European Partnership on Radioactive Waste Management

Deliverable 4.2: Guidance on SMR implementation and deployment needs from the back end of the fuel cycle perspective; an overall vision from the 3 colleges

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Authors	**David García (Amphos 21), Irene Canals (Amphos 21), Andrea Perri (Amphos 21), Paula Keto (VTT), Sami Naumer (VTT), Timothy Schatz (VTT), Virginie Wasselin (Andra), Robert Mandoki (Andra), Bérengère Cordier (Andra), Gabriele Magugliani (POLIMI), Fabio Fattori (POLIMI), Eros Mossini (POLIMI), Anne Saturnin (CEA), Magaly Tribet (CEA), Kateryna Fuzik (SSTC NRS), Oleksandr Soloviov (SSTC NRS), Olesia Drozd (SSTC NRS), Nadja Zeleznik (EIMV), Barbara Horvat (EIMV), Alan Tkaczyk (UTARTU)**

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Executive Summary

The Green Paper (Deliverable 4.2), developed within the EURAD-2 FORSAFF work package, provides a comprehensive early-stage analysis of radioactive waste management challenges associated with Small Modular Reactors (SMRs). This analysis comes from the vision of several entities (Waste Management Organizations, Technical Support Organizations, Research Entities) ensuring an overall perspective of the topic and representing the three different colleges involved in the EURAD-2 partnership.

As global interest in SMRs grows due to their potential benefits in terms of safety, flexibility, and low-carbon energy generation, it is critical to examine the back-end implications of their deployment. This paper addresses key technical, regulatory, and stakeholder-related dimensions of waste management for SMRs, focusing on four primary technologies: Light Water Reactors (LWRs), Molten Salt Reactors (MSRs), Liquid Metal Fast Reactors (LMFRs), and High Temperature Gas-cooled Reactors (HTGRs).

Each SMR type exhibits unique characteristics that influence the volume, composition, and treatment needs of radioactive waste. LWRs, which are conceptually closest to most existing nuclear reactors, are expected to produce waste streams similar to conventional systems, though their compact design may lead to higher material activation. HTGRs generate significant quantities of irradiated graphite and use TRISO fuel which, while resistant to degradation, poses challenges for both reprocessing and disposal due to its embedded structure. LMFRs rely on sodium or lead coolants and can operate within closed fuel cycles, but their use of chemically reactive materials and fast neutron spectra complicates waste management. MSRs are associated with the most non-standard waste streams, including highly reactive molten salts and volatile fission products, and often involve online reprocessing that introduces complex radiological and chemical considerations.

The back-end of the fuel cycle further complicates the picture, especially for non-LW SMRs. While LWRs might continue using established disposal or reprocessing pathways, HTGRs, LMFRs, and MSRs demand new strategies. TRISO fuel, though durable, presents volumetric and conditioning challenges. LMFRs, depending on fuel type and reactor operation, can act as net waste reducers but require advanced reprocessing capabilities. MSRs introduce reprocessing and disposal difficulties tied to the chemical reactivity of their fuel salts. A general lack of operational experience, prototype data, and material behaviour under irradiation adds uncertainty to waste characterization efforts.

SMRs also raise questions about applicable strategies for interim storage, treatment, conditioning, transport, and final disposal of waste. Key decisions must be made regarding direct disposal versus reprocessing, particularly in light of each reactor's operational goals (whether for electricity, heat, co-generation, or fuel cycle closure). SMRs will challenge existing infrastructure, potentially requiring new treatment technologies, storage protocols, and geological disposal design considerations. Regulatory frameworks, currently designed around conventional nuclear technologies, may need to evolve, especially for GENeration (GEN) IV SMRs. Their novel materials, designs, and mobile or decentralized nature may require revised licensing, oversight, and safety procedures.

Stakeholder engagement is an important factor. Public perception of SMRs remains cautious, shaped by past nuclear incidents, concerns over waste transport, and doubts about transparency and accountability. Engaging stakeholders early and transparently, with robust access to information and inclusive dialogue, is essential to building trust. International cooperation also plays a vital role in aligning waste management practices, fostering shared learning, and ensuring coherence in policy and regulation across borders. The FORSAFF WP seeks to support these goals and inform sustainable deployment strategies for SMRs.

