1-4	2 518
Temelin 1,2	2 553
Nuclear new-build (up to 4 units)	up to 5 050
SMR (up to 6 units)	up to 4 377

It will be necessary to update the quantity of HLW to be disposed of in the DGR when the required information is available and to ensure sufficient disposal capacity in the DGR.

9.1.7.2. RW management

The Rolls-Royce SMR will not use boric acid in the coolant, which would simplify the RW management system. The generation of problematic RW from SMRs is not foreseen; already available/applicable technologies can be used for the RWM.
Expected management of RW from SMR operation in Czechia is:

- cementation of concentrates, fixation of sorbents and sludge into geopolymer matrices,
- incineration, high-pressure compacting,
- use of mobile processing lines at the SMR site and services of external contractors,
- the possibility of a central processing facility is not currently considered (also linked to the implementation of the construction of the number of units at the site),
- the possibility of incinerating waste domestically is also being considered, subject to a techno-economic assessment.

As the amount of conditioned RW from the SMR operation to be disposed of in the repository is not yet known, an estimate of 50 m^3/GWe increased by a factor of 1.1 is used, considering the expected larger amount of RW from the SMR operation (i.e. 55 m^3/GWe), i.e. about 26 m^3/year.
An assessment of the quantities of RW is included in the update of the Policy for RW and SF Management in the Czech Republic. The data will be further refined depending on the progress of the work in the area of preparation and implementation of the planned NPPs and SMRs.

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Table 7: Predicted inventory of RW as provided in the draft of updated (MIT2025)

Waste category	Waste origin	Volume/weight (m3/t)
Low- and intermediate level waste (meeting WAC of RW disposal facilities)	*Operational RW from NPPs (to RW Disposal Facility Dukovany)*	
	• 60 y of operational lifetime of existing NPP units	8 573 m^3
	• 60 y of operational lifetime of planned NPP units	up to 12 720 m^3
	• 60 y of operational lifetime of planned SMR units	up to 9 360 m^3
	RW from NPPs decommissioning (to RW Disposal Facility Dukovany) – immediate decommissioning	
	• 60 y of operational lifetime of existing NPP units	9 760 m^3
	• 60 y of operational lifetime of planned NPP units	up to 9 600 m^3
	• 60 y of operational lifetime of planned SMR units	up to 7 218 m^3
Intermediate- and high-level waste (not meeting WAC of RW disposal facilities – to DGR)	*Operational RW and RW from decommissioning*	
	• 60 y of operational lifetime of existing NPP units	2 934 t
	• 60 y of operational lifetime of planned NPP units	up to 2 800 t
	• 60 y of operational lifetime of planned SMR units	up to 3 012 t

For the existing NPP, the capacity of the Dukovany repository is sufficient for all operational and decommissioning RW. However, the capacity of the Dukovany repository is not sufficient for RW from operation and decommissioning of more than one new NPP (SMR). A possible solution could be to dispose LLW in the existing (or expanded) Dukovany repository; and to dispose VLLW in a new repository. Due to the expected volume of VLLW from NPP decommissioning, it might be appropriate to build a disposal facility for VLLW at the NPP sites, so that large volumes of this RW do not have to be transported.
RW not acceptable to the LLW repository will be disposed of in the DGR, which will be put into operation after 2050. It will be necessary to update the amount of RW to be disposed of in the DGR and to ensure sufficient disposal capacity in the DGR.

9.1.8. Applicability of the existing system for management of SF and RW to SMR

9.1.8.1. Selection of storage method for SF from SMR

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The method of management of SF from SMR will be similar to that for SF from operating or new NPPs. The fuel will be stored in at-reactor pools after removal from reactors for several years. Then the fuel will be transferred to long term SF stores. Dry storage is assumed, suitable transport/storage casks need to be developed. It would be inefficient (in terms of cost, security, permitting and stakeholder relations) to build a storage facility at each site; existing storage facilities at Temelin and Dukovany (or an extension of their existing capacity) could be used for storage of SF or a central storage facility could be built. It will also be necessary to analyse the conditions for transporting SF from power reactors, which are not yet implemented in the Czech Republic, incl. suitable transport routes.
In terms of the quantity of SF, predictions of storage capacity requirements from SMRs will need to be continuously refined and updated once the technology supplier is known.

9.1.8.2. Selection of technology for processing of RW from SMR

It is not only the waste from SMRs that will be added to the RWM system, but also the infrastructure needed to process it. Technologies for collection, sorting and pre-treatment of RW are usually an integral part of the design and delivery of the NPP of the relevant type. The technologies for treatment, and especially for conditioning, are, on the other hand, conceived as optional, depending on the requirements of the investor or its domestic legislation and the existing or foreseen downstream infrastructure. The technology or the final product (e.g. solidification matrix) should meet at least the following conditions:

- Comply with the acceptance criteria of existing or envisaged repositories or, where appropriate, modify these conditions in a timely manner on the basis of appropriate safety analyses.
- Be compatible as far as possible with downstream infrastructure or be modified or supplemented by it.
- Be verified.
- Supporting engineering background should be established for the modification of processing procedures.
- The technologies selected for SMR should be the same as those used in the future on existing and new NPPs.

Once the contract with the selected SMR contractor has been concluded, the analysis will include a detailed assessment of the design link between the RW processing technologies and the existing infrastructure. It can be assumed that for solidification of liquid RW, e.g. cementation of highly preconcentrated concentrate may be used, or small quantities of waste types may be generated for which disposal in DGR may be effective (e.g. sorption cartridges and/or in-reactor sensors). In such a case, the question of their storage until the opening of the DGR will have to be addressed. The assessment will also include the expected radionuclide composition of the waste, which may differ from that typical of VVER plants with respect to the construction materials, fuel used and the chemical regime of the primary circuit. While no significant change is expected, the impacts will be reflected in the analysis of disposal volumes and in the safety analyses of the repositories.
In the context of the deployment of SMRs even at the today's non-nuclear sites, and with regard to the efficient use of technical and professional human capacities, it is also advisable to deal with the processing of RW from these units (and the storage of SF) in a centralised manner (e.g. for the first SMR at an existing nuclear site) and possibly also using mobile technologies. A detailed assessment of the possible alternatives will have to be carried out.

9.1.8.3. Disposal of SF and RW for SMR

The capacity of the currently available LLW repository is not sufficient for SMR RW, therefore a suitable solution will have to be found (see chapter 9.1.7.2). The SMR RW must meet the

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acceptance criteria of existing or envisaged repositories, or these criteria must be modified in due time on the basis of appropriate safety analyses.
RW unacceptable to the LLW repository will be disposed of in the DGR that will be commissioned after 2050. It will be necessary to update the quantity of RW to be disposed of in the DGR and to ensure sufficient disposal capacity in the DGR.

9.1.9. Conclusions for the Czech Republic

In Czechia, two NPPs with 6 units are in operation, construction of up to four new large units is planned. Construction of SMR is also considered. The pilot project in the Czech Republic should be Rolls-Royce SMR at Temelin with an installed capacity of 470 MWe and announced start-up in 2035. There are plans for the construction of up to 5 additional Rolls-Royce SMR reactors also at the so far non-nuclear sites. In addition to ČEZ Group, other companies are evaluating the possibility of using SMR technology at their sites.

Legislation and Policy of RW and SF management

With regard to SMRs, the amendment to the Atomic Act responds to the need to adapt licensing processes and regulatory requirements to the advent of new technologies, in particular SMRs, which are being considered for wider deployment in the near future. In particular, the amendment introduces the possibility of shorter and simpler permitting processes for new NPPs and SMRs, which should speed up the overall process of their introduction in Czechia. It also introduces more precise conditions for the application of the so-called graded approach and the possibility of specific exemptions from regulatory requirements, which is intended to allow for a more flexible response to technological innovations and authoritative assessment and state approval of activities with facilities that is currently under development and whose exact parameters will only be known within a few years.
Management of RW and SF from NPP operation fully complies with the Policy of Radioactive Waste Management and Spent Fuel Management in the Czech Republic. New recommendations have been proposed or updated by the update of the policy concerning management of RW and SF from SMRs in 2025. An assessment of the quantities of SF and RW is included in the update too. Special attention is paid to the required capacities of RW and SF repositories. The data will be further refined depending on the progress of the work in the area of preparation and implementation of the SMR.

Management of SF and RW at NPPs

After removal from the reactors, SF is stored for several years in the pools of the main production units and then transferred to dry storage where it is placed in the storage casks. Until the operation of the DGR, SF from NPPs will be stored in transport and storage casks located in SF stores. Storage capacity will be expanded to meet needs of currently operated and planned NPPs and SMRs.
RW from NPP operation is continuously processed at the NPP sites and disposed of in the Dukovany LLW repository. RW that does not meet the acceptance criteria for disposal in the LLW repository, is stored and will be disposed of in the future in the planned DGR. RW from operation of new NPPs and SMR will be managed similarly.

Applicability of the existing system for management of SF and RW from SMR

SF management

So far, only limited information is available on the assumed SF from SMR operation. It is expected to be a shortened standard fuel for LW reactors, with similar enrichment. The burnup will be similar or lower than the fuel for standard NPPs. The method of management of SF from SMR will be similar to SF from operating NPPs. Dry storage is assumed. It would be inefficient (in terms of cost, security, permitting and stakeholder relations) to build a storage facility at each

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site; existing storage facilities at Temelin and Dukovany (or an extension of their existing capacity) could be used for storage of SF or a central storage facility could be built. SF will be disposed in the planned DGR that will be commissioned after 2050.

RW management

Limited information on the assumed management of RW from LW SMRs is available. The generation of problematic RW is not foreseen; already available technologies can be used for the RWM. It can be assumed that for solidification of liquid RW, e.g. cementation of highly preconcentrated concentrate may be used, or small quantities of waste types may be generated for which disposal in DGR may be effective (e.g. sorption cartridges and/or in-reactor sensors). In such a case, the question of their storage until the opening of the DGR will have to be addressed.

The expected radionuclide composition of the waste, which may differ from that typical of VVER plants with respect to the construction materials, fuel used, and the chemical regime of the primary circuit will be also assed. While no significant change is expected, the impacts will be reflected in the analysis of disposal volumes and in the safety analyses of the repositories.

It is also advisable to deal with the processing of RW from SMR units in a centralised manner (e.g. for the first SMR at an existing nuclear site) and possibly also using mobile technologies. A detailed assessment of the possible alternatives will have to be carried out.

The capacity of the currently available LLW repository is not sufficient for SMR RW, therefore a suitable solution will have to be found. The SMR RW must meet the acceptance criteria of existing or envisaged repositories, or these criteria must be modified in due time on the basis of appropriate safety analyses. RW unacceptable to the LLW repository will be disposed of in the DGR.

9.2. Finland

9.2.1. Introduction

In Finland, there are currently five nuclear reactors in operation: Fortum Power and Heat Oy operates two VVER-440 units at Hästholmen, Loviisa, and Teollisuuden Voima Oyj operates two BWR units and one EPR unit at Olkiluoto, Eurajoki. (TEM1) (TEM 2)

- NPP Loviisa, 2 x VVER-440/V-213 (output of 2 x 507 MWe), in operation since 1977 and 1980, planned operation until 2050.
- NPP Olkiluoto, 2 x ASEA-III, BWR-2500 (output of 2 x 890 MWe), in operation since 1979 and 1982, planned operation until 2038 (with possible extension under consideration).
- NPP Olkiluoto, 1 x EPR (output of 1 x 1,600 MWe), in operation since 2023, planned operation for 60 years (until around 2083).

Potential for new builds in the future are being studied with SMRs among the options. In addition, some municipal energy companies have shown interest in nuclear power, specifically building SMRs for district heating purposes or cogeneration of heat and electricity.

The SF from the operating power plants is managed by Posiva Oy, which is owned by the two companies currently producing nuclear energy in Finland: Teollisuuden Voima Oyj (TVO) and Fortum Power and Heat Oy. Posiva is responsible for the final disposal of spent fuel produced by their owners at the ONKALO® facility (ONKALO® is a registered trademark of Posiva). The operating license of the facility is currently under review by the authorities. LILW is managed by the producing companies themselves locally at the NPP sites.

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9.2.2. Legislation

9.2.2.1. Legislation concerned

Finland's legislative framework for managing SF and RW is based on the Nuclear Energy Act (990/1987) and Radiation Act (859/2018). In addition, binding regulations are given in Decrees by Ministry and Government, of most relevance here is the Nuclear Energy Decree (161/1988), and STUK Regulations issued by the Radiation and Nuclear Safety Authority (STUK) including also specific regulation on safe disposal of nuclear waste (Y/4/2018). Detailed safety requirements on management of SF and RW are presented in the YVL Guides by STUK.
The construction of a nuclear facility of considerable general significance, like NPPs, storages and nuclear waste disposal facilities require a Decision-in-Principle (DiP) by the government, which is ratified by the Parliament. In this process, the need for the facility is assessed from the perspective of the overall good of society. The application should include an assessment of the environmental impacts of the facility (EIA) and its safety. The municipality where the facility is to be built has a veto right and public hearings are organized during the process, meaning that in practice Finland has a consent-based siting process for a nuclear facility. Separate licenses are needed for construction, operation, and decommissioning of the facilities. The licenses are granted by the government, or in case of near-surface disposal for VLLW by STUK.

9.2.2.2. Legislative changes

The Finnish nuclear energy legislation and related regulations are currently being renewed comprehensively. The key principles of the renewal are according to Liukko et al. (TEM 2020):

- Finland will continue to ensure compliance with international agreements, commitments and best practices related to the use of nuclear energy.
- It is necessary to keep in place a licensing system that covers the entire life cycle of nuclear facilities and transparently and effectively upholds democratic decision-making. However, there is room for improvement in the permit system.
- Requirements and expectations for the safety and technology of a nuclear facility as well as for the relevant actors and authorities at different stages of the life cycle of the nuclear facility must be clearly specified and proportionate to the risks arising from the operations to people, the environment and society.
- The concepts used must be clear and understandable.

The working group's guidelines on the development of the licence system would also promote the implementation of modular and serial-produced nuclear facility (SMR) projects.
Recent comments, prior to releasing the drafts of the new law and regulations for public consultation, from a STUK representative raised the following (STUK 2024a).

- The main objectives for the reform are to increase risk-awareness and emphasize the responsibility of license holders.
- Requirements will be more risk-informed, focusing regulatory and operator attention on the most significant safety issues. STUK's regulatory guidelines are also being developed to be more enabling, allowing for new and diverse nuclear solutions (such as SMRs), or use of nuclear energy for new purposes (e.g., district heating, or marine reactors) provided operators ensure safety.
- While safety remains the core focus, the reform seeks to streamline licensing for new nuclear facilities and create conditions favourable to the deployment of SMR, without compromising the high safety standards for existing and future nuclear plants.

9.2.3. Policy of the RW and SF management

The policy on the management of SF and RW is described in the National Programme (MEAE 2022). Long-term safety, environmental protection, and public acceptance are core objectives. Other key items of the waste management policy include:

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- SF and RW shall be managed and disposed of in Finland.
- Isolation of SF and RW from the living environment is carried out by means of disposal of SF and RW.
- Management of SF and RW is to be implemented mainly during the generations that produce the waste.
- Defined responsibilities for SF and RW management and its financing.

The “polluter pays” principle is central: nuclear operators are financially responsible for the entire lifecycle of waste management, including decommissioning, with annual financial provisions paid into the National Nuclear Waste Management Fund to ensure that sufficient resources are always available-even in cases of operator insolvency.
For currently operating NPPs, these principles are implemented through immediate or phased decommissioning strategies, the ONKALO® DGR (using the KBS-3V multi-barrier system) for SF disposal, LILW facilities at NPP sites with strict regulatory oversight to maintain radiation exposures below acceptable limits. (990/1987)(STUK 2020)(STUK 2024b)

Classification of radioactive waste
The Finnish RW classification system is in accordance with IAEA classification and includes two main categories: nuclear waste, and RW not originating from the use of nuclear energy and the associated nuclear fuel cycle (non-nuclear RW). Waste classification according to disposal route is illustrated in Figure 8.