Keywords SMR, Characterization, Waste Management, Pre-Disposal, Disposal, Safety, Regulatory framework, Stakeholder

Table of contents

Executive Summary 4

Keywords SMR, Characterization, Waste Management, Pre-Disposal, Disposal, Safety, Regulatory framework, Stakeholder 4

Table of contents 5

List of Acronyms 6

1. Introduction 8
2. Overview of SMR technologies and their relevance to future nuclear energy 9
3. Waste Generation from SMRs 10
4. SMR Waste Management 12
5. Regulatory and Policy Considerations 14
6. Stakeholder Engagement 16
7. International Actions 17
8. Recommendations and Conclusion 19
9. References 21

List of Acronyms

BWR – Boiling Water Reactor

DGR – Deep Geological Repository

EASI-SMR – Ensuring Assessment of Safety Innovations for SMR

EIA – Environmental Impact Assessments

EU – European Union

EURAD – European Joint Programme on Radioactive Waste Management

FP – Fission Products

FORSAFF – is a strategic study of the Work Package (WP) of EURAD about "Waste Management for SMRs and Future Fuels"

HALEU – High-Assay Low-Enriched Uranium

HLW – High-Level Waste

HTGR – High Temperature Gas-Cooled Reactor

IAEA – International Atomic Energy Agency

ILW – Intermediate Level Waste

LLW – Low-Level Waste

LMFR – Liquid Metal Fast Reactor

LWR – Light Water Reactor

MOx – Mixed Oxide

MSR – Molten Salt Fast Reactor

NEST – Nuclear Education, Skills and Technology

NEA – Nuclear Energy Agency

NHSI – Nuclear Harmonization and Standardization Initiative

NPP – Nuclear Power Plant

OECD – Organisation for Economic Co-operation and Development

PWR – Pressurized Water Reactor

R&D – Research and Development

RWM – Radioactive Waste Management

SEA – Strategic Environmental Assessments

SMR – Small Modular Reactor

SNF – Spent Nuclear Fuel

TRISO – Tri-Structural Isotropic particle fuel

UC – Uranium Carbide

UOx – Uranium Oxide

WAC – Waste Acceptance Criteria

WENRA – Western European Nuclear Regulators' Association

EURAD-2 Deliverable 4.2 – Guidance on SMR implementation and deployment needs from the back end of the fuel cycle perspective; an overall vision from the 3 colleges

WM – Waste Management

WP – Work Package

1. Introduction

There is growing enthusiasm worldwide for the deployment of Small Modular Reactors (SMRs)[1]. Much of this enthusiasm stems from the potential ability of small modular reactors and their associated fuel cycles, as claimed by designers and developers, to provide a number of advantages, such as improvements in economic competitiveness, reductions in environmental impact and enhancements in nuclear safety and proliferation resistance.

One broad issue related to SMR that generally receives little to no attention is that of radioactive waste management (RWM). The management of waste streams from these new reactors, including those from front-end processes, reactor operations, spent fuel and high-level waste, any processing and/or reprocessing, and decommissioning, should be taken into account when selecting technologies for deployment.

Most of the emerging reactor types under development (IAEA, 2024a; NEA, 2024) would generate waste streams for which there is little experience or mature technical ability to handle. The management and disposal of unique waste streams from these reactors may in fact pose a challenge for disposal, from technical, regulatory, social, ethical, and economic perspectives. Gaining a clear understanding of the challenges and opportunities associated with SMR deployment can help policymakers and stakeholders make informed decisions.

This Green Paper (D4.2) is a product of Work Package 4 (WP4) "Waste Management for SMRs and Future Fuels" (FORSAFF) of the EURAD-2 project and builds upon findings from complementary activities across Tasks 3–6. It draws on a systematic assessment of waste generation (Task 3), including the development of a common methodology for waste stream identification, inventory profiling, and characterization of both operational and spent fuel waste. This information is gathered from literature, SMR vendors, end-user groups, and expert consultations.

The document also reflects current insights into waste predisposal and reprocessing options (Task 4) and is informed by preliminary policy and regulatory mapping (Task 5), as well as stakeholder perspectives gathered through dialogue processes (Task 6). As such, this Green Paper integrates early technical, scientific, and managerial knowledge to outline implementation and deployment needs for SMRs from a back end of the fuel cycle perspective.

The Green Paper also draws on the EURAD Roadmap (Beattie et al. 2021), which provides a structured view of programme goals and capability needs across the phases of radioactive waste management, offering a useful context for examining SMR-specific challenges.