The Nuclear Energy Act defines SF from the operation of nuclear reactors as nuclear waste. The classification system for the predisposal management of LILW from nuclear facilities, including NPPs, is based on activity concentrations. The classification for the disposal purpose distinguishes short-lived and long-lived waste as given in Regulation STUK Y/4/2018. (STUK 2024b)

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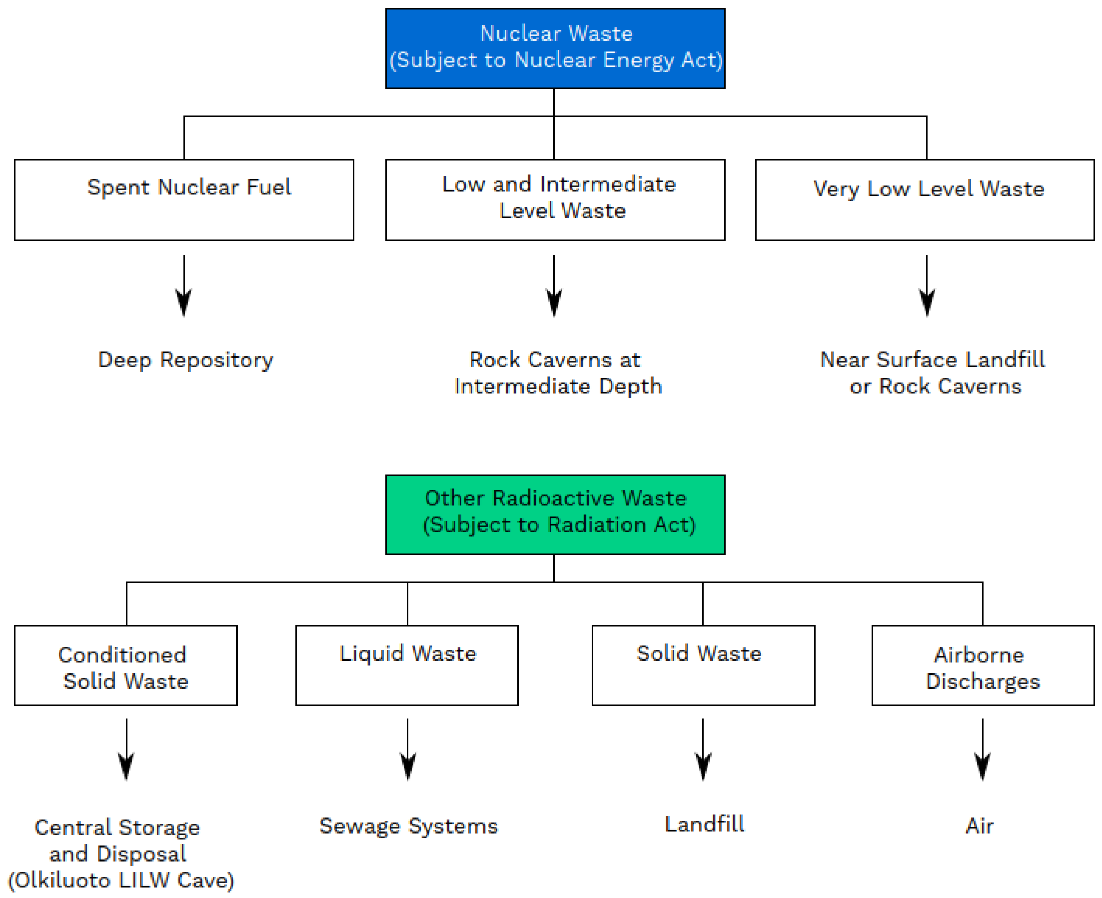

Figure 8: Classification of RW for disposal purpose (STUK 2024b)

9.2.4. Management of SF and RW at NPPs

9.2.4.1. SF Management

Management of SF from the operating NPPs is based on a multi-stage system that ensures both operational safety and long-term isolation from the biosphere. After removal from the reactor, SF is stored in on-site wet pools at each NPP for one to five years to provide shielding and cooling and to allow for the decay of short-lived radionuclides. Following this initial phase, the fuel is transferred to dedicated interim storage facilities at the plant sites – an integrated pool-type facility at Loviisa and a separate on-site facility at Olkiluoto, where SF is stored for several decades. The final stage is deep geological disposal at the ONKALO® repository in Olkiluoto, constructed 400–450 meters depth in crystalline bedrock, which is designed to accommodate all SF from the operating reactors using the KBS-3V concept with copper canisters of cast-iron inserts, bentonite clay barriers, and the surrounding host rock as natural protection.
Total projected inventory of SF from NPPs for final disposal is approximately 6,500 tonnes of uranium, which will be encapsulated in about 3,250 canisters and emplaced in the ONKALO® DGR at Olkiluoto (STUK 2024b). The following figure includes the timetable of SF management from Loviisa and Olkiluoto (all units, including OL3 EPR), based on operational lifetime projections.

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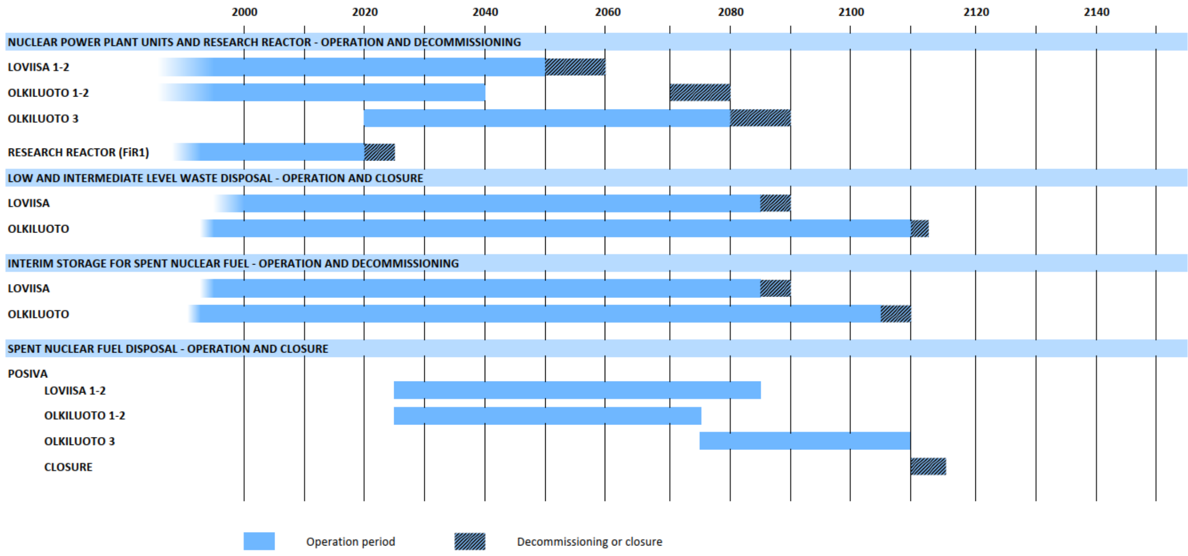

Figure 9: Timetable for the management of SF from NPPs in Finland (STUK 2024b)

SF Management of Loviisa NPP (VVER-440)

At the Loviisa NPP, which operates two VVER-440 units, SF is first stored in the reactor building pools for an initial cooling period of 1–5 years. After this, it is transferred to a separate integrated pool-type interim storage facility located on-site. The facility has been expanded with denser fuel racks to ensure sufficient capacity for the plant's operational lifetime, currently licensed until 2050.

The interim storage is designed for approximately 40 years, enabling further decay of heat and radioactivity. When the fuel is ready for final disposal, it is loaded into robust transport casks and shipped to the encapsulation plant at Olkiluoto. There, the fuel assemblies are placed in copper canisters with cast-iron inserts, which are then transferred to the ONKALO® DGR. The repository is designed to be able to accommodate the estimated total inventory of SF from Loviisa, with disposal operations scheduled to be completed by the 2080s.

SF Management of Olkiluoto NPP (BWR units)

The Olkiluoto NPP comprises two BWR units (OL1 and OL2), with a third EPR unit (OL3) also on the site. At Olkiluoto, SF from all reactor units is initially stored in on-site wet pools for a period of several years.

The interim storage facility, common to all reactor units, has been expanded to accommodate storage needs for up to 50 years, including provision for future decommissioning. After the interim storage period, the SF is transferred to the encapsulation plant at Olkiluoto, where it is sealed in copper canisters with cast iron inserts. These canisters are then emplaced in the ONKALO® repository.

The repository is designed to accept up to 6,500 tonnes of uranium, corresponding to about 3,250 canisters, and will be expanded as needed to accommodate the entire inventory from Olkiluoto's BWR units.

SF Management of Olkiluoto NPP (EPR units)

The Olkiluoto EPR unit (OL3), which began commercial operation in 2023, follows the same SF management approach as the BWR units. SF is initially stored in the shared wet pool facility, benefiting from the expanded capacity developed for the BWR units. The fuel will remain in interim storage for approximately 40 years, after which it will be transferred for encapsulation and final disposal in the ONKALO® DGR.

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The EPR FAs are compatible with the KBS-3V disposal system, and the repository's design and operational schedule have been adjusted to accommodate the additional inventory from OL3. The first EPR FAs are expected to be disposed of by 2090, in line with the overall schedule for SF management and disposal. The management practices for OL3 are integrated with those for the other Olkiluoto units and are subject to the same regulatory oversight and safety requirements.

9.2.4.2. RW Management

Type and quantities of RW

According to STUK(2024b), as of the end of 2023, the cumulative volume of LILW disposed of or in storage at the NPP sites is approximately 11,100 m^3:

- Loviisa NPP: approximately 4,100 m^3 (excluding activated metal waste)
- Olkiluoto NPP: approximately 7,000 m^3 (excluding activated metal waste)

Activity inventories for LILW are reported as Loviisa (~18 TBq) and Olkiluoto (~78 TBq).
Finnish NPP operators manage VLLW through a combination of on-site storage, disposal in dedicated or existing repositories, and recycling or clearance for landfill. TVO has complete an environmental impact assessment (EIA) process for a surface disposal facility for VLLW at Olkiluoto (TEM 2022) (STUK 2024b) (TVO 2020) (TVO 2021).

Gaseous RW

Gaseous RW is generated primarily from reactor operation and maintenance activities. These wastes are managed through advanced filtration systems, including high-efficiency particulate air (HEPA) and carbon filters, which capture radioactive particles and volatile isotopes such as iodine and noble gases (Kr-85). The filtered air is then released under strictly controlled and monitored conditions, ensuring that emissions remain well below regulatory limits-typically less than 1% of the maximum allowed by Finnish authorities. Continuous monitoring and regular reporting to the Radiation and Nuclear Safety Authority (STUK) are mandatory, ensuring transparency and public safety.

Solid RW

Solid LILW includes contaminated metals, spent ion-exchange resins, filters, protective clothing, and other operational debris. These materials are treated by compaction or cementation to reduce their volume and immobilize radioactivity. The conditioned waste is then placed in containers, which are transported to and disposed of in engineered rock caverns excavated in bedrock at each NPP site – 110 meters deep at Loviisa and 60–100 meters at Olkiluoto.
The repositories are designed to accommodate all operational and decommissioning waste generated over the lifetime of the plants. For example, Loviisa produces about 100–150 m^3 and Olkiluoto about 150–200 m^3 of operational waste annually, and both repositories are sized to also serve as final disposal sites for decommissioning waste when the plants reach the end of their service life. All containers are appropriately marked and recorded, and the transport and emplacement procedures are strictly regulated.

Liquid RW

Liquid RW arises from reactor coolant purification, decontamination, and other plant processes. In Finland, liquid RW is typically treated by evaporation to reduce its volume by up to 90%, with the radioactive concentrate subsequently mixed with solidifying agents such as bitumen or cement.
The resulting solidified waste is then packed in barrels and further cemented before final disposal. All liquid waste is processed on-site and ultimately disposed of in the engineered rock caverns at each NPP site.

9.2.4.3. RW and SF disposal

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For LILW, each NPP in Finland operates its own on-site repository. At the Loviisa plant, the LILW repository is located on Hästholmen island at a depth of approximately 110 meters below ground, while at Olkiluoto, the repository is situated at Ulkopää Cape at a depth of 60 to 100 meters. Both repositories are designed to accommodate operational and decommissioning waste from their respective plants, including solidified resins, filters, contaminated metals, and other plant-derived materials.
The ONKALO® facility at Olkiluoto is likely to be the world's first DGR for SFs. After the Olkiluoto site was selected as the site for the disposal facility, the construction of an underground research facility started in 2004 to confirm the suitability of bedrock for high-level waste disposal.
Since then, ONKALO® has evolved into an underground disposal facility containing access routes, tunnels, technical rooms, and the first deposition tunnels. Copper canisters with a five-centimeter-thick copper shell are deployed at the encapsulation plant on the surface. The sealed canisters 1.05 m in diameter are then transferred underground and emplaced vertically in deposition holes that are approximately eight meters deep and 1.75 meters in diameter, drilled into the bedrock floor of the disposal tunnels. Each canister is surrounded by highly compacted bentonite clay, which acts as a buffer due to its ability to swell when in contact with groundwater, retard groundwater and radionuclide migration, and protect the canister from geological and chemical processes. The deposition tunnels are then backfilled with bentonite and sealed with concrete plugs, and other parts of the repository are backfilled and closed. The entire system relies on stable mechanical and chemical conditions, the engineered barriers, and the absence of significant groundwater flow to ensure long-term containment.

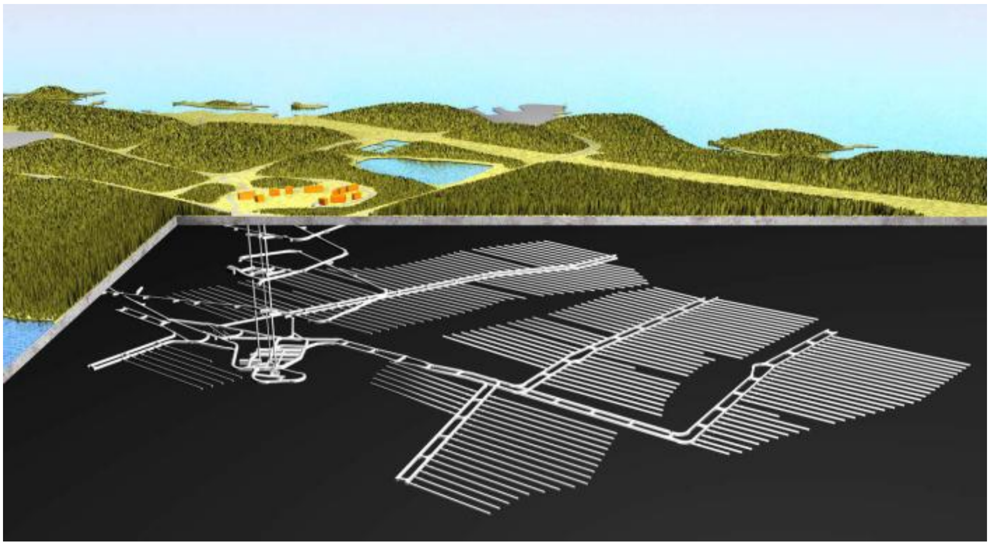

Figure 10: Layout of the underground facility and disposal tunnel for vertical disposal option. (POSIVA 2021)

9.2.4.4. Decommissioning of NPPs

Loviisa Nuclear Power Plant

Loviisa houses two VVER-440 PWRs, operational since 1977 and 1980. Decommissioning is planned for immediate dismantling after license expiration (2050). The strategy includes a 5-year transition phase for fuel removal and system decontamination. Waste management focuses on an on-site repository at Hästholmen Island, excavated 110 meters into granite bedrock. This facility will accommodate ~21,000 tonnes of operational and decommissioning waste, including activated components. Fortum's selective ion exchange technology minimizes liquid waste volumes, while safety assessments project containment integrity for up to one million years (Fortum 2018) (STUK 2024b).

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Olkiluoto Nuclear Power Plant (BWR Units 1 & 2)
Olkiluoto's two boiling water reactors (BWRs), operational since 1978 and 1980, will undergo immediate dismantling post-2038. Decommissioning waste (~8,800 m^3) includes LILW such as contaminated metals and concrete, disposed in on-site silos. Bituminized ILW from operational phases will be encapsulated for final disposal (TEM 2022) (STUK 2024b).

Olkiluoto Nuclear Power Plant (EPR-Olkiluoto 3)
The Olkiluoto 3 EPR, operational since 2023, represents Finland's newest nuclear unit. While its decommissioning strategy remains under development, preliminary estimates indicate that decommissioning waste will amount to ~8,800 m^3, including LILW such as activated metals and contaminated concrete. SF will be disposed of in Posiva's ONKALO® geological repository, a 450-meter-deep facility in crystalline bedrock. Future plans will integrate lessons from Loviisa's VVER-440 decommissioning, particularly in waste categorization, stakeholder engagement, and optimization of disposal volumes (Fortum 2018) (TEM 2022).