[1] *SMR definitions*
The IAEA Platform on Small Modular Reactors and their Applications defines: SMRs are advanced nuclear reactors with a power capacity of up to 300 MW(e), and whose components and systems can be factory built and then transported as modules to sites for installation as demand arises. SMRs are under development for all types of reactor technologies (e.g. water cooled reactors, high temperature gas cooled reactors, liquid metal cooled and gas cooled reactors with fast neutron spectrum and molten salt reactors (MSRs)).
The NEA Small Modular Reactor Dashboard: Second Edition. OECD 2024, NEA No. 7671: SMR are smaller, both in terms of power output and physical size, than conventional gigawatt-scale nuclear reactors. SMRs are nuclear reactors with power output less than 300 megawatts electric (MWe), with some as small as 1-10 Mwe. SMRs are designed for modular manufacturing, factory production, portability, and scalable deployment. SMRs use nuclear fission reactions to create heat that can be used directly or to generate electricity

2. Overview of SMR technologies and their relevance to future nuclear energy

SMRs are advanced nuclear reactors (IAEA, 2022) designed to be smaller in size and electrical/thermal output than conventional nuclear power plants. Their modular nature proposes to allow for factory fabrication and potentially faster, more cost-effective deployment. SMRs are typically defined as having electrical outputs below 300 MWe per unit, and they may be deployed individually or in arrays depending on energy needs.

The diversity of SMR designs currently under development reflects different priorities in energy policy, safety, economics, sustainability and innovation (IAEA. 2021, 2024a; NEA, 2024). They vary in neutron spectrum (thermal vs fast), coolant and fuel types, and operating temperatures and power. This technological diversity has direct implications on the type, volume, and management of radioactive waste generated during their life cycle.

Unlike traditional large-scale nuclear reactors, SMRs can be deployed incrementally to match demand growth and are often designed with passive safety systems that should enhance resilience and reduce the risk of severe accidents (IAEA, 2023a). Their smaller footprint also opens up new siting options, including repurposing of existing coal or gas infrastructure.

WP FORSAFF within EURAD-2 project focuses its analysis on four major SMR technology groups, which are considered the most relevant in terms of their development status, deployment potential, and their distinct implications for waste management:

- Light Water Reactors (LWRs) use water as both coolant and moderator and typically rely on low-enriched or high-enriched (HALEU) uranium oxide fuels. While conceptually similar to existing pressurized or boiling water reactors, small modular-LWRs feature innovations in size, passive safety, and system integration. Their waste streams are relatively well understood, and differences might be expected mainly as a consequence of smaller fuel rods (i.e., burnup degree, decay heat-cooling time) and reactor cores.
- High Temperature Gas-cooled Reactors (HTGRs) use helium as a coolant and TRISO[2] fuel particles embedded in graphite pebbles or blocks. The robust nature of TRISO fuel offers, in principle, high safety margins but may create complex waste forms requiring adapted approaches for conditioning and disposal.
- Liquid Metal Fast Reactors (LMFRs) operate in the fast neutron spectrum and use coolants such as lead, lead-bismuth, or sodium. They are typically envisioned for plutonium or minor actinide management and support closed fuel cycles.
- Molten Salt Reactors (MSRs) use molten salts as both fuel carrier and coolant, often operating at high temperatures and low pressures. They offer design flexibility and inherent safety features but generate non-standard waste streams such as salt-based residues and volatile fission products. Their fuel cycles may operate in continuous reprocessing modes, complicating radiological inventory tracking and conditioning strategies.

SMRs are increasingly seen as a flexible tool to meet Europe's decarbonization targets, especially in scenarios involving integration with variable renewables to ensure grid stability,

[2] TRISO stands for TRi-structural ISOtropic particle fuel. TRISO was invented in the United Kingdom as part of the Dragon reactor project and has been used in many different reactors since. The TRISO-coated particle is a spherical, layered composite. The layers that comprise a TRISO particle are the kernel, buffer, inner pyrolytic carbon, SiC, and outer pyrolytic carbon (Wells et al., 2021).

deployment in remote locations or smaller-scales and reliable energy sources for industrial applications.

The wide design diversity makes SMRs both an opportunity and a challenge from a waste management perspective. Proactive planning, informed by current R&D and strategic studies, like FORSAFF, is thus critical.

Each SMR technology brings unique characteristics influencing waste stream composition, decay heat profiles and chemical stability among others. These factors impact predisposal operations, reprocessing feasibility and design of associated facilities, disposal pathway suitability, including compatibility with current disposal concepts and waste characterization methods. Understanding these implications early in the technology development process enables better alignment of reactor designs with waste management infrastructure and knowledge gaps identification. FORSAFF's targeted analysis across the four SMR technologies aims to provide foundational insights to support this goal and information completion needs.