9.2.5. Plans for the construction of SMRs

Some power companies in Finland are assessing the feasibility to construct new NPPs including SMRs. For example, Fortum has performed a feasibility study (Fortum 2025) that identified new nuclear power as possible long-term option for energy production. Fortum continue their studies with selected technology vendors including also an SMR developer GE-Hitachi. Another example is Helen, Helsinki based power company, which has launched a nuclear energy programme in 2024 to evaluate SMRs to produce heat or both electricity and heat (Helen 2023). A SMR development project in Finland is carried out by Steady Energy, a spin-off from VTT Technical Research Centre of Finland Ltd., which is developing the LDR-50 low-pressure, low-temperature LWR for district heating. The LDR-50 reactors provide an option for the power companies to replace their current district heating energy sources. Municipal power companies that have signed agreements with Steady Energy with intent to build LDR-50 reactors are, for example, Helen, Kuopion Energia and Keravan Energia. Steady Energy and Fortum have also agreed on Fortum's support in the technology development. The LDR-50 plant pilot has been planned to Salmisaari Helsinki, a former coal power station site, with aimed construction start in late 2025. The aimed schedules to build the first LDR-50 power plants range from late 2020s to early 2030s (Steady Energy 2024).
According to the study on SMR in Finland (STUK 2019), SMR technology is technically feasible for both electricity and district heat production in Finland. The study reviewed several SMR designs, including water-cooled, gas-cooled, and other advanced reactor types, and found that water-cooled SMRs are closest to commercial deployment due to their technological maturity and regulatory familiarity. The study also concludes that SMR waste streams (SF and RW) can be managed using existing or planned Finnish infrastructure, such as the Posiva ONKALO® repository for SF. However, new organizational models may be needed for waste management if SMRs are operated by smaller or municipal entities. Centralized or cooperative waste management solutions are recommended (STUK 2019).
Considering licensing a fleet of SMRs with the same concept/design, synergies in the concept evaluation may streamline the approval of modular SMR units, minimizing repetitive licensing work for each module. However, some site or plant specific design modifications can be anticipated. One goal of the renewal of the Nuclear Energy Act is to be more technology-neutral and risk-informed. The emergency planning requirements have been already updated (STUK/Y/2/2024) allowing more flexible siting for SMRs in comparison to conventional NPPs.

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9.2.6. Expected management of SF and RW from SMRs

The management of SF and RW from SMRs in Finland is expected to follow the established practices and regulatory requirements applied to conventional NPPs. According to Finnish legislation, all SF and RW generated from SMRs must be managed and disposed of within Finland, and the costs and responsibilities remain with the party with the waste management obligation (license holder producing the waste) (STUK 2024b) (EcoSMR 2023).

Considering a new SMR license holder producing nuclear energy (and waste), there are currently a few alternatives for handling the waste. The company can either handle the waste itself, through a jointly owned company (like Posiva is currently disposing the SF produced by its owners) or through an agreement with a waste management company. The latter requires a process called '*transfer of waste management obligation*' from one party to another and licenses for storage/transport and disposal of the waste. If the license holders are small and do not have sufficient expertise to manage nuclear waste, centralized solutions are preferred, such as cooperation with Posiva Oy and power companies that already handle their own LILW (STUK 2020).

9.2.6.1. SF management

In principle, it can be assumed that the SF produced in SMRs based on LWR technology can be managed and disposed in the similar manner as the SF from currently operating NPPs in Finland (VTT 2022).

Depending on the LWR-SMR reactor type, some differences in the fuel characteristics (dimensions, burnup, decay heat) would require canister design optimisation for the specific SMR fuel type. Also to be considered is the post irradiation criticality safety. For non-LWR SMR technologies, additional pre-disposal management may be necessary, or alternative disposal strategies could be considered. However, these options require further study and regulatory evaluation (VTT2022).

9.2.6.2. RW management

For SMR LILW, the proposed strategy involves utilizing either existing or newly adapted intermediate-depth repositories, similar to those currently in use at Finnish NPPs. Accessing existing facilities would require updated licenses and agreements regarding ownership or usage rights. VLLW from SMRs could be safely disposed of in near-surface facilities.

The choice of centralized, decentralized, or hybrid waste management models depends on the number of SMR units, their ownership, and deployment. Centralized disposal at existing facilities is feasible for small waste volumes if the license holder can use them. Local or hybrid solutions might be suitable if SMRs are widely distributed or operated by multiple entities.

Public and stakeholder acceptance will play a critical role in both SMR plant and repository siting, and all management strategies must comply with Finland's stringent safety, environmental, and transparency requirements.

Organizational and Regulatory Aspects

For both NPPs and SMRs, the license holder is fully responsible for the safe management and funding of all waste generated, from interim storage to final disposal. The Finnish State ensures oversight through STUK and maintains ultimate responsibility for long-term safety. The licensing and regulatory framework is evolving to accommodate SMRs, including new business models, modular deployment, and possibly smaller or municipal operators (STUK 2024a).

- Centralized vs. Decentralized Models: Large NPPs have centralized waste management at plant sites. SMRs, especially if widely distributed, may require new centralized, decentralized, or hybrid approaches for waste collection, transport, and disposal, depending on ownership and deployment patterns.
- Waste Characteristics: LWR-SMR SF may have lower burnup and decay heat, but potentially higher volumes per energy unit. LILW from LWR-SMRs is expected to be

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similar in composition to that from NPPs, but the amounts may be smaller and more distributed.

- Public and Stakeholder Acceptance: Both NPP and SMR waste management require transparent processes and local consent, but SMR deployment in urban or industrial settings may increase the importance of stakeholder engagement and logistics.
- Technical Adaptations: While the KBS-3V concept is technically suitable for LWR-SMRs, repository design and operational procedures may need refinement for SMR-specific waste forms and deployment scales.

9.2.7.Comparison of RW and SF management between SMR and existing and planned NPPs

A detailed comparison of the RW and SF management between existing NPPs and planned SMRs would require the specification of the SMR types which, in turn, would require a decision to build new SMRs in Finland by the power companies. In general, the management of SF and RW from SMRs in Finland is expected to follow the established practices and regulatory requirements applied to conventional NPPs.

9.2.8. Applicability of the existing system for management of SF and RW from SMR

The existing system to manage SF and RW from the current NPPs includes SNF disposal in DGR by Posiva (owned by the NPP operating power companies) and RW disposal in on-site repositories by the NPP operating power companies. In principle, it can be assumed that the SF (and RW) produced in SMRs based on LWR technology can be managed and disposed in the similar manner as the SF (and RW) from currently operating NPPs in Finland (VTT 2022), but it would require an agreement of a new SMR licence holder with the current SF and RW disposal systems owners as well as licence and likely also technical updates based on the selected SMR specification. However, it should be noted that the operating LILW facilities and planned DGR are dimensioned for the waste produced from currently operated NPPs taking into account geological boundary conditions at the disposal site (Pere et al. 2012). Therefore, volume of the new SMR waste and geological repository layout determining features may also be limiting factors and new disposal facilities may need to be considered depending on the waste volumes generated in the future Finnish SMRs. In addition, characteristics of the SF and RW should be compatible with the waste currently produced in NPPs. This may not be the case for non-LWR SMRs and technical R&D and development of the safety case would be needed to dispose these new type of SF and RW.

9.2.9. Conclusions for Finland

Finland currently operates five nuclear reactors. The potential for future developments is being evaluated, with SMRs among the options under consideration. Furthermore, several municipal energy companies have expressed interest in nuclear power, specifically in the construction of SMRs for district heating or the cogeneration of heat and electricity.

Legislation and Policy Foundation

Finland’s legislative framework for managing SF and RW is based on the Nuclear Energy Act (990/1987) and Radiation Act (859/2018). In addition, binding regulations are given in Decrees by Ministry and Government, of most relevance here is the Nuclear Energy Decree (161/1988), and STUK Regulations issued by the Radiation and Nuclear Safety Authority (STUK) including also specific regulation on safe disposal of nuclear waste (Y/4/2018). Detailed safety requirements on management of SF and RW are presented in the YVL Guides by STUK.

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The Finnish nuclear energy legislation and related regulations are currently undergoing a comprehensive renewal. According to Liukko et al. (TEM 2020), the key principles of this renewal include the working group's guidelines, which aim to enhance the licence system to support the implementation of modular and serial-produced nuclear facilities, such as SMRs.

Management of SF and RW at NPPs

Finland's five operational reactors – two VVER-440 units at Loviisa and three BWR/EPR units at Olkiluoto – generate approximately 100 tonnes of SF annually, with a cumulative inventory of ~2,400 tonnes of uranium as of 2022.

SF is managed through a three-stage system that includes initial cooling in on-site wet pools (1–5 years), interim storage in dedicated facilities for several decades and final disposal in the ONKALO® DGR, which uses the KBS-3V multi-barrier system (copper-canister with cast-iron inserts, bentonite buffer, and crystalline bedrock).

LILW from NPPs is processed on-site through compaction, cementation, or bituminization and disposed of in engineered rock caverns at depths of 60–110 meters. Annual LILW volumes range from 100–200 m^3 per plant, with cumulative disposal reaching 11,100 m^3 by 2023.

Plans for SMR Construction

Several power companies in Finland are currently evaluating the feasibility of constructing new NPPs, including SMR. According to a study on SMR technology in Finland conducted by STUK in 2019, SMRs are technically viable for both electricity generation and district heating in Finland. The study reviewed various SMR designs, including water-cooled, gas-cooled, and other advanced reactor types. It concluded that water-cooled SMRs are the closest to commercial deployment due to their technological maturity and regulatory familiarity. Additionally, the study determined that the waste streams from SMRs, such as SF and RW, can be managed with existing waste management methods. In principle, centralized or cooperative waste management solutions are preferred (STUK 2019).

Licensing a fleet of SMRs with consistent concepts or designs can create synergies in concept evaluation, streamlining the approval process for modular SMR units and reducing redundant licensing work for each module. Nonetheless, some modifications specific to certain sites or plants can be anticipated.

A primary objective of the renewal of the Nuclear Energy Act is to adopt a more technology-neutral and risk-informed approach. The emergency planning requirements have already been updated (STUK/Y/2/2024), permitting more flexible siting options for SMRs compared to conventional NPPs. The ongoing comprehensive reform of the Nuclear Energy Act aims to further facilitate SMR deployment in Finland.

Expected Management of SF and RW from SMRs

The management of SF and RW from SMRs in Finland is expected to adhere to the same practices and regulatory requirements as those applied to conventional NPPs. Finnish legislation mandates that all SF and RW generated from SMRs must be managed and disposed of within Finland, with costs and responsibilities falling to the party obligated with waste management (the license holder producing the waste).

For new SMR license holders producing nuclear energy and waste, there are several options for waste handling. The company can manage the waste independently, through a jointly owned entity (similar to Posiva, which currently disposes of the SF produced by its owners), or via an agreement with a waste management company. The latter option requires a process known as *'transfer of waste management obligation'* and involves obtaining licenses for storage, transport, and disposal of the waste. If license holders are small and lack sufficient expertise in managing nuclear waste, centralized solutions such as collaboration with Posiva Oy and power companies already managing their own LILW are preferred (STUK 2020).

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9.3. Ukraine

9.3.1. Introduction

Since launching its first nuclear power units in the 1970s, Ukraine has become one of Europe's most nuclear-reliant countries, with over 50% of its electricity consistently generated from nuclear sources. Today, Ukraine operates four NPPs (the national operator is NNEGC Energoatom), comprising 15 power reactor units (Energoatom 2023):

- Zaporizhzhia NPP (ZNPP) – 6 × VVER-1000 units,
- Rivne NPP (RNPP) – 2 × VVER-440 and 2 × VVER-1000 units,
- Khmelnytskyi NPP (KhNPP) – 2 × VVER-1000 units (with plans to complete units 3, 4 – VVER-1000 and 5, 6 – AP1000),
- South Ukraine NPP (SUNPP) – 3 × VVER-1000 units.

All reactors are pressurized water reactors (PWRs), using low-enriched uranium dioxide (UO_2) fuel.

None of the nuclear facilities operated by Energoatom are in the "decommissioning" stage of their life cycle.

In its activities, Energoatom implements the practice of extending the operating life of nuclear installations (namely, NPP power units), which is based on the positive results of the periodic safety reassessment. It also takes all possible technical measures (modification, modernization of power unit equipment, etc.) to extend the operating life and maintain the trend of extending this life in general.

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Table 8: List of operated NPP in Ukraine (SNRIU 2023)

Nuclear installation	Start date of the "operation" life cycle phase	The term of operation is established by the license or the next periodic safety reassessment
Rivne NPP		
Power unit No. 1	12.22.1980	12.22.2030
Power unit No. 2	12.22.1981	12.22.2031
Power unit No. 3	11.12.1986	11.12.2027
Power unit No. 4	07.06.2005	07.06.2025
South Ukrainian NPP		
Power unit No. 1	02.12.1983	02.12.2033
Power unit No. 2	05.12.1985	12.31.2025
Power unit No. 3	02.10.1990	10.02.2030
Khmelnytskyi NPP		
Power unit No. 1	13.12.1988	13.12.2028
Power unit No. 2	07.09.2005	07.09.2025
Zaporizhzhia NPP (temporarily occupied by the Russian Federation)		
Power unit No. 1	12.23.1985	12.23.2025
Power unit No. 2	02.19.1986	02.19.2026
Power unit No. 3	03.05.1987	05.03.2027
Power unit No. 4	04.04.1988	04.04.2028
Power unit No. 5	05.27.1990	05.27.2030
Power unit No. 6	10.21.1996	10.21.2026

The war that began in 2022, and particularly the occupation of the Zaporizhzhia NPP, has dramatically challenged the safety and stability of Ukraine's nuclear infrastructure. Despite these risks, Ukraine has upheld its commitment to nuclear power and is preparing for the eventual decommissioning of its aging fleet. Most VVER-1000 units are expected to remain in operation into the 2030s–2040s, with systematic decommissioning beginning around or after 2040. Preparatory work – including radiological surveys, licensing frameworks, and centralized waste storage is already in motion.

Looking ahead, Ukraine envisions the deployment of SMRs as a key component of its post-war energy transition. These reactors promise enhanced safety, flexibility, and modularity, enabling decentralized generation and simplified decommissioning.

This section provides a short description of the RW and SF management system at Ukrainian NPPs, the main stages of RW and SF management, critical parameters affecting safety justification, legislative support for the implementation of this activity, and an assessment of the feasibility of using the existing RW and SF management infrastructure for the development of SMR technology in Ukraine. The presented description of SF management is based on critical elements and characteristics that affect safety and may impact the feasibility of using this technology for SMR SF operations. The purpose of the analysis is to explore the possibility of

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fully or partially using the existing RW and SF management infrastructure in Ukraine to perform SMR's operations. When considering the legislation of Ukraine, which defines the RW and SF management procedure, an attempt was made to determine the existing level of legislative regulation sufficient for the implementation of SMR technology in Ukraine.

9.3.2.Legislation

Ukraine's legal and regulatory framework for RW and SF management is founded on internationally recognized principles of nuclear safety, environmental protection, and regulatory transparency. Since the 1990s, the country has built a comprehensive system of national laws, technical standards, and international agreements to govern all stages of the nuclear fuel cycle.

The key legal pillars include the Law of Ukraine "On the Use of Nuclear Energy and Radiation Safety" and the Law "On Radioactive Waste Management", both of which define institutional responsibilities, safety requirements, licensing conditions, and public engagement mechanisms. These laws are supported by technical regulations—such as the Basic Sanitary Rules (BSRU-2005), and safety provisions for RW storage and disposal (e.g., NP 306 series)—which align with IAEA standards including SSR-6 and GSR Part 5.

Table 9: Key legislative and regulatory documents for RW and SF management in Ukraine

No	Document Title	Document Code	Level
1	On Ukraine's accession to the Vienna Convention on Civil Liability for Nuclear Damage	Law of Ukraine №334/96-ВР	International/National
2	On Ukraine's participation in the 1980 Convention on the Physical Protection of Nuclear Material	Resolution of Verkhovna Rada №3182-XII	International/National
3	On ratification of the Amendment to the Convention on the Physical Protection of Nuclear Material	Law of Ukraine №356-VI	International/National
4	On ratification of the Joint Convention on the Safety of Spent Fuel Management	Law of Ukraine №1688-III	International/National
5	On the Use of Nuclear Energy and Radiation Safety	Law of Ukraine №39/95-ВР	National
6	On Licensing Activities in the Field of Nuclear Energy Use	Law of Ukraine №1370-XIV	National
7	On Transportation of Dangerous Goods	Law of Ukraine №1644-III	National
8	On Radioactive Waste Management	Law of Ukraine №255/95-ВР	National
9	On Protection from Ionizing Radiation	Law of Ukraine №15/98-ВР	National
10	On Physical Protection of Nuclear Installations and Materials	Law of Ukraine №2064-III	National
11	Regulations on Radioactive Materials Transportation	Cabinet Resolution №1373-2004-п	National
12	On the Establishment of JSC "Energoatom"	Cabinet Resolution №1268-96-п	National
13	On the Role of the Operating Organization for Nuclear Installations	Cabinet Resolution №830-98-п	National

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14	Assignment of Functions for Centralized SF Storage Operation	Ministry Order №284	National
15	SF Storage Facility Siting and Construction Regulation	-	National

Oversight and enforcement are entrusted to the State Nuclear Regulatory Inspectorate of Ukraine (SNRIU), the national authority responsible for licensing, supervision, and regulatory development in the field of nuclear and radiation safety. SNRIU works closely with international partners to ensure harmonization with global safety norms and adaptation to emerging nuclear technologies.

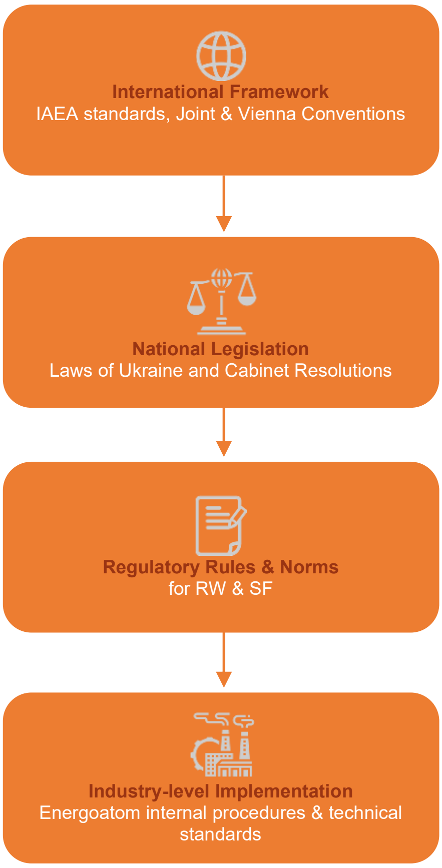

Figure 11: Legislative and regulatory structure for RW & SF management in Ukraine

Recent years have seen proactive steps toward integrating SMRs into Ukraine's legal landscape. Planned regulatory revisions aim to address the novel features of SMRs—such as multi-module configurations, non-traditional siting (e.g., underground or floating platforms), and extended sealed-core operation. These developments call for new licensing approaches, more flexible oversight mechanisms, and updated safety assessment tools.

Ukraine's participation in international cooperation programs (e.g., the U.S. FIRST initiative, IAEA working groups, and EURATOM R&D projects) supports institutional capacity-building for SMR licensing and waste management planning. Early regulatory engagement is already underway for potential technologies like the Holtec SMR-300, with focus areas including modular production, passive safety validation, and long-term RW and SF handling requirements.

In conclusion, Ukraine's RW and SF legislation is robust, but the introduction of SMRs will require targeted updates to accommodate innovative fuel cycles, novel reactor designs, and evolving operational models. Ongoing modernization efforts ensure Ukraine remains aligned with international safety practices while preparing for next-generation nuclear deployment.

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9.3.3.Policy of the SF and RW Management in Ukraine

Ukraine's national policy on the management of SF and RW is grounded in a comprehensive legal and strategic framework that reflects both international obligations and the country's unique nuclear history. Shaped by the experience of Chernobyl and the operation of 15 VVER-type reactors, the policy is oriented toward long-term safety, international harmonization, and the creation of an integrated waste infrastructure.

The fundamental policy framework is underpinned by several key legislative acts, including the Law of Ukraine "On the Use of Nuclear Energy and Radiation Safety" and the Law "On Radioactive Waste Management," both of which define the principles of state responsibility, safety prioritization, and international cooperation. Since 2019, these laws have been substantially amended to reflect modern classification systems, define types and criteria for disposal, and reinforce central control over decision-making related to the siting and construction of facilities for RW management.

The National Strategy for Radioactive Waste Management, originally approved in 2009 and updated in 2021, is the cornerstone document outlining the 50-year vision (2010–2059) for managing all classes of RW in Ukraine (RW Strategy 2021). The strategy foresees the stepwise development of the entire infrastructure required for treatment, storage, and disposal — including near-surface repositories for (LLW and ILW, and a future DGR for long-lived and high-level waste (HLW), including waste from fuel reprocessing.

A central element of this policy is waste minimization, supported by improved operational practices at NPPs, enhanced characterization and classification of RW, and the implementation of integrated processes from generation to disposal. Ukraine adheres to international classification schemes aligned with IAEA GSG-1 standards, and in its current legislation, RW is officially divided into class of RW (based on Law (Law of Ukraine №255/95) presented in table 10.

Table 10: Classification of RW

Class RW	Description	Disposal
VLLW	very low-level waste	surface landfill
LLW	low-level waste	near-surface vault
ILW	intermediate-level waste	vault or DGR
HLW	high-level	DGR

The streams of RW generated in Ukraine arise from several major sources: the operation of NPPs, including reactor maintenance, decontamination, and equipment replacement; medical and industrial use of radioactive materials; and decommissioning activities. The long-term RW policy provides for the isolation of waste at different stages: on-site interim storage, centralized pre-disposal processing (e.g., at the VECTOR complex), and eventual final disposal based on waste class and longevity (SNRIU 2023).

Strategically, Ukraine's current RW management is guided by a tiered policy structure: minimization and processing at source, centralized handling and storage, and future isolation in geological repositories. Implementation is supported by specific regulatory provisions, such as NP 306.4.213-2017 and NP 306.4.219-2018, which establish detailed safety requirements for waste treatment and disposal before and after repository acceptance. Further technical criteria, including acceptance specifications, radiological limits, packaging standards, and conditioning requirements, are also developed under regulatory oversight.

Spent fuel policy follows a "deferred decision" model. In the past, SF was returned to the Russian Federation for reprocessing, but Ukraine has since shifted to a self-reliant model (RW Strategy

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2021). Ukraine's policy on SF management has evolved significantly to reflect the nation's commitment to safety, energy sovereignty, and adherence to international standards. At its core, the policy prioritizes stringent radiation protection and environmental safeguarding through the secure storage, transport, and planned final disposal of SF, deploying advanced containment technologies to prevent leaks and environmental contamination. It also emphasizes Ukraine's strategic goal of reducing reliance on foreign nuclear infrastructure, demonstrated by the 2022 commissioning of the Centralized Spent Fuel Storage Facility (CSFSF) within the Chornobyl Exclusion Zone, which has fundamentally transformed the country's approach to fuel sovereignty, enabling long-term dry storage of SF from VVER-1000 and VVER-440 reactors. Storage is planned for up to 100 years, during which final disposal solutions, such as deep geological repositories, will be designed and licensed. This shift supports efficient long-term dry storage solutions that lower costs and mitigate geopolitical risks.

As Ukraine progresses on its pathway to European integration, its SF regime is being harmonized with EU nuclear regulations and IAEA safety standards, including compliance with the Joint Convention on the Safety of Spent Fuel Management. At the same time, the policy explores domestic reprocessing options to optimize fuel recovery and minimize waste volume, reinforcing both economic efficiency and fuel cycle sustainability. From a non-proliferation perspective, Ukraine maintains tight regulatory controls over SF handling and robust physical security measures to prevent unauthorized access, all aligned with IAEA safeguards and Non-Proliferation Treaty obligations. Ensuring transparency and public trust, the government consistently conducts environmental impact assessments and encourages stakeholder and community consultations throughout SF facility planning and operation.

One of the most critical challenges Ukraine faces is the lack of a fully implemented system for HLW and the absence of an operational DGR. However, strategic planning is underway, and international cooperation, particularly with EU bodies under the INSC, Euratom, and EURAD frameworks, continues to inform Ukraine's long-term RW and SF handling vision. The updated State Environmental Program on RW Management (2025–2032) is expected to fill critical gaps, especially in planning for future waste from emerging reactor types such as SMRs.

9.3.4. Management of SF and RW at NPPs

SF and RW management at Ukrainian NPPs are regulated by detailed national regulatory requirements and standards of the nuclear operator and is also supervised by the State Nuclear Regulatory Inspectorate of Ukraine. The operator, NNEGC Energoatom, directly manages RW at all operating sites (ZNPP, RNPP, KhNPP, SUNPP) with long-term transfer to centralized storage facilities such as VECTOR or temporary on-site storage.

9.3.4.1. SF Management

SF management is a vital aspect of nuclear power operations in Ukraine, where 15 nuclear reactor units at four major power plants (Zaporizhzhia, Rivne, Khmelnytskyi, and South Ukraine) collectively generate roughly half of the country's electricity. Upon removal from the reactor core, spent FAs are initially stored on-site in water-filled SF pools, where they remain for a period of five to ten years. This stage is essential for ensuring sufficient decay of residual heat and radiation levels. However, as Ukraine's nuclear fleet continues long-term operation, some of these pools are approaching their design capacity, necessitating a transition to alternative storage solutions.

To address this challenge, Ukraine has adopted a progressive shift toward dry storage systems. After sufficient cooling, SF is transferred from wet pools into sealed metal and concrete casks designed for long-term dry storage. These systems, including technologies such as Holtec's HI-STORM and NAC's MAGNASTOR, offer enhanced safety by eliminating reliance on active cooling and water shielding, while also increasing resilience against external threats such as power outages or military aggression – a factor that has become acutely relevant given the current security environment.

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The cornerstone of Ukraine's national SF strategy is the development and operation of the Centralized Spent Fuel Storage Facility, located in the Chornobyl Exclusion Zone and operated by Energoatom. This facility became operational in 2022 and is designed to house over 16,500 spent FAs from the Rivne, Khmelnytskyi, and South Ukraine NPPs. The CSFSF significantly reduces Ukraine's dependence on foreign fuel cycle services, particularly eliminating the need to send SF to the Mayak reprocessing facility in the Russian Federation. Its deployment not only strengthens national energy sovereignty but also contributes to the long-term security and economic sustainability of the back end of Ukraine's nuclear fuel cycle.

Transportation of SF in Ukraine is governed by both IAEA SSR-6 transport regulations and domestic rules, such as those issued by the Ministry of Health. Only certified Type B(U) or Type B(M) transport casks, such as TUK-19 or CONSTOR, are used, which provide advanced shielding against radiation and mechanical impact. During transit, SF shipments are escorted by security services and tracked in real-time to ensure protection against sabotage or diversion. Compliance with national and international radiation protection limits is essential, with exposure levels for workers not exceeding 20 mSv/year and public exposure capped at 1 mSv/year. In line with the ALARA (As Low As Reasonably Achievable) principle, operational practices are constantly optimized to minimize radiation doses to personnel.

Physical protection of SF storage and transport operations is ensured through multiple redundant security measures, including 24/7 surveillance systems, armed guards, and adherence to the guidelines of IAEA INFCIRC/225/Rev.5. Facilities are designed to resist unauthorized access and malicious acts, with strict control of personnel and vehicle movements.

Emergency preparedness is another essential component of SF safety. Each facility maintains detailed response plans for incidents such as leaks, fires, or transportation accidents. These plans are regularly updated and rehearsed through drills conducted in coordination with the State Emergency Service of Ukraine (DSNS), ensuring the readiness of all involved stakeholders.

From a technical standpoint, safe handling of SF requires strict control over key operational parameters. The effective neutron multiplication coefficient must remain below 0.95 to prevent inadvertent criticality. Temperature limits for both FAs and their cladding must be respected to prevent structural compromise. Additionally, in any emergency situation, the release of radioactivity must not exceed defined thresholds, with reference to the established evacuation criteria for the Ukrainian population.

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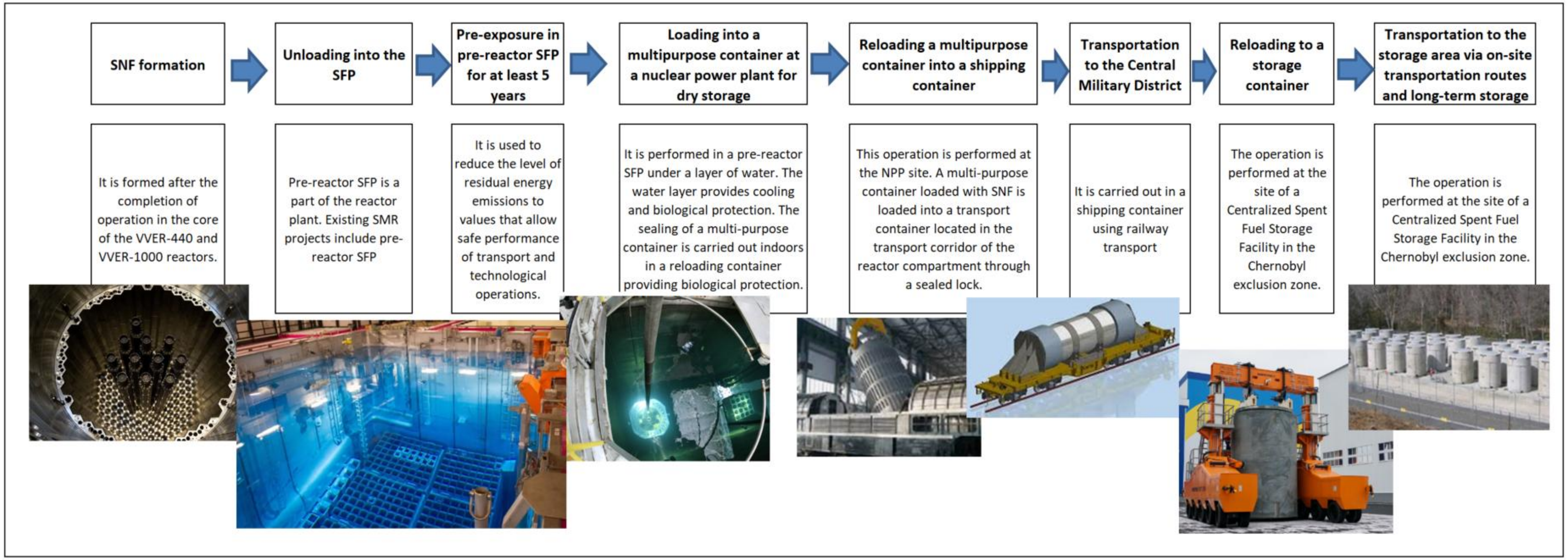

Figure 12: Main steps of SF operation in Ukraine (Energoatom 2023)

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9.3.4.2. RW Management

The management of RW at Ukrainian NPPs reflects a systematic approach that has matured over decades of operational experience, particularly under the auspices of the national operator Energoatom (Energoatom 2023). Given Ukraine's high reliance on nuclear power, accounting for more than 50% of total electricity generation, the country has developed integrated systems for the collection, treatment, conditioning, and interim storage of RW, both at the plant level and through national infrastructure such as the VECTOR complex.

As of 2025, RW management operations at all four active NPP sites – ZNPP, RNPP, KhNPP, and SUNPP, follow a standardized approach based on the minimization of RW generation, safe onsite processing, and preparation for future disposal. Despite the war-induced disruptions, including the temporary occupation of ZNPP, these practices remain anchored in international safety standards and supported by continued regulatory oversight from the SNRIU.

RW volumes and waste characterization

Sources of RW:

- maintenance and operation of primary circuit equipment and systems,
- decontamination of equipment,
- releases from SF aging pools.

(Energoatom 2023) indicates the annual generation of various types of waste, primarily LLW and ILW, with volumes depending on reactor performance, maintenance cycles, and waste minimization strategies.

Before the temporary occupation of the Zaporizhzhia NPP, Ukraine's nuclear power plants generated approximately 2,500–3,000 m^3 of RW annually during standard operations. This volume reflects the total amount of RW generated before processing.

However, as of recent years, the average annual volume of RW generated before processing at the remaining operational NPPs—Rivne, Khmelnytskyi, and South Ukraine ranges between 1000 and 1500 m^3. This reduction is due not only to ongoing waste minimization strategies and technological upgrades, but also to the fact that Zaporizhzhia NPP has remained under military occupation by the Russian Federation since March 2022, making accurate data collection from that site currently impossible.