3. Waste Generation from SMRs

The identification of waste generation pathways and resulting waste streams is one of the key steps necessary to plan for a safe and effective WM strategy. Among the intricate chain of activities, the act of waste generation can be considered as the source term, to which the subsequent technical actions, i.e., (pre-)treatment, conditioning and disposal, should conform. A thorough waste generation assessment is therefore also useful in highlighting possible challenging waste for which no management options are presently available, hence suggesting future R&D needs. In addition to the planning of technical activities, knowledge of expected waste streams can also aid in drafting or adapting regulatory policies and can serve as a tool to implement the general principles of waste prevention and minimization (IAEA, 2016; 2019, Kim et al., 2022).

Accurate and comprehensive waste stream identification is especially relevant in the case of new reactor designs, such is the case of SMRs, which may result in uncommon waste types endowed with challenging radiological and non-radiological aspects. From a technical point of view, the properties of generated waste are directly linked to the decisions of the waste producer, among which the type of fuel, moderator and coolant play a significant role. However, design-specific waste generation pathways are not easily quantifiable *a priori*, and actual waste stream characteristics will be partly dictated by individual design and operational choices. Since most SMRs designs are still in the early development stages, and hence very limited direct knowledge on their associated waste streams is available, a comprehensive assessment of waste generation is presently challenging.

Nevertheless, some general considerations can be drafted for each of the four identified technologies:

- For LWRs the general type, nature and composition of waste streams can be expected to be somewhat similar to those associated with larger size PWRs/BWRs, for which extensive operational experience and a consolidated knowledge on fuel cycle operations are available (in 2025, 350 LWRs are in operation with 124 permanently shutdown, IAEA, 2024b). In principle, a smaller core size may result in a relatively higher activation of materials due to increased neutron leakage from a less favourable neutron economy and higher core surface-to-volume ratio. Generalizations are however still difficult to draft, and quantitative waste generation assessments should be performed on a case-by-case basis.

- For HTGRs, large inventories of irradiated graphite (used as both moderator and reflector) will be produced at the decommissioning stage. The high operational temperature should prevent the buildup of Wigner energy in the graphite. The actual activity concentration, the significant C-14 inventory, and the presence of long-lived radionuclides will likely represent the key factor in defining the associated WM policy to be adopted for these waste streams.
- LMFR technology has been studied and developed in a few countries but to a lesser extent than LWR (in 2025 2 LMFRs are in operation, in Russia, with 8 permanently shutdown within Europe, IAEA, 2024b). The fast neutron spectrum adopted by LMFRs, coupled with the use of such non-standard materials, can also result in (long-lived) activation products which are less commonly encountered in thermal reactors, thus generating potential new waste streams.
- MSRs will arguably be associated with some of the most challenging waste streams, encompassing both molten salt coolants and graphite moderators. The former will present unique management challenges, deriving mostly from high chemical reactivity. The online removal of FP from the liquid fuel will also result in high activity waste streams requiring dedicated, and often on-site, management.

Back-end of the fuel cycle

Waste stream assessments related to the SMR fuel cycle back-end are worthy of dedicated considerations (IAEA, 2023b). For most light-water SMRs spent fuel characteristics will likely be qualitatively similar to those of their larger size counterparts employing oxide-based fuel (UOx or MOx); although in some cases higher enrichment levels are foreseen (i.e. HALEU). In the context of LWR, fuels containing Thorium (Th) should be also accounted for as some reactor designs consider the use of mixed Th-U fuels. These types of fuels can optimize fuel burnup but may introduce additional challenges for spent fuel management compared to the standard ones. Significant differences in physico-chemical and radiological properties may arise in case of long refuelling cycles and high-burnup fuels.

However, for the other three SMR technologies (i.e., HTGR, LMFR and MSR) fuel design choices, including the potential use of Th-U mixtures, present marked differences with respect to those of LWRs. These differences have a significant impact on the characteristics and management of the associated waste streams (IAEA, 2024b):

- HTGRs typically employ TRISO or UC fuel. These fuel types are characterized by very high physical durability and radiation stability. Such aspects, which might be favourable in the case of direct disposal, should however be carefully considered with respect to the recovery of nuclear materials through reprocessing. Spent TRISO fuel is also expected to have lower specific activity and lower specific heat generation with respect to spent LWR fuel assemblies, but this comes at the cost of a larger volume.
- LMFR designs encompass a wide variety of fuel types. In general, they are characterized by a long fuel cycle. By allowing the burning of Pu and minor actinides, this reactor type can decrease the thermal power of vitrified waste and, by extension, the DGR footprint. Depending on how the reactor is operated (breeding/burning), the

relative content of new nuclear materials and of fission products can be expected to vary significantly in irradiated fuel elements.