The management of RW at Ukrainian NPPs has developed into a structured, multi-stage process that aligns with international safety standards while addressing the specific operational realities of VVER-type reactor technology. The quantity of RW produced annually across the Ukrainian NPP fleet reflects both the scope of their operation and the country's efforts towards minimization.

Infrastructure for RW treatment

Liquid RW treatment systems

At Ukrainian NPPs, the treatment of liquid RW includes multi-stage purification and concentration:

- centrifugation of wastewater,
- filtration through special water treatment plants,
- primary evaporation to reduce volume,
- deep evaporation in a deep evaporation plant to form a dense salt melt (except for the SUNPP).

The solid concentrates, filter materials and sludges are then processed for conditioning.

Energoatom has prioritized the reduction of untreated liquid RW volumes through the implementation of highly effective filtration and chemical treatment systems, thereby substantially lowering the burden on storage facilities and minimizing the generation of secondary RW.

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Liquid RW waste primarily arises from decontamination processes, regeneration of ion-exchange resins, and maintenance activities. A significant stream, the evaporator bottom residue (cube residue, CR), is produced during the evaporation of contaminated water in special treatment systems (SVO-3, SVO-7).
Despite increased operational stress, technical solutions such as repair of pool leakages, separation of flow streams, and optimized filter regeneration have helped significantly reduce the volume of CR across most NPPs. South Ukraine NPP implements repeated evaporation, which reduces CR volume but increases salt content.
Ion exchange materials, or spent filter media, accumulate in liquid RW storage tanks and represent a challenge for temporary storage. Their processing is not yet industrially implemented, although immobilization recipes are under development.
Sludge generation is concentrated at RNPP and KhNPP, using centrifugation systems for pre-treatment. As of the end of 2024, 174.4 m³ of dewatered sludge had been accumulated.

Solid RW management technologies
At the core of the RW management system at Ukraine's NPPs lies a philosophy of safe, staged handling and conditioning that prepares waste for either long-term interim storage or final disposal. Each NPP site, whether at Zaporizhzhia, Rivne, South-Ukraine, or Khmelnytskyi, possesses on-site facilities for the preliminary treatment of RW. However, a clear distinction must be made: only Zaporizhzhia NPP and Rivne NPP currently operate full-cycle RW management complexes.
Two fully equipped Solid radioactive waste processing complexes (SRWPCs) are modular facilities capable of handling the full treatment cycle for solid RW, including:

- sorting and fragmentation,
- thermal drying (RNPP) and incineration of selected waste batches (ZNPP),
- supercompaction of solid LLW waste to achieve volume reductions by a factor of four to six,
- decontamination systems,
- activity measurement (passportization),
- cementation of conditioned waste for transport or interim storage.

In contrast, Khmelnytskyi NPP and South Ukraine NPP operate only partial-cycle facilities, with plans for further modernization and capacity expansion.
The third facility for KhNPP is under construction, with commissioning expected at the end of 2027, while there are long-term plans for the South-Ukraine NPP, and the facility design process is ongoing.
A suite of over 30 individual facilities is already in operation or planned for commissioning under the Comprehensive National RW Program, including new facilities for cementation, incineration, and metal decontamination (SNRIU 2023).
The interim storage of treated RW is accomplished on the NPP sites in reinforced concrete vaults, which are designed to provide containment, shielding, and environmental isolation over an extended period. The storage facilities are engineered in accordance with IAEA recommendations and national Ukrainian safety standards, featuring radiation monitoring systems, leachate control, and routine inspection programs.

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Table 11: Existing Installations for RW Management at Ukrainian NPPs

Facility / Installation Name	Purpose	Technical Specification	Year of Commissioning
Zaporizhzhia NPP (ZNPP)			
UGU-500	Deep evaporation of evaporator bottom residue	500 dm³/h	1987
UGU-1-500	Deep evaporation of evaporator bottom residue	500 dm³/h	2000
Pressing Unit VNR-500	Volume reduction of low-level solid RW	P = 500 kN	1991
Supercompaction Unit	Reduction of RW volume through briquetting	4 – 6 briquettes/hour	2019
RW Incineration Unit with Monitoring	Thermal processing of solid and liquid RW	30 kg/h (solid RW)	2019
Fragmentation Unit	Fragmentation of solid RW	30 kg/h (≈200 t/year)	2019
Characterization Unit	Measurement of RW activity and radionuclide composition	20 containers/day	2019
RW Retrieval Unit	Retrieval of stored solid RW	45 m³/month (≈315 m³/year)	2020
Ultrasonic Decontamination Unit	Decontamination of radioactive-contaminated metal	-	2020
Rivne NPP (RNPP)			
UGU-1-500M (Line 1)	Deep evaporation of evaporator bottom residue	500 dm³/h	2004
UGU-1-500M (Line 2)	Deep evaporation of evaporator bottom residue	500 dm³/h	2007
Centrifugation Unit	Purification of drainage waters	1,5 – 7 m³/h	2004
Bituminization Unit (conserved)	Bituminization of liquid RW	150 dm³/h	1995
Supercompaction Unit	Volume reduction of solid RW	4 – 6 briquettes/hour	2018
Cementation Unit	Conditioning of RW in cement matrix	8 containers/shift	2018
Metal Decontamination Unit	Decontamination of contaminated metallic waste	800 kg/day (≈200 t/year)	2018
Oil Purification Unit	Treatment of radioactive oil	≥ 0.58 m³/h	2018
RW Retrieval Unit	Retrieval of accumulated solid RW	15 m³/week	2018
Fragmentation & Sorting Unit	Sorting and fragmentation of RW	4,5 m³/shift	2018

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RW Activity Measurement Unit	Radiological characterization of containers	12 containers/shift	2018
Khmelnytskyi NPP (KhNPP)			
UGU-1-500	Deep evaporation of evaporator bottom residue	500 dm^3/h	1990
Radioactive Oil Incineration Unit	Combustion of radioactive oil	5 dm^3/h	1994
Centrifugation Unit	Purification of drainage waters	1 – 10 m^3/h	2011
South Ukraine NPP (SUNPP)			
Pressing Unit C-26	Volume reduction of low-level solid RW	P = 2000 kN	1997
RW Activity Measurement Unit	Radiological characterization of RW containers	12 containers/shift	2019

Table 12: Existing RW Storage Facilities at Ukrainian NPPs

Storage Facility Name	Purpose	Capacity	Year of Commissioning
Zaporizhzhia NPP (ZNPP)			
Liquid RW Storage Unit SC-1	Acceptance and storage of liquid RW	3800 m^3	1984
Liquid RW Storage Unit SC-2	Acceptance and storage of liquid RW	1000 m^3	1987
Solid RW Storage Facility SC-1	Acceptance and storage of solid RW	5910 m^3	1984
Solid RW Storage Facility SC-2	Acceptance and storage of solid RW	1907 m^3	1989
Solid RW Storage in Treatment Building	Storage of conditioned solid RW	11174 m^3	1986
Rivne NPP (RNPP)			
Liquid RW Storage SC Units 1&2	Acceptance and storage of liquid RW	4590 m^3	1981
Liquid RW Storage SC Units 3&4	Acceptance and storage of liquid RW	3800 m^3	1986
High-Activity Solid RW Storage (Units 1&2)	Storage of high-level solid RW	84.2 m^3	1981
Ionization Chambers Storage (Units 1&2)	Storage of ion chambers and related RW	2.66 m^3	1981
Solid RW Storage SC-1	Acceptance and storage of solid RW	4180 m^3	1981
Solid RW Storage SC-2	Acceptance and storage of solid RW	6042 m^3	1986
Solid RW Storage at Central Processing Facility	Centralized acceptance and storage of RW	11242 m^3	2001
Khmelnytskyi NPP (KhNPP)			
Liquid RW Storage SRV-1	Acceptance and storage of liquid RW	800 m^3	1987

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Liquid RW Storage SRV-2	Acceptance and storage of liquid RW	2250 m³	2004
Solid RW Storage Block	Acceptance and storage of solid RW	7183 m³	2002
Solid RW Storage SC	Acceptance and storage of solid RW	6368 m³	1987
South Ukraine NPP (SUNPP)			
Liquid RW Storage No.1	Acceptance and storage of liquid RW	2121 m³	1982
Liquid RW Storage No.2	Acceptance and storage of liquid RW	1969 m³	1987
Liquid RW Storage No.3	Acceptance and storage of liquid RW	760 m³	1989
Low-Level RW Storage Facility	Storage of solid low-level RW	12000 m³	1982
Solid RW Storage Facility No.1	Acceptance and storage of solid RW	1250 m³	1982
Solid RW Storage Facility No.2	Acceptance and storage of solid RW	3053 m³	1989
Solid RW Storage Facility No.3	Acceptance and storage of solid RW	10811 m³	2002

Special Waste Forms

Salt Melt

Salt melt is a solidified residue resulting from the deep evaporation of liquid RW, predominantly carried out at Zaporizhzhia (ZNPP), Rivne (RNPP), and Khmelnytskyi (KhNPP) NPPs. Initially categorized as liquid RW, a significant regulatory update in 2019 reclassified this material as solid RW due to its physical form and reduced mobility. However, despite this reclassification, no final disposal route or facility has yet been formally designated for this waste stream under Ukraine's current RW management strategy.

As of 2023, over 9,600 cubic meters of salt melt has accumulated at Ukrainian NPPs, stored primarily in CRO-200 type containers designed for safe interim storage. These containers offer effective shielding and structural integrity, but are not yet approved for final disposal without further qualification of their contents. The absence of a defined strategy for long-term handling, whether via conditioning, immobilization, or direct disposal, poses a growing logistical and regulatory issue. Notably, uncertainties remain concerning the salt melt long-term chemical stability, radiological behavior under storage conditions, and potential for volume reduction or alternative reuse. Given the quantity involved, this waste stream is a priority for policy development under upcoming revisions to the national strategy and environmental program.

Bitumen Compound

Bituminized waste is another legacy stream of special concern, though its volume is more limited and localized. The Rivne NPP is the only Ukrainian site where bitumen compound was historically used to immobilize liquid RW. A total of approximately 147,8 m³ of bitumenized waste remains from earlier operations, stored in standard containers.

This waste is considered technically sensitive due to its potential chemical instability, particularly under elevated temperature conditions, which may pose fire and explosion risks if improperly handled or characterized. Such safety concerns have led to strict international guidelines on its management, making it unsuitable for many standard disposal pathways.

In response, a disposal campaign has been initiated involving the transfer of the first 60 drums of bitumen waste to the Chornobyl Exclusion Zone, specifically to the VECTOR site, where

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Energoatom and Chornobyl NPP personnel cooperate to assess and implement safe disposal procedures. These initial transfers have demonstrated feasibility; however, comprehensive radiological and physico-chemical characterization is still pending for the remaining inventory. Final acceptance at VECTOR or any long-term repository will require verification that the waste meets safety and performance criteria—particularly regarding non-radiological safety risks (e.g., flammability and gas generation potential).

Dry salt

One of the notable categories of specific RW managed at Ukrainian NPPs is the dry salt residue generated through deep evaporation processes, particularly at the SUNPP. Unlike traditional liquid waste treatment, this method produces a crystalline solid waste form as a result of repeated evaporation cycles applied to liquid LLW streams. The process significantly reduces the final volume of liquid RW requiring long-term storage but results in a highly concentrated salt by-product.

As of 2024, over 850 m^3 of dry salt waste has been accumulated at SUNPP. This material is stored in dedicated containers, classified as solid RW under current Ukrainian regulations following amendments adopted in 2019. The waste is managed in CRO-200 containers, which ensure safe shielding and containment during interim storage. Due to its non-standard physical form and elevated concentrations of radionuclides, the dry salt residue requires specific conditioning strategies and is currently subject to research under national waste management programs to determine optimal treatment and final disposal options.

In this cases, salt melt, bitumen compound and dry salt are illustrative of broader challenges Ukraine faces in managing non-standard RW forms: uncertainty in long-term disposal pathways, evolving classification standards, and gaps in conditioning technologies. Addressing these issues is essential for maintaining compliance with international safety norms and ensuring the sustainability of the national RW program.

Centralized storage and conditioning

The broader waste management philosophy is increasingly oriented toward centralization and long-term predictability. Operational RW is expected to be processed on-site to a final or near-final waste form and then transported to the VECTOR complex in the Chernobyl Exclusion Zone. This facility is operated by the State Specialized Enterprise "Central Enterprise for RW Management".

Transport of conditioned waste between NPPs and centralized facilities such as VECTOR, located in the Chornobyl Exclusion Zone, is performed using certified Type B(U) transport casks in compliance with IAEA SSR-6 regulations. In 2023, a major operational milestone was achieved when the first fully certified shipment of packaged RW from Rivne NPP to VECTOR was completed, showcasing Ukraine's technical and organizational readiness for large-scale centralized waste management.

In parallel, SF management has shifted from reliance on foreign reprocessing or indefinite wet storage toward a national model based on dry cask interim storage and future geological disposal, anticipated by mid-century. In 2023, Ukraine began shipping SF to the Centralized Spent Fuel Storage Facility at the Chornobyl Exclusion Zone, enabling dry storage of VVER-1000 and VVER-440 SFI in advanced, sealed casks for a projected period of up to 100 years.

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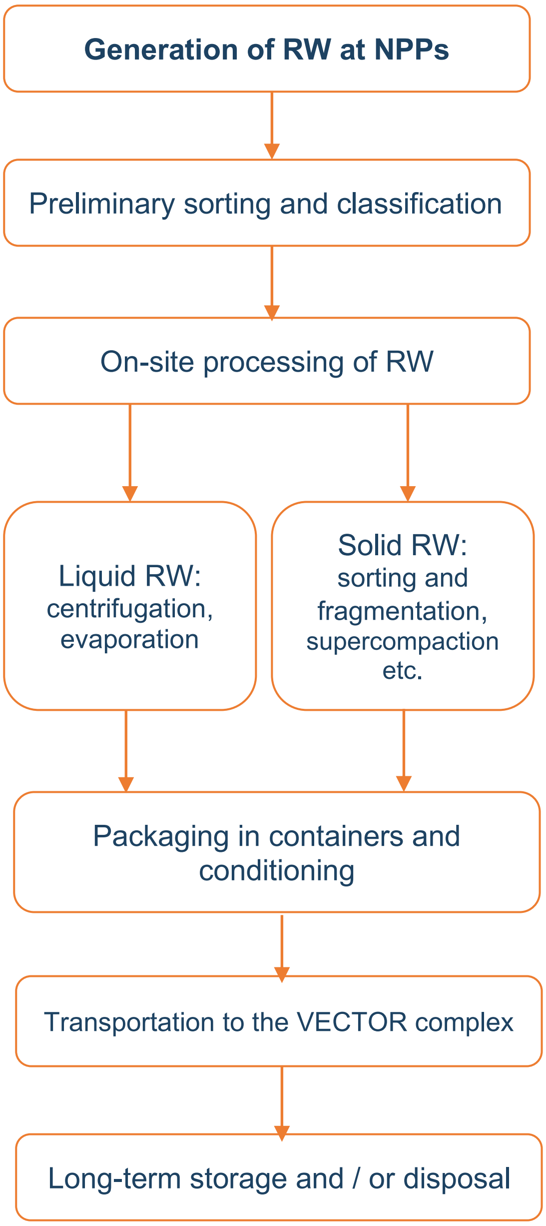

Figure 13: The broader waste management philosophy (RW Strategy 2021)

Future development

As part of Ukraine's National Radioactive Waste Management Strategy for 2025–2032, significant infrastructure upgrades are planned across all operating NPPs to ensure comprehensive processing, conditioning, and transfer of RW to the VECTOR site. At Zaporizhzhia NPP, future facilities include a RW drying unit, a clearance site for materials released from regulatory control, a light-type storage building for up to 1,000 concrete containers with conditioned RW, and a specialized facility to accommodate up to 20,000 CRO-200 containers containing salt residues. Khmelnytskyi NPP will host a full-scale Central RW Processing Facility by 2028, comprising a sorting and fragmentation unit, incinerator, supercompactor, cementation line, retrieval units for legacy waste, a decontamination station for metal waste, an RW characterization system, and specialized systems for sludge and spent filter retrieval. South Ukraine NPP will introduce liquid and solid RW processing lines by 2029–2030, alongside sludge retrieval systems and a clearance facility by 2032. Rivne NPP is scheduled to establish a clearance site by 2030. These projects aim to fully integrate waste conditioning at the site level and enable systematic transfer of standardized, certified RW

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containers to centralized disposal facilities at VECTOR, in line with international safety and lifecycle management requirements.