- MSRs offer the possibility of online fuel reprocessing and minor actinide burning, with potentially very long fuel cycles. The disposal of spent fuel salts, and their potential reprocessing, will need to take into account the unique chemical characteristics of the salt-based fuel (i.e., in particular fluoride salts), mainly its incompatibility with water and hydrometallurgical processes. MSRs offer the possibility of breeding, so the presence of nuclear materials, fission and activation products will need to be taken into account during the management of blanket materials.

In addition to the specific considerations just mentioned, other general aspects influencing the overall uncertainty in waste generation assessments can also be highlighted:

- In all cases where innovative spent fuel reprocessing methods are considered, streams of recovered nuclear materials, fission products and minor actinides will be expected. Since these processes have not yet reached sufficient maturity, large uncertainties still exist on the properties (radiological and non-radiological) of the waste that will be produced as well as on the final waste forms (conditioning matrix).
- Since for some SMRs designs component re-use is foreseen (modularity and modularisation concepts), depending on actual regulatory policies these materials might not be considered as actual waste, and could potentially be excluded by the overall assessment.
- Due to lack of working prototypes or first-of-a-kind reactors for SMR designs in the early development stages, scientific literature might represent the only source of waste stream data. In these cases, scale effects and the actual representativeness of investigated conditions should be verified before extrapolating laboratory-scale data to the industrial scale.
- Large uncertainties still exist about the actual composition and impurity content of materials that will be employed for SMR construction, resulting in a proportional uncertainty in activation estimates through simulation.

4. SMR Waste Management

The waste management of SMRs must be approached with flexibility and foresight. These technologies, while diverse in design, will ultimately require infrastructure and strategies that guarantee safety, public acceptance, and regulatory compliance across all WM stages: pretreatment, storage, conditioning, transport, and disposal. The suitability of any given management solution depends heavily on the reactor type, its specific fuel and coolant system, and the broader national policy on spent fuel treatment and disposal (Tromans et al., 2024).

Depending on the SMR concept, either direct disposal or reprocessing may be considered for future spent fuel management. The suitability of each option should be assessed in light of the intended role of the four SMR technology families. While some technologies are at more advanced or mature stages of R&D, others remain conceptually distant from enabling spent fuel reprocessing. The identification of data gaps necessary to assess the readiness of each approach will be investigated within the FORSAFF project.

LW-type SMRs can build on the well-established waste management practices developed for larger PWRs and BWRs. Spent fuel is typically cooled in pools for several years to reduce decay heat before being transferred to dry storage systems, sent for reprocessing, or encapsulated for disposal, depending on national policy. Direct disposal of spent fuel remains a valid option, with repository design considerations depending on the heat output and radionuclide inventory of the fuel. Operational waste streams, such as spent resins and filters, are treated and packaged using standard techniques, typically destined for near-surface disposal.

For HTGRs, the waste management strategy must take into account the particularities introduced by both the use of TRISO fuel and graphite as structural and moderating material. While the TRISO fuel design provides enhanced containment of fission products due to its multi-layered ceramic structure, it also presents considerable complexity in terms of reprocessing. The high chemo-mechanical resistance of these fuel particles may be favourable for direct disposal, but their volumetric footprint and chemical inertness pose challenges for conditioning and repository integration.

From an operational perspective, the helium coolant is not expected to be a significant source of waste. However, trace amounts of activation products or contaminants may accumulate in filters and purification systems, which will require appropriate treatment and classification as low-level waste.

Large volumes of irradiated graphite will be produced from the core moderator and reflector components. Its radiological profile, particularly the presence of long-lived, mobile radionuclides such as C-14 and Cl-36 (Li et al., 2017), raises concerns for long-term safety. These isotopes are known for their mobility and environmental persistence, and their presence in porous or fragmented graphite structures may exacerbate the associated risks. Historical experience with similar graphite-bearing systems has demonstrated that graphite degradation, expansion, and fracturing can further complicate handling, decontamination, and packaging.

The long-term performance of TRISO particles in geological disposal conditions also remains largely untested, particularly with regard to the neutronic and chemical behaviour of spent fuel in repository-relevant environments.

Fast neutron spectrum reactors, such as LMFRs employing MOX fuel and cooled by liquid metals like sodium or lead, are typically designed with the objective of enabling fuel cycle closure. Waste management for LMFRs centres around complexities associated with the activation, toxicity and poor chemical stability of the coolant. Depending on the metal chosen as coolant, different levels of considerations need to be made regarding conditioning for disposal or reprocessing. Activated sodium requires chemical conversion to a more stable form such as sodium carbonate which could be presumably treated as LLW and/or ILW. The disposal of lead waste involves issues relating to its toxicity.

MSRs employ liquid fluoride or chloride salts as both fuel carrier and primary coolant, resulting in highly non-standard waste streams that require specific and dedicated management approaches. The chemical nature of these salts, often reactive and corrosive, poses challenges for long-term containment, particularly if their stability under repository conditions cannot be guaranteed over extended timescales or the generation of volatile radioactive/toxic gases during management is uncertain.

In addition to the chemical waste, MSRs are expected to generate structural waste: particularly irradiated graphite used as moderator. This material will contribute significantly to low- and intermediate-level waste inventories. Although several treatment methods are under investigation, including thermal reduction techniques aimed at minimizing waste volumes, the safe disposal of irradiated graphite remains an unresolved issue. As in the case of HTGRs, the presence of long-lived and mobile radionuclides within the graphite matrix complicates repository integration and long-term safety assessments.

Effective waste management for MSRs, as with all SMRs, must begin with robust waste classification. According to IAEA guidelines (IAEA, 2009), radioactive waste is categorized into six classes, based on radiological hazard and required containment measures. In addition to radiological parameters, waste forms must also be evaluated for chemical toxicity, leaching resistance, and reactivity. Conditioning and packaging solutions must be tailored accordingly to ensure compatibility with selected disposal pathways and to meet long-term safety and environmental protection goals.

Waste reprocessing

Reprocessing of LWR spent fuel is practiced in several countries and results in the production of high-level vitrified waste and intermediate-level process waste.

In the case of LMFR, reprocessing is generally considered the preferred strategy for managing spent fuel in these systems although its feasibility still needs to be investigated and demonstrated. LMFR spent fuel can potentially be recycled through hydro- or pyrometallurgical processes. However, these technologies remain at a low maturity level, and industrial-scale application is not yet feasible. Conditioning and disposal of the resulting waste streams, including process residues and structural materials, requires further development.

Regarding a closed fuel cycle to recover actinides and minimize high level waste volumes hydro- or pyroprocessing can be considered. The elevated fissile isotope concentrations in the spent fuel additionally raise criticality concerns during storage and disposal. Thus, even if the feasibility of reprocessing MOx fuel assemblies from a French fast Na-cooled reactor in La Hague facilities has been studied and tested, the reprocessing technology has not yet been deployed on an industrial scale. Therefore, this technology should rely on a strong R&D strategy to address both radiochemical and physical challenges.

For MSR, where long-term chemical stability is not ensured, current waste conditioning strategies typically involve the conversion of fluoride or chloride salts into more stable forms. These processes, however, remain under development and have not yet been validated for full-scale application. The integrated nature of fuel and coolant in MSRs further complicates waste handling, as online reprocessing schemes are often envisioned. While such configurations may offer operational advantages, they introduce new radiological and logistical challenges for real-time waste separation and treatment. At present, the reprocessing of spent fuel salts remains a major technical hurdle, and no industrially mature process is currently available.

5. Regulatory and Policy Considerations

The analysis of selected documents published by international organizations (i.e., IAEA, WENRA, NEA), binding documents of international law and relevant scientific publications showed that SMRs, due to their compact design, mobility and modularity, can provide decentralized energy sources for a wide geographical and geopolitical range of deployment. These new characteristics of modular nuclear power facilities, especially with the proposed new nuclear reactor design specifications and fuel types, may generate new regulatory requirements and result in changes to current RWM policy and regulatory frameworks for SMRs and their waste management.

The long-term and broad experiences with the operation of predominantly light water nuclear reactors suggest a deployment of SMRs using LWR technology in the forthcoming decade. In the context of RWM for this type of SMRs, technological transferability from existing NPPs to SMRs can be assumed and the current legislation, regulatory framework and several technological instructions can be applied with minor modifications.