All conditioned RW from Ukrainian NPPs, once processed and certified, is planned to be transferred to the centralized VECTOR Industrial Complex. Currently, disposal is carried out at the operational Specially Equipped Near-Surface Repository for Solid Radioactive Waste (SOPSTRW) facility, while future volumes are expected to be directed to the engineered near-surface repositories TRW-1 and TRW-2 following their licensing. Additional disposal capacity is planned through the construction of new modules TRW-3, TRW-4, and TRW-2.1, as outlined in the national program. This centralized disposal system will ensure long-term environmental safety, standardized logistics, and regulatory oversight in accordance with international principles of final RW isolation.

Table 13: Planned Radioactive Waste Management Facilities (per National RW Policy and Strategy)

Facility / Equipment	Purpose	Specification / Capacity	Planned Commissioning Year
Zaporizhzhia NPP (ZNPP)			
RW Drying Unit	Reduction of RW moisture content	Data not available	-
Clearance Site for Materials	Clearance of materials from regulatory control	Data not available	-
Light-type Storage for RW in Concrete Containers	Storage of concrete containers with conditioned RW	Up to 1000 containers	-
Storage for CRO-200 Containers with Salt Residues	Storage of CRO-200 containers containing salt melt	20,000 containers	-
Rivne NPP (RNPP)			
Clearance Site for Materials	Clearance of materials from regulatory control	Data not available	2030
Khmelnytskyi NPP (KhNPP) – Central Processing Facility			
Sorting and Fragmentation Unit	Sorting and fragmentation of solid RW	3 m^3 per shift	2028
RW Incineration Unit	Thermal treatment of solid a liquid RW	35 kg/h	2028
Supercompaction Unit	Volume reduction of low-level solid RW	Up to 20,000 kN	2028
RW Activity Measurement Unit	Characterization of RW containers	12 containers per shift	2028
RW Retrieval Unit	Removal of accumulated RW from storage compartments	Up to 15 m^3/week	2028
Cementation Unit	Immobilization of RW in concrete matrix	4 KTRVf-0.2 containers per shift	2028
Decontamination Unit for Metals	Decontamination of radioactive-contaminated metals	Up to 200 t/year	2028

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Clearance Site for Materials	Clearance of materials from regulatory control	Data not available	2028
System for Retrieval of Filter Materials and Sludge	Retrieval of spent filter liquid media and sludge from liquid RW tanks	Data not available	2028
South Ukraine NPP (SUNPP)			
Clearance Site for Materials	Clearance of materials from regulatory control	Data not available	2032
Solid RW Processing Facility	Processing and conditioning of solid RW for disposal	Data not available	2030
Liquid RW Processing Facility	Treatment and conditioning of liquid RW	Data not available	2029
System for Retrieval of Sludge and Sediment from liquid RW Tanks	Cleaning of long-term storage tanks	Data not available	2030

9.3.4.3. Decommissioning of NPPs

In Ukraine, the decommissioning of NPPs is not an abstract or distant concern, but a carefully planned and regulated process embedded in the national nuclear strategy. For all operating NPPs, the selected approach is deferred dismantling. This method reflects both practical and strategic priorities: cost optimization, protection of personnel, and the use of radioactive decay as a natural mechanism for hazard reduction (IAEA 2014).

According to Ukrainian regulatory documents, such as (SNRIU 2020), and plant-specific strategies, decommissioning will proceed in three distinct phases. The first begins immediately after permanent reactor shutdown and involves the transition to safe storage. This includes the complete removal of SF from the reactor buildings to designated interim storage facilities such as the CSFSF, deactivation of non-essential systems, and the isolation of contaminated areas to ensure environmental and radiological stability. Critical infrastructure is either sealed or maintained in a surveillance state, preparing the facility for decades of latency.

The second phase, known as the latent or surveillance period, may last between 30 and 50 years. During this time, the plant remains under constant radiological monitoring and structural maintenance, allowing for the gradual decay of short- and medium-lived radionuclides. This period significantly reduces the radiological burden of decommissioning operations to follow, thereby enabling dismantling with fewer risks and lower technical complexity. In addition to passive safety, this approach also provides regulatory institutions the time needed to develop and approve technical conditions for final dismantling and disposal of the resulting waste.

The final phase is the active dismantling and site remediation. At this stage, the remaining reactor structures, systems, and components, including activated internals and embedded contamination, are disassembled and processed. The resulting RW is segregated, characterized, and processed in accordance with national waste acceptance criteria. The site itself is then decontaminated and returned to a state suitable for either unrestricted release or repurposed industrial use, depending on radiological clearance results. Upon successful verification, the site is officially released from regulatory control.

Expected waste from decommissioning operations will largely consist of intermediate-level and low-level materials, including steel components, pipelines, embedded concrete contamination, and auxiliary systems. Initially, much of this material may qualify as ILW due to high levels of residual activity, but after decades of decay, a significant portion can be reclassified as LLW or even VLLW. This shift will reduce the demand for long-term disposal space and allow for more efficient packaging and storage.

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The VECTOR facility within the Chornobyl Exclusion Zone plays a central role in this strategy. It is envisioned as the primary location for the reception, interim storage, and eventual disposal of conditioned RW resulting from both operational and decommissioning activities. The facility already accommodates containerized and cemented waste from other sources and will be expanded to include modules suitable for large-volume dismantling campaigns. Mobile waste processing units may be deployed directly at decommissioning sites to reduce logistical burdens and enhance efficiency.
The management of SF removed during the first phase will rely heavily on the CSFSF, which is specifically designed to host VVER-type SF in dry, passively cooled metal-concrete containers for up to a century. This offers a safe and cost-effective buffer period before the commissioning of a DGR for final disposal.
Ukraine's most relevant and valuable experience in decommissioning comes from the Chornobyl NPP. Units 1 through 3 are currently in deferred dismantling status, and the vast infrastructure developed for their stabilization and surveillance, including the New Safe Confinement over Unit 4, has informed broader national policy. Through Chornobyl, Ukraine has tested methodologies for safe enclosure, real-time radiation monitoring, remote dismantling technologies, and regulatory flexibility under crisis conditions. These lessons are already being transferred into the strategic planning for future decommissioning of power reactors.

9.3.5. Plans for the construction of SMRs

Ukraine is actively pursuing the development of SMRs as a pivotal component of its strategy to enhance energy security, achieve carbon neutrality, and modernize its energy infrastructure. The adoption of SMRs is seen to replace aging coal-fired power plants, decentralize energy production, and integrate advanced nuclear technologies into the national grid.

Key Partnerships and Projects
Holtec International – SMR-300 (Holtec 2023)
In April 2023, Ukraine's state nuclear operator Energoatom and U.S.-based Holtec International signed a cooperation agreement to deploy up to 20 SMR-300 units across Ukraine. The first pilot plant is scheduled to begin supplying power by March 2029. Additionally, plans are underway to establish a manufacturing facility in Ukraine for producing components of Holtec's SMR-300 reactors, aiming to support both domestic needs and potential exports to European markets.
Westinghouse Electric Company – AP300 SMR (Westinghouse 2023)
In September 2023, Energoatom and Westinghouse Electric Company signed a Memorandum of Understanding to develop and deploy the AP300 SMR in Ukraine. Westinghouse aims to achieve design certification by 2027, with construction anticipated to commence by 2030 and the first unit becoming operational in the early 2030s.

Table 14: Characteristics of Selected SMRs for Ukraine

SMR type	Developer, country	Technology type	Capacity, MWe	Fuel type	Passive Safety Features	Current status
SMR-300	Holtec International (USA)	PWR-based SMR	300	Standard low-enriched uranium	Full passive cooling (no operator action for 14 days)	Deployment Agreement Signed
AP300	Westinghouse (USA)	PWR-based SMR	300	Standard low-	Passive safety with	Feasibility and

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				enriched uranium	gravity-fed systems	licensing phase

Potential siting options in Ukraine include:

- reuse of brownfield sites (former coal plants);
- existing nuclear sites;
- Chornobyl Exclusion Zone as an experimental deployment area for modular energy hubs.

These strategies aim to reduce capital costs, leverage existing grid infrastructure, and accelerate permitting.

SMRs are designed for up to 60 years of operation with possible life extensions. Modular dismantling, centralized decommissioning hubs, and enhanced recyclability of materials are planned to simplify the final shutdown phases.

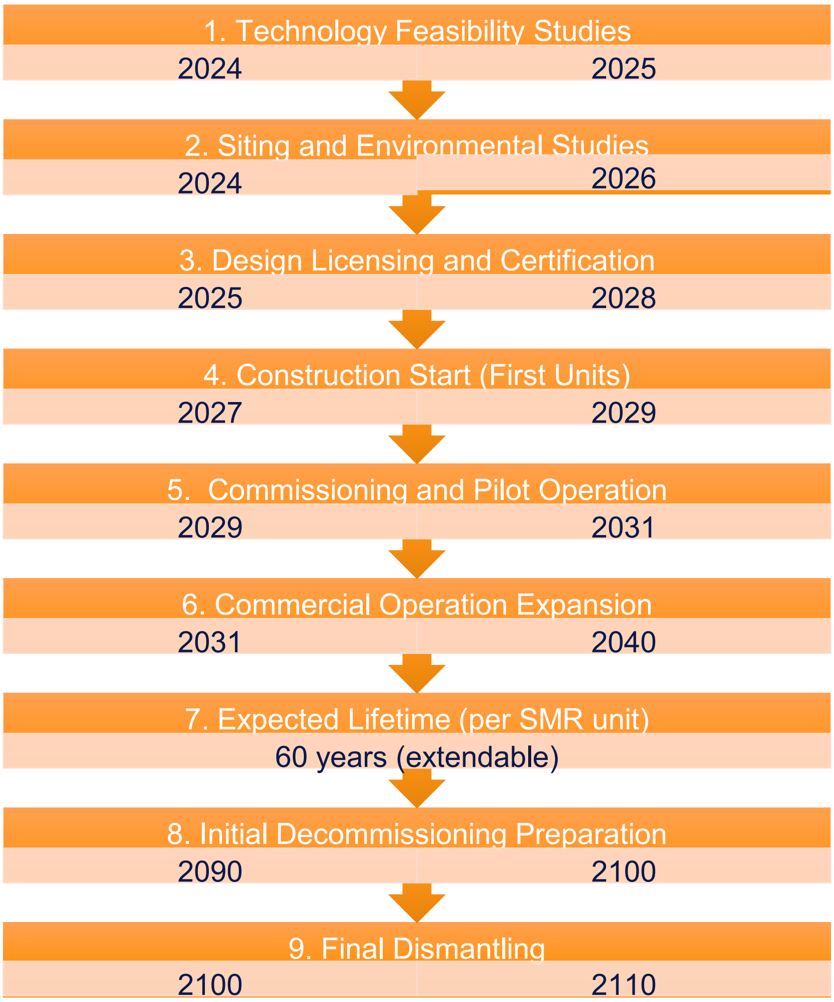

Figure 14: Approximate time schedule for SMRs (from operation to decommissioning)

9.3.6. Expected Management of SF and RW from SMR

The deployment of SMRs in Ukraine introduces not only a shift in energy generation but also a paradigm shift in the management of the back end of the fuel cycle. While SMRs differ from traditional VVER-type NPPs in terms of design, size, and operational approach, studies (e.g. Krall L. M., Macfarlane A. M., Ewing R. C. (2022)) suggest that LW SMRs may generate higher overall

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volumes of RW and SF per unit of electricity produced. This is primarily due to increased neutron leakage, lower fuel burnup, and greater activation of structural materials.
Despite this, the compactness of SMRs, sealed modular designs, and inherent passive safety features significantly reshape the RW and SF profiles compared to conventional reactors, resulting in higher decay-heat densities, more compact but non-standard waste geometries, increased activation of internals due to neutron leakage, and sealed cores that limit accessibility for conventional fuel handling approaches.
Future RW management systems in Ukraine, as well as in other countries considering SMRs such as Finland and the Czech Republic, must anticipate these changes and adapt through regulatory revisions, infrastructure upgrades, and scalable strategies.

9.3.6.1. SF Management

This section addresses only the SF management considerations for LW SMRs planned in Ukraine, specifically the Holtec SMR-300 and Westinghouse AP300. These two designs are both PWRs with advanced passive safety systems and underground configurations. While they share commonalities with traditional LWRs, they present unique backend management features that warrant specific consideration.

Key Characteristics and SF Implications of LW SMRs planned in Ukraine

1) SMR-300

The Holtec SMR-300 is a 300 MWe (~1050 MWth) Generation III+ PWR with a single-loop system. It employs natural circulation for reactor cooling and features fully underground siting of the reactor vessel and SF pool within a robust containment structure.

Fuel

The reactor uses standard UO_2 fuel with enrichment up to 4.95% U-235, in a 17×17 assembly configuration.

Refueling Cycle

18–24 months per cycle. The design uses a small core, with approximately 121 fuel assemblies.

SF Storage

After irradiation, fuel will remain in the reactor's below-grade SF pool for 4 to 5,5 years for initial cooling.

Dry Storage

Once cooled, SF is transferred to HI-STORM UMAX underground dry storage canisters—fully passive, air-cooled modules licensed by the U.S. NRC. Only 24 canisters are needed to hold all SF for the full 80-year plant life.

Transport and Central Storage

On-site storage may negate the need for centralized storage; however, the option to transport fuel to national facilities remains open.

Thermal Safety

Passive decay heat removal without operator action reduces cooling risks. The use of natural circulation also lowers accident scenario severity.

Security and Safeguards

Underground configuration reduces vulnerability. Limited fissile material in the pool at any time (due to batch refueling) lowers criticality and proliferation risks.

2) AP300

The Westinghouse AP300 is a 300 MWe (900 MWth) integrated PWR derived from the AP1000 design. It features a compact reactor vessel submerged within a pool and passive core cooling mechanisms.

Fuel

Utilizes conventional UO_2 fuel with enrichment <5%, likely in 17×17 grid assemblies. Core configuration expected to be similar in size to the AP1000, adjusted for smaller output.

Fuel Cycle

18–24 month cycles. Standard light water cooling and moderation.

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SF Storage
SF will be stored in the integrated pool for 4–5.5 years, allowing for decay heat reduction.
Dry Storage
After pool cooling, SF will be transferred to Type B(U)F-certified casks suitable for long-term storage and transport. Compatibility with existing dry cask systems will need to be confirmed.
Centralized Storage Potential
Like the SMR-300, the AP300 may benefit from national consolidation strategies using facilities like CSFSF at Chornobyl, if compatibility is verified.

Common Backend Considerations

- Same Type of Fuel Use:

Both reactors use low-enriched uranium fuel only.

- Decay Heat Management:

Due to compact core sizes and high fuel burnup, decay heat and shielding requirements may exceed those of legacy VVER fuel. Thermal modeling will be required.

- Modularity and Logistics:

With reactors likely deployed across diverse sites, Ukraine must plan for modular dry storage, safe transport logistics, and decentralized oversight.

- Regulatory Alignment:

Licensing frameworks, originally developed for VVER-400, 1000, will need to be adapted to accommodate smaller core geometries, passive safety assumptions, and new dry storage solutions.
In conclusion, although SF from SMR-300 and AP300 shares many characteristics with traditional PWR fuel, several technical and logistical differences must be addressed (Idaho NL 2022). Ukraine should prioritize early planning for dry storage capacity, national licensing adaptations, and transport coordination to ensure a robust and secure back end for its future LW SMR fleet.

9.3.6.2. RW Management

The introduction of SMRs in Ukraine signifies more than just a shift in reactor size or siting – it represents a fundamental transformation in how the back end of the nuclear fuel cycle will be conceived, regulated, and executed. While SMRs are often promoted for their compact footprint, enhanced safety, and operational flexibility, these very characteristics lead to distinctive RW profiles that diverge in meaningful ways from those associated with large, traditional VVER-type reactors currently operating in Ukraine.
Although some early assumptions suggested that SMRs would generate lower overall volumes of RW per unit of electricity produced, recent studies (e.g. Krall L. M., Macfarlane A. M., Ewing R. C. (2022)) indicate that LW SMRs, in fact, generate higher overall volumes of radioactive waste and spent fuel per unit of electricity produced due to:

- increased neutron leakage,
- lower fuel burnup,
- greater activation of structural components.

Despite this, the nature of the waste from LW SMRs remains distinct from traditional reactors. Compact sealed modules, extended operation cycles, and modular fuel designs may lead to waste forms with:

- higher specific activity,
- concentrated decay heat,
- novel material compositions.

These differences require a reconceptualization of how waste is:

- classified,
- conditioned,
- stored,

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- and ultimately disposed.

Waste arising from SMRs will reflect the highly integrated and modular nature of these reactors – characterized by sealed components, non-traditional fuel forms, and longer operational cycles without refueling.

From a regulatory standpoint, Ukraine's future waste management system must prepare to:

- accept different types of waste,
- enable earlier and more proactive engagement with reactor developers,
- modernize regulations,
- reconfigure infrastructure,
- introduce adaptive, scalable strategies.

The existing VECTOR facility and the recently launched CSFSF provide a foundation, but neither was initially designed with SMR-specific waste streams in mind.

Key RW characteristics from LW SMRs:

- higher decay heat densities:

may require longer cooling/shielding before transport or disposal.

- compact but diverse waste forms:
- varying in physical, chemical, and radiological properties.

Table 15: Expected categories of SMR RW

No.	Type of RW	Description	Expected Form
1	**Operational LLW**	Filters, resins, maintenance waste	Similar to conventional NPPs
2	**ILW**	Sealed module components, structural parts	Higher specific activity, compact forms
3	**HLW**	Particle fuel elements	High activity, long-lived
4	**Decommissioning RW**	Dismantled internals, contaminated auxiliary systems	LLW / ILW, reduced after decay

Strategic Approaches

Managing SMR-derived RW in Ukraine requires specific, proactive measures tailored to the higher activity, compact form, and thermal challenges of these waste streams.

The VECTOR facility must be upgraded to:

- accept sealed modules and high heat-load waste packages,
- incorporate advanced thermal modelling,
- enhance shielding infrastructure.

Conditioning and pre-disposal systems should include:

- high-integrity encapsulation for activated components,
- modular transport casks adapted for non-standard geometries and decay heat.

Waste strategies must be incorporated into SMR licensing from the outset, with back-end management plans required, reviewed, and updated as part of regulatory oversight.

In short, Ukraine's strategy must shift from general frameworks to technology-specific solutions focused on the unique properties of LW SMR waste. In the SMR era must move beyond the notion of simply scaling down existing methods. Instead, it must embrace a new paradigm that acknowledges the complexity and novelty of SMR waste streams. The core challenge lies not in the volume of waste, but in its radiological nature – and in building the robust, adaptable systems needed to manage it safely, sustainably, and responsibly.

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9.3.6.3. Decommissioning of SMRs

The decommissioning of LW SMRs in Ukraine represents a new chapter in nuclear infrastructure management — one marked not by simplicity or miniaturization, but by increased complexity in RW and SF handling per unit of electricity generated.

Recent studies demonstrate that LW SMRs may produce significantly greater volumes of RW and SF per MWh than traditional large-scale reactors such as VVER. This is driven by:

- increased neutron leakage, due to compact reactor cores,
- lower fuel burnup, resulting in greater quantities of SF,
- greater activation of structural materials, leading to more ILW.

These factors introduce novel challenges in decommissioning, which must be addressed from the outset of SMR deployment.

Key Decommissioning Challenges of LW SMRs

1) Higher Specific Activity and Decay Heat

While total mass or volume may appear modest, the radiological intensity of SMR waste is significantly higher:

- sealed modules and compact FAs concentrate heat and radioactivity,
- extended decay cooling and shielding will be essential before any dismantling or transport.

2) Novel RW Forms

SMRs include non-traditional components, such as:

- embedded metallic internals,
- reactor modules with neutron-activated steel and alloys.

3) Long-Term Storage Burden

Due to high decay heat and radiotoxicity:

- interim storage requirements extend far beyond those of typical LLW/ILW,
- existing facilities like VECTOR or CSFSF may be structurally or thermally inadequate without modification.

Also, while modular construction simplifies some physical aspects of dismantling, it does not reduce the radiological complexity. Instead: Factory-built units may allow for segmented or whole-module removal. However, remote handling systems, hot cells, or shielded enclosures will be essential due to the high specific dose rates of decommissioned modules.

Decommissioning LW SMRs is not a matter of simplifying existing VVER protocols. It is a qualitatively different challenge — shaped by higher radioactive intensity, denser heat loads, and non-standard waste forms.

9.3.7. Comparison of SF and RW management between SMR and existing NPPs

The transition from conventional large-scale NPPs to LW SMRs in Ukraine introduces not only new reactor designs, but also a fundamentally different landscape for RW management. While SMRs are often associated with advantages in modular deployment and enhanced safety, recent analyses show that they may generate greater quantities of RW per unit of electricity produced, particularly in terms of specific activity, heat output, and structural material activation.

These differences have profound implications for Ukraine's RW management infrastructure, which was developed primarily around VVER-type reactors. A comparative understanding is essential to adapt existing systems and plan future facilities.

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Table 16: Key differences of RW management from VVER to LW SMRs

Parameter	VVER-type NPPs	LW SMRs
RW volume per MWh	Lower on average per unit of electricity	Higher due to neutron leakage and lower fuel burnup
ILW (activated materials)	Bulk components (vessels, shielding)	Higher neutron activation per kg, more compact but more intense
ILW (Operational waste)	Filters, resins, contaminated surfaces	Similar forms, but potentially higher activity concentration
Decommissioning Waste	Large heterogeneous components	Compact modular components with elevated activation
Conditioning requirements	Established for known waste types	Requires new shielding, heat management, and packaging designs

Key differences of RW management from VVER to LW SMRs

1) Higher RW intensity:

Although some SMR components are smaller and more modular, the radiological and thermal intensity per waste package is significantly greater. This requires specialized containment, shielding, and potentially longer interim storage before disposal.

2) Greater volume of activated materials:

Neutron leakage in compact LW SMR cores results in more extensive activation of structural components, particularly stainless steels and support internals, leading to higher ILW volumes per MWh.

3) Incompatibility with existing repositories:

Facilities like VECTOR and CSFSF may not be able to safely or efficiently manage SMR-derived waste without:

- revised waste acceptance criteria,
- upgraded shielding and ventilation systems,
- enhanced thermal modeling for high-output HLW.

RW from LW SMRs presents a more complex, more intense, and less predictable challenge than that from traditional VVER-type NPPs. Ukraine's existing infrastructure must be not only scaled but re-engineered to address greater heat density, higher activity per unit volume and non-standard geometries and materials.

Strategic planning must incorporate these realities early, embedding RW management into reactor licensing, infrastructure modernization, and national policy development. The focus must not be on waste volume alone, but on waste behavior, hazard, and long-term containment demands.

Types and Brands of Nuclear Fuel for VVER-440 and VVER-1000 Reactors Used at Ukrainian NPPs

Ukrainian NPPs with VVER-440 and VVER-1000 reactors use various types and brands of nuclear fuel, including both Russian and Western alternatives. Below is a detailed breakdown.

Table 17: Main parameters of VVER-1000 fuel

Parameter	TVS-M	TVS-A	TVS WR	TVS-W (LTA)
mass of fuel material (in kg)	455.52 ±4.5	491.4 ± 4.5 494.5 ± 4.5	550.4 ± 5	536 ± 5
fuel material	UO2	UO2	UO2	UO2
enrichment, wt. % 235U	1.6 – 4.4 1.3 – 4.40 2.00	1.3- 4.40	- 4.20 (central zone)	3.0 – 4.4

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Table 18: Characteristics of VVER-440 fuel

Parameter	of FA of the 1st generation		FA of the 2nd generation	
	RA	FA	RA	FA
mass of fuel material (in kg)	136.96	131.17	143.8	136.7
fuel material	UO2		UO2/UO2+5% Gd 2Gd2O3	
enrichment, wt % 235U	1.6 – 4.4		1.6 – 4.6	

When handling SF, nuclear and radiation safety conditions must be ensured that exclude excessive release of radioactivity and exposure of personnel and the public. Safe operation conditions are ensured by maintaining safety parameters within the specified limits, which must be ensured under normal and emergency safety conditions. The main parameters are:

- the effective neutron multiplication coefficient should not exceed 0.95,
- the maximum temperature of the fuel element and nuclear fuel shells,
- dose rate at the external boundaries of the SF management system,
- the release of activity in emergency situations should not exceed the limits of radiation exposure to the population - for Ukraine, the lower levels of the evacuation of the population have been selected.

Table 19: Main parameters for the safety of SF management using the existing storage system

Criteria	Value	Influenced factors	Possible measures	Comment
Nuclear safety	K_{ef}<0.95	Enrichment + fuel assembly geometry	additional absorption materials, geometry factor	For higher burnout SF isn't important
Thermal conditions	T_{UO2} < 1400 ^{0}C, T_{Zr+Nb}< 450 ^{0}C	Residual power + residual power density	change minimal exposure time before storage	Need more space in SF pool (provide by SMR project)
Dose rate for personal	< 20 mSv/y	saved activity (burnup + exposure time)	change minimal exposure time before storage, limit of SF in storage unit	
Dose rate for population	< 10 mSv (for emergency conditions)	saved activity + amount of SF in storage system unit (burnup + exposure time)	change minimal exposure time before storage, limit of SF in storage unit	

From the presented matrix, we can see that the main parameter that affects the safety of SF management using the existing storage system is the initial enrichment and burnout, which determine the accumulation of fission products in SF and, accordingly, the level of residual energy release, radiation safety.

The level of residual energy emissions can be estimated using the Wei-Wigner formula:

$$\frac{W_{\beta,\gamma}}{W_0} = 6,5 \cdot 10^{-2} \cdot \left[\tau_c^{-0,2} - (\tau_c + T)^{-0,2}\right]$$

Where:

$W_{\beta,\gamma}$ the residual heat output of the reactor at time Tc after its shutdown

W_0 initial power which reactor worked during T time

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Greater burnout can be achieved by increasing the specific capacity of nuclear fuel or by extending the duration of operation of the reactor.
In the case of an increase in power, the level of residual energy emissions increases in direct proportion, and for an increase in operating time at a given power level, the estimate is given in the table below. Preliminary assessment performed for the same power density.

Table 20 : Residual Power and Burn-up Estimates vs. Operating Time

Working time, years	Exposure time	Related residual power of initial power	Burn-up approximately level, MWt·d/kgUO2	Power Change, %
1	5	5.34E-03	14	3.23E+01
2	5	9.70E-03	28	5.87E+01
3	5	1.34E-02	42	8.09E+01
4	5	1.65E-02	56	1.00E+02*
5	5	1.93E-02	70	1.17E+02
6	5	2.17E-02	84	1.32E+02
7	5	2.39E-02	98	1.45E+02
* Current level for VVER-1000/VVER-440				

The estimates of residual energy release performed above are rather crude, but they show the order of increase in the level of residual energy release and a proportional increase in the content of long- /medium-existing radionuclides such as Cs-137 and Sr-90.
Although the initial estimates of residual energy release may be simplified, they reflect a key principle: the residual heat output and the inventory of long- and medium-lived radionuclides, particularly Cs-137) and Sr-90, scale with fuel burnup and irradiation history. In high-burnup fuels (e.g., up to 100 MWd/kgU), these isotopes become the dominant contributors to decay heat beyond the first year of cooling, with heat output and radionuclide concentrations increasing by a factor of up to 4,5 over a 5-year decay period.
However, LW SMRs typically operate with lower fuel burnup compared to large advanced LWRs. Despite this, their compact cores and higher specific power density mean that residual heat per unit of SF mass can remain high, and cooling and shielding requirements remain critical.

This has several technical implications:

1) Cs-137 and Sr-90 remain key contributors to decay heat in LW SMRs over intermediate timeframes (5–30 years), potentially requiring longer in-reactor or near-core decay periods.

2) Although SMR designs often include on-site storage capacity, high local heat generation will require more thermally resilient SF pools or dry storage systems with enhanced passive cooling.
3) Extended exposure periods prior to transport will likely be necessary to reduce decay heat to acceptable levels for conventional cask handling.
4) According to Ukrainian nuclear safety regulations, SF must be subcritical under all conditions, including that equivalent to fresh fuel parameters.
Although fuel enrichment in LW SMRs remains within the LEU threshold (≤5%), their higher specific burnup and compact core design may still require:

- adjustments to dry storage cask design, particularly in terms of thermal performance and internal geometry for denser fuel modules,
- evaluation of neutron shielding and absorber materials, considering potential local reactivity effects,
- confirmation of subcriticality margins during transport, storage, and accident scenarios, due to increased fuel mass per package and higher residual reactivity.

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In conclusion, although LW SMRs may not reach the extreme radionuclide concentrations associated with high-burnup large reactors, their high specific activity, compact fuel form, and atypical geometry require early consideration in fuel handling, storage, and transport strategies. This includes thermal modeling of SF assemblies, regulatory adjustments for enriched fuels, and customized cask design to ensure long-term safety and compliance with national standards.

SF a RW Types

Existing NPPs (VVER-440/1000):

- SF assemblies – relatively standardized,
- cemented sludges, filters, ion-exchange resins and compacted operational LLW,
- activated structural steel from internals (pressure vessels, piping) and support structures,
- decommissioning waste: tons of contaminated concrete and structural metals, typically low in specific activity but large in volume.

LW SMRs:

LW SMRs generate greater volumes of high-activity waste per MWh, due to increased neutron leakage, lower burnup, and intensified activation of internals:

- compact SF modules with higher specific decay heat and radioactivity per unit mass; non-standard geometry may complicate handling,
- highly activated metallic internals, including reactor block components and control assemblies — classified as ILW, with elevated gamma/neutron fields,
- operational LLW/ILW, while modular in form, exhibit higher activity per package and require customized shielding and packaging solutions,
- decommissioning waste consists of smaller total volumes but significantly higher specific activity, requiring longer decay and shielding times.

Some SMR-related waste forms may have higher activity concentrations and different physical profiles compared to those anticipated by current Ukrainian RW packaging standards, necessitating the development of new certified container types and updated regulatory procedures.

Requirements for Capacity of near-surface repository and DGR

Near-Surface Repository:

Near-surface repositories (like VECTOR) are sized to accommodate LLW/ILW from operational and decommissioning activities of VVER NPPs, with vaults suited to:

- large, low-heat packages,
- predictable decay profiles of conventional LLW/ILW.

Challenges posed by LW SMRs:

- ILW with higher specific heat and radiation levels may exceed design limits for existing vaults,
- RW is more dense and modular, requiring individualized containers and possibly passive cooling during early storage stages.

Necessary Adjustments:

- revise waste acceptance criteria for activated metallic modules and compact ILW,
- expand or retrofit vaults to support decentralized, modular SMR waste accumulation,
- increase cooling and shielding capacity in interim storage, particularly during decommissioning phases.

Deep Geological Repository (DGR):

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Ukraine plans a national DGR for long-term isolation of HLW and SF from VVER reactors. However, LW SMRs introduce new HLW characteristics that challenge current repository design assumptions.

Key considerations for LW SMRs:

- compact SF modules with higher decay heat density may require wider tunnel spacing or extended cooling before emplacement,
- altered migration behavior of radionuclides due to new fuel matrices or structural materials (e.g., higher corrosion susceptibility of compact cores),
- potential need for enhanced engineered barriers to mitigate heat and radiological effects on repository systems.

Strategic Needs:

- update DGR thermal management models to accommodate dense waste packages (e.g., high ventilation, heat spacing),
- designate "hot galleries" for SMR-derived HLW with elevated thermal output,
- initiate waste form qualification programs specific to SMR fuels and activated materials.

Table 21: Key requirements for design of DGR

No.	Aspect	Traditional SF	SMR HLW
1	Waste form	Large zirconium-clad fuel assemblies	Small, dense modules
2	Thermal load	Predictable, known decay curves	Higher per kg, faster decay of short-lived isotopes
3	Repository space use	Extensive (due to bulk)	Potentially smaller volume, tighter engineering controls
4	Barrier systems	Standard multi-barrier concept	May require enhanced engineered barriers

While LW SMRs will not overwhelm Ukraine's RW system in terms of sheer volume, they fundamentally alter the radiological, thermal, and mechanical nature of both short- and long-lived waste streams.

Their deployment requires:

- redesign of interim storage systems with improved shielding and cooling performance,
- modernization of repository design and acceptance criteria, including for dense, high-heat waste,
- development of specialized packaging and transport systems for compact, but high-intensity waste forms.