The situation is different for SMRs which are expected to use new cooling technologies, new reactor materials and new fuel types. These new processes and technologies will result in new types of radioactive waste and the need for new fuel reprocessing processes, for which current legislation, regulatory frameworks or technical guidelines may not be directly applicable. Since the technical development of these SMRs is currently at an early stage, it is therefore necessary to have more detailed technical information and characterisation of the waste streams, on the basis of which appropriate, safe and economically reasonable waste management systems can be designed. RWM policy and regulatory frameworks as they are currently used in different national context might be challenged and would need to be reassessed.

Given that SMRs may be geographically widely distributed, including siting close to municipal areas and industrial applications, there is a new need for updated requirements for the safe handling, storage, transport and disposal in a centralised, decentralised or in hybrid manner. Considering disposal of new type of RW an updated WAC system for existing and new repositories may be needed.

New procedures for decommissioning nuclear installations, e.g., microreactors that would be decommissioned in a factory, will also be a challenge for the update of the regulatory framework.

SMR deployment may also result in the entry of new and international/non-state actors including new licence-holders (the party producing the RW), owners, operators or actors in the field of backend services (for example re-processing and even final disposal). These new changes need to be taken into account in reviewing the policy and regulatory framework related to licencing of SMRs and, SMR waste management and disposal facilities.

International nuclear organizations such as IAEA, NEA, WENRA play a crucial role in the development of regulatory guidelines for SMR RWM. International initiatives such as IAEA's SMR Regulators' Forum or NHSI, pose future regulatory changes in line with evolving global practice.

A brief description of the current situation in the development of SMRs in Belgium, Bulgaria, the Czech Republic, Finland, Slovenia and Ukraine highlights the following:

- Plans for the deployment of SMRs are in the process of preparation or of being adopted in national strategic policies for the use of nuclear energy.
- SMR technology and its potential applications, including the four reactor family types discussed in FORSAFF have been considered in many countries. However, many of these reactors are still under development, with significant technical, financial and licensing challenges.
- Current licensing, oversight, and waste management procedures can be applied with certain adjustments for RWM of LWR-SMRs. However, other SMR technologies could introduce advanced cooling methods, alternative fuel cycles, and distinct waste profiles that exceed the scope of existing regulations or technical guidelines.

6. Stakeholder Engagement

Stakeholder and public engagement, including interaction with Civil Society, aims at encompassing all aspects of the nuclear fuel cycle related to RW from SMRs, whether it be generation or management of the RW, or the policy and regulatory framework. Not all aspects will be equally relevant at the same time, but in order to provide and maintain an overall stakeholder perspective, no part is excepted.

The legal framework for stakeholder engagement in the EU is based on requirements from the Aarhus convention (UNECE, 1998) which provides the main pillars of environmental democracy also in the nuclear field. These pillars, in particular access to information and public participation in decision making, are implemented in different ways, respecting national, contextual and cultural situations, and should be developed before the actual start of the SMR project. There is experience from recent similar projects, like repository or NPP sitings, on how to ensure transparency, tailor stakeholder engagement and build trust for implementation.

An analysis of a recent study (Durdovic et al., 2025) and exchanges with stakeholders, highlights some perceptions and concerns people have regarding SMRs. One issue is the potential establishment of a specific legal definition and framework for SMRs within the European context. Such a framework could have significant implications for stakeholder rights and participation, as legal classifications often determine the scope of public involvement in decision-making processes.

Safety remains a dominant issue, with many people expressing fears rooted in historical nuclear disasters such as Chernobyl and Fukushima. There is widespread concern about radiation risks, potential accidents, and whether cost-cutting and simplified designs compromise the safety of SMRs compared to traditional reactors. Similarly, the environmental impact of SMRs is questioned. Although they are marketed as low-carbon, doubts persist about their land and water use, thermal pollution, emissions linked to construction and fuel logistics, and whether they truly align with sustainable energy goals. Some argue that resources would be better allocated to advancing renewable energy technologies.

Economic viability is another contested point. The public questions whether SMRs can compete with increasingly affordable renewables like wind and solar, particularly when storage or disposal is factored in. There are fears that high upfront costs, unforeseen expenses, and possible subsidies could burden taxpayers and drive-up electricity prices.

Regulatory and policy issues also provoke significant scepticism. There is uncertainty about whether current nuclear regulations are adequate for SMRs, and concern that relaxed rules could undermine safety. Questions also remain around long-term accountability, waste management, and whether developers will be responsible for decommissioning. Additionally, the applicability and effectiveness of existing public engagement mechanisms, such as Environmental Impact Assessments (EIA) and Strategic Environmental Assessments (SEA), in the context of SMRs is still unclear.