By proactively updating its RW infrastructure and regulation, Ukraine can safely accommodate the transition to SMRs – maintaining high environmental and safety standards while embracing next-generation nuclear technology.

9.3.8. Applicability of the existing system for management of SF and RW from SMR

Ukraine's current RW and SF management system is well-developed and internationally aligned, built around decades of experience with large VVER-type PWRs. Central facilities such as the CSFSF and the VECTOR complex serve as pillars of this system, providing centralized long-term interim storage for SF and processing/disposal services for LLW and ILW. However, these

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facilities were not originally designed to accommodate the waste streams expected from modern LW SMRs, including SMR-300 and AP300.

Both of these SMR types operate on standard fuel (<5% U-235) and share many basic fuel and coolant characteristics with traditional LWRs. Nonetheless, their core configurations are much more compact, and their power density per unit volume is significantly higher. These differences affect the nature of the spent fuel and operational waste they generate.

Table 22: Applicability of current RWM system for SMR

Aspect	Current Ukrainian system (for VVERs)	SMR-300 / AP300 requirements
Fuel enrichment	3–4,5% U-235	≤5% U-235
Burnup and fuel volume	~45–55 GWd/tU; low SF volume per GW-year	similar or slightly lower burnup; more SF per GW-year
Fuel geometry	long (~4 m) VVER assemblies	shorter, compact PWR-style assemblies
Decay heat	predictable, lower specific heat	higher decay heat per volume; longer cooling required
Dry storage compatibility	CSFSF designed for VVER assemblies	incompatible; new cask geometries and cooling solutions needed
ILW origin and form	Structural metals, resins, filters	more activated internals; compact, but high-activity ILW
RW conditioning	cementation, compaction of homogeneous waste streams	likely need for modular encapsulation, advanced shielding
VECTOR vault suitability	large packages with low–medium heat output	requires upgrades for smaller, hotter, shielded modular waste units

Although SMR-300 and AP300 do not introduce fuel forms outside LEU limits, the thermal and spatial characteristics of their SF and ILW differ markedly from VVER-derived waste. Their smaller reactor cores result in greater neutron leakage, leading to more activation of internal components and proportionally greater ILW volume per MWh produced.

The CSFSF must be equipped to store SF that, while based on standard UO_2 low-enriched uranium fuel as used in VVER reactors, differs in assembly geometry, thermal output, and neutron multiplication characteristics. Likewise, VECTOR's vault-based storage must be enhanced to safely accommodate more intense, modular waste forms, including sealed reactor internals and compact activated steel components.

Additionally, since SMRs may be deployed in decentralized locations, mobile or regional buffer storage systems may be required to ensure safe interim containment before transfer to centralized facilities. Ukraine's current centralized model remains advantageous, but flexibility in logistics and regulatory licensing will be essential to accommodate this evolving architecture.

9.3.9. Conclusions for Ukraine

Ukraine's existing infrastructure for SF and RW provides a solid regulatory and technical base for the future integration of SMR-300 and AP300. However, while these SMRs use conventional LEU fuel and share core principles with VVER reactors, they differ significantly in operational configuration and RW characteristics.

Specifically, they are expected to produce more SF per unit energy, higher decay heat per volume, and greater volumes of compact, but highly activated internals, often in non-standard module geometries. These differences exceed the design assumptions of current systems such as CSFSF and VECTOR.

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To realistically accommodate these changes, Ukraine's backend system will require phased technical adjustments, including:

- development or licensing of modified dry cask systems suited to compact, hotter fuel,
- targeted upgrades at VECTOR to handle modular ILW forms with higher shielding and ventilation demands,
- refinements to classification and acceptance procedures for SMR-specific waste streams,
- practical solutions for decentralized deployment, such as interim buffer storage near SMR sites.

With gradual, needs-based modernization, Ukraine can support safe and effective SMR deployment without overhauling its entire waste management strategy.

10. Evaluation of expected differences between commercial LWRs and SMRs and applicability of current system and technologies

As Ukraine and other European states consider integrating SMRs into their national energy strategies, it is essential to critically assess their compatibility with existing systems built around conventional large light-water reactors. While SMRs offer potential advantages in terms of siting flexibility, passive safety, and modular deployment, their implementation requires a detailed technical evaluation including SF and RW management.

10.1. Design and operational differences

LW SMRs are a subclass of SMRs that retain the core physics and coolant/moderator system of traditional pressurized or boiling water reactors but introduce novel structural and fuel cycle configurations. Their most distinctive features include:

- ***Modular and compact design***

  LW SMRs are factory-fabricated units designed for transport and rapid deployment. Their smaller physical size enables:
  - standardized components and reduced construction time,
  - siting flexibility (e.g., remote or industrial zones),
  - potential for phased power capacity expansion via multi-module operation.
- ***Passive safety systems***

  Passive safety features are a hallmark of LW SMRs, employing:
  - natural convection,
  - gravity-driven coolant circulation,
  - elevated thermal margins without active systems.

  These characteristics significantly enhance reactor safety and reduce emergency response complexity. It should be emphasized, however, that passive and inherent safety systems in SMRs require comprehensive validation through experimental testing and regulatory review, as many of these systems have not yet been deployed at commercial scale.
- ***Fuel enrichment and burnup***
  - most LW SMRs use low-enriched uranium (<5% U-235), which is compatible with existing international non-proliferation norms, including IAEA safeguards and NPT provisions,

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- target burnup values generally range from 35 to 60 GWd/tU, similar to large LWRs,
- refueling intervals are extended (e.g., every 4–10 years), reducing operational disruption and handling frequency. However, it must be considered that some SMR designs may require new fuel fabrication routes, including the production and certification, which may not currently be available in many countries. These supply chain requirements will need to be factored into fuel cycle planning and infrastructure development.

However, compact cores with higher power density result in:

- increased neutron leakage – which not only causes greater activation of structural components, but also limits achievable fuel burnup, resulting in higher overall volumes of SF and RW per unit of electricity produced.,
- lower fuel utilization efficiency – greater spent fuel mass per unit energy.

10.2. SF and RW Management

The transition to LW SMRs brings fundamental changes to the nature of SF and RW, requiring a reassessment of current backend strategies. While the basic radiological principles remain constant, the physical form, thermal profile, and activation characteristics of SMR-derived waste will diverge from those of large PWR.

SF characteristics

One of the most notable differences lies in the potential increased volume of SF per unit of energy. Despite similar or even higher burnup targets compared to conventional LWRs, LW SMRs may have lower fuel utilization efficiency, driven by compact core designs and greater neutron leakage. As a result, they may produce greater SF mass per GW-year, which has direct implications for storage capacity, cooling requirements, and shielding needs.

Volume and composition of RW

It is a common misconception that smaller reactors produce less waste. In reality, LW SMRs tend to:

- create RW with higher specific activity and decay heat, particularly in compact ILW forms such as sealed internal modules or activated metallic components,
- introduce novel fuel geometries that complicate storage, transport, and disposal planning.

These factors imply that while the absolute volume may appear modest, the handling complexity and safety implications of SMR-derived waste may be greater than in traditional systems.

Intermediate and low-level RW

Operational and decommissioning RW from LW SMRs is also distinct. Due to the increased neutron leakage from small cores, structural components such as internal cladding, control rods, and reflector assemblies become more intensely activated than in large LWRs. This may lead to:

- higher volumes of ILW per unit of energy,
- smaller but significantly hotter and more radioactive individual waste packages,
- longer decay times and stricter shielding requirements before final disposal or transport.

Decommissioning waste may be reduced in total volume due to the smaller reactor footprint, but its specific activity is substantially elevated, especially in modular designs where sealed vessels or internals are replaced as whole units.

Compatibility with existing infrastructure

Current backend infrastructure in many European countries (including dry storage systems, interim vaults, and transport casks) was developed for standardized LWR fuel. Accommodating SMR-derived waste will likely require:

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- design modification of dry casks and transport flasks,
- thermal and shielding upgrades at storage facilities to cope with hotter, more radioactive ILW packages,
- development of specialized conditioning processes for waste streams not currently foreseen in existing processing facilities.

Regulatory Frameworks and Licensing

The introduction of LW SMRs challenges the regulatory landscape across Europe. Many current rules were developed around conventional LWRs and may not account for longer in-core fuel lifetimes and sealed module operation and hybrid waste forms with ILW/HLW characteristics.

Regulatory bodies will need to initiate SMR-specific reviews to define appropriate waste classification schemes, licensing pathways, and performance criteria for new back-end technologies.

10.3. Country-specific considerations

Finland

Finland's geological repository at Olkiluoto, designed for standardized LWR SF, may not directly accept SMR-derived waste without adaptation. Factors such as higher heat output per unit volume and non-standard module geometry would require re-evaluation of tunnel spacing, canister design, and thermal modeling.

Czech Republic

The Czech Republic's current SF and RW management strategies would need assessment for compatibility with SF and RW from SMR. The required capacity for storage and disposal of SF and RW must be assessed.

Ukraine

Ukraine's Centralized Spent Fuel Storage Facility, designed for VVER-type reactors, may need adaptations to handle SMR-generated waste, especially if SMRs with different fuel types are deployed.

France

France's reprocessing infrastructure, centered around the La Hague facility, is optimized for LWR fuel. The integration of SMRs may require adjustments in reprocessing techniques or the development of new processes.

Germany

With its nuclear phase-out policy, Germany's focus is on decommissioning and waste management. The potential introduction of SMRs would necessitate a reevaluation of current strategies and policies.

Sweden

Sweden's planned DGR at Forsmark is designed for LWR waste. The inclusion of SMR waste would require analysis to ensure compatibility and safety.

Slovenia

Slovenia's joint venture with Croatia for the Krško NPP's waste management would need to consider the implications of SMR deployment on shared facilities and agreements.

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10.4. Generalization for all countries

The integration of SMRs into the European nuclear framework presents both opportunities and challenges. While SMRs offer potential benefits in terms of safety, cost, and flexibility, their successful deployment hinges on the adaptability of existing systems and the development of new technologies and regulatory approaches. Despite their lower absolute capital cost and enhanced siting flexibility, some economic analyses indicate that SMRs may currently face higher specific construction costs per MWe compared to conventional NPPs. Cost competitiveness will therefore depend on factors such as fleet deployment, modular standardization, and supply chain maturity.

Key considerations include:

- infrastructure adaptation:

Countries must evaluate the suitability of their existing waste storage and disposal systems, particularly regarding: thermal performance, RW packaging formats, geometry of storage modules.

- regulatory evolution:

It is critical to update regulatory frameworks to address the unique operational and safety aspects for new fuel types, long-life sealed modules, increased ILW generation and decay heat per package.

- research and development:

R&D should focus on understanding the long-term behavior of SMR-specific RW, designing new container types, shielding systems, and vault geometries, modeling thermal and radionuclide migration profiles unique to SMRs.

- international collaboration:

Collaboration between EU nations will be vital to harmonize classification and regulatory practices, pool knowledge on RW processing and conditioning technologies, support joint infrastructure (e.g., shared DGR access or interim hubs).

LW SMRs represent a promising evolution of nuclear power, but their backend implications cannot be overlooked. Through coordinated infrastructure upgrades, regulatory reform, and cross-border cooperation, Europe can ensure that SMR deployment is not only innovative and efficient but also safe, sustainable, and future-ready.

A synthesis of the main differences and their implications are presented in Table 23, which highlights the specific challenges LW-SMRs introduce to existing RW and SF management systems.

Table 23 - Key differences between LW-SMRs and large LWRs in terms of SF and RW management

Category	Large LWRs	LW-SMRs	Main implications / challenges
1) Core & Fuel Use	Large cores, higher burnup, efficient utilization	Compact cores, higher neutron leakage, limited burnup	More SF per GWe-year; lower fuel efficiency
2) SF	Standard assemblies, predictable decay heat, mature storage solutions	Smaller non-standard assemblies, higher decay heat density, sealed modules possible	Need for adapted canisters, casks, and repository layouts
3) ILW / LILW	Conventional activated waste, lower specific activity	More activated internals, compact high-activity packages	Higher ILW per unit energy; stricter

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			shielding & conditioning
4) Operational RW	Well-characterized, handled in existing systems	Waste with higher activity, non-standard forms	New certification regimes; repository acceptance revisions
5) Decommissioning RW	Larger volume, but proportionally less activated	Smaller volume overall, but highly activated sealed units	Fewer packages, but much "hotter"; more demanding dismantling
6) Infrastructure Fit	Optimized for LWR fuel (e.g., canisters, CSFSF, DGR tunnels)	Not directly compatible with new geometries & heat output	Upgrades to storage, transport, repository needed
7) Regulation	Established LWR-oriented standards	Rules not fully covering sealed modules, long cycles	Updates required in classification, licensing & criteria
8) Economics	Economies of scale, proven backend logistics	Higher cost per MWe; backend uncertainty adds risk	Need fleet standardization, international cooperation

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11. Conclusions

The deployment of LW SMRs represents a significant step forward in nuclear energy, with the potential to decentralize electricity generation and contribute to energy grid stability and decarbonization goals, particularly in remote or industrial areas.

However, these benefits must be weighed alongside the challenges associated with RW and SF, which must comprehensively manage the different characteristics of SF and RW, such as higher specific activity of waste and new fuel geometries.

This report has assessed the compatibility of existing RW systems with the LW SMRs, drawing on national case studies, technical comparisons, and existing infrastructure evaluations within selected EU countries.

One of the key findings is that while the fundamental processes of RWM — including storage, transport, processing, and disposal — are technically transferable from large LWs to SMRs, adaptations will be needed in areas such as cask design, acceptance criteria, and decay heat management. Furthermore, given the design diversity among SMRs, including differences in core configuration and material selection, future disposal strategies must account for waste variability. This includes ensuring that geological repositories and surface facilities can accept a broader range of waste forms, potentially requiring more flexible packaging and shielding standards. These adjustments stem from the distinct operational and design characteristics of LW SMRs. For example, LW SMRs typically will have smaller core volumes and lower fuel burnups, leading to higher neutron leakage and, in many cases higher volume of SF generated per GWe-year of energy produced (especially for advanced technology) than conventional LW NPPs.

These fuel-specific attributes, such as shorter fuel assemblies and different enrichment or burnup profiles, may necessitate changes in fuel handling systems, canister designs, and disposal facility layout — particularly in DGRs. Nonetheless, the overall characteristics of SMR fuel, especially when using standard UO_2 pellets, remain compatible with existing encapsulation and long-term disposal concepts, especially those already under development in countries like Finland and Sweden.

In terms of LILW, SMRs are expected to produce waste streams similar in composition to those from current large-scale reactors, though potentially at a higher volume per unit of energy due to greater neutron activation in integrated or compact designs. This is especially true for decommissioning waste, where smaller reactor modules may generate proportionally more activated materials.

Despite these challenges, the report finds that current waste processing technologies as well as classification and regulatory frameworks, are generally adequate for LW SMR deployment. However, attention must be paid to whether waste acceptance criteria at existing or planned repositories will accommodate the specific characteristics of SMR-derived waste, especially in terms of geometry, activity concentration, and long-term radiotoxicity. Successful fulfilment of these requirements calls for early dialogue between SMR vendors and repository operators so that criteria can be aligned before deployment.

Results of the study highlight the importance of considering centralized, decentralized, or hybrid waste management approaches depending on the scale and distribution of LW SMRs deployment. Other factors, such as distance from central facilities, transport constrains, or the regional infrastructure capacity, also have a very important impact on this decision-making process. Centralized approaches may be more efficient for national-level infrastructure, while decentralized or on-site solutions could be attractive for remote SMR applications. In the case of SMR decommissioning, the study points to two approaches: centralized decommissioning, where entire SMR modules are dismantled in specialized facilities, and a hybrid decommissioning model, which enables flexible decision-making based on local context and could offer cost and safety benefits.

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In conclusion, while there is no immediate technical barrier to incorporating LW SMRs into national RWM systems, essential and timely adaptation is required. This includes updating waste acceptance criteria, scaling waste processing and storage capacities, and ensuring that SMR-specific waste forms are considered in repository design. The lack of detailed operational data on many SMR designs currently under development underscores the need for continued international collaboration, demonstration projects, and anticipatory regulatory planning. As the deployment of SMRs becomes increasingly likely in Europe and globally, a harmonized and forward-looking approach to waste management will be key to ensuring their safe, sustainable, and publicly accepted integration into the energy landscape. Only through coordinated planning, shared innovation, and transparent engagement can SMRs fulfil their promises.

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