Radioactive Waste Management (RWM) remains a major concern surrounding the deployment of Small Modular Reactors (SMRs). Despite design innovations, questions persist about how radioactive waste will be handled over the long term:

- **Public Concerns Over Waste Management and Transparency**: Citizens are concerned about where radioactive waste from SMRs will be stored and disposed of, how it will be managed, and in what quantities. There is a demand for transparent, accessible information on the full lifecycle of nuclear materials, from generation to final disposal.

- **Multiplication of Waste Sites and Transport Risks**: Unlike large-scale nuclear power plants that centralize waste in fewer locations, SMRs if deployed widely could result in geographically dispersed locations. This would increase the need for waste transportation across regions or countries, raising concerns over accidents, potential for leaks, and security risks during transit. It also complicates regulatory oversight and emergency response planning.
- **Comparability with Existing Radioactive Waste Management (RWM) Strategies**: There is uncertainty about whether SMR waste will follow current RWM strategies or require new approaches. If the latter, the public wants clarity on what these changes entail, including their technical, regulatory, and financial implications as well as the degree of their impact on the environment and safety. For example, some SMR designs may produce more chemically complex or highly radioactive waste per unit of energy due to higher burn-up fuels or novel coolant systems (e.g., liquid metal or molten salt). This divergence may challenge existing RWM infrastructures, potentially requiring new containers, new storage protocols, and adapted geological disposal criteria.

A long-standing source of unease is the absence of a universally accepted, long-term solution for HLW including spent fuel. Many worry about potential leaks or contamination from interim storage or disposal facilities, especially if oversight is perceived as inadequate. These concerns are intensified by the relatively unproven track record of many SMR designs and the possibility that a fragmented deployment of reactors could result in decentralized, harder-to-monitor waste sites.

Public engagement and transparency are central to addressing these concerns but are currently seen as lacking. Communities often report limited access to clear, unbiased information about SMR technologies, partly due to industrial confidentiality and commercial secrecy. This perceived complexity fosters suspicion that decisions are being made behind closed doors, without adequate public consultation or consent. The issue of trust is deeply connected with the history of nuclear energy. Past accidents, controversial decisions, and insufficient transparency have left many sceptical of both governments and industry actors. The growing number of SMR vendors, many of them start-ups with limited track records, and the increasing frequency of cancelled or stalled projects further erode public confidence. In some regions, SMRs are viewed not as an opportunity, but as a top-down imposition that communities are expected to accept without meaningful dialogue or influence.

To gain public support, it is crucial that SMR development includes robust, inclusive, and transparent engagement processes, with clear accountability on long-term waste management. Without this, trust in both the technology and its promoters is unlikely to improve.

7. International Actions

Deployment of SMRs in Europe will benefit from international cooperation in various areas including research, regulatory framework, waste management policies and practices, and stakeholder involvement. Cooperation between authorities and agreements between the different parties and even countries may be needed to ensure that the roles and responsibilities are clear already in the planning stage of SMRs plants.

While FORSAFF focuses on the SMR back-end, information exchange and in some cases official collaboration with international programmes on small modular reactors is seen as beneficial. Such programmes can produce inputs needed for back-end considerations and potentially identify larger issues that consider both the SMR front- and backend. As an example, FORSAFF is looking into ways to foster collaborations with the EU-project EASI-SMR (i.e., potential organization of joint workshops, presentation of main project drivers at internal meetings). While EASI-SMR mainly focuses on light water reactors and their passive safety systems, it also addresses regulatory and societal challenges towards SMR deployment. Other programmes or initiatives (i.e., NEA, IAEA) could also offer input considerations for SMR waste management.

The European Commission has set up the European Industrial Alliance on SMRs with the objective to facilitate and accelerate the development, demonstration and deployment of SMRs through a strategic action plan and roadmaps. Corresponding outputs, especially those from the Working Group on Fuel Cycle and Waste Management would be interesting for FORSAFF to understand which actions have been identified.

The IAEA has launched two programmes related to SMRs: the SMR Platform and Nuclear Harmonization and Standardization Initiative and the IAEA Platform on SMRs and their Applications (https://www.iaea.org/services/key-programmes/smr-platforms-nhsi). The former supports SMR development, deployment and oversight. The latter aims to harmonize aspects such as SMR design and regulation. Both programs promote international collaboration amongst their members. IAEA also has a Technical Working Group on Small and Medium Sized of Modular reactor, which provides expert advice and shares information on SMRs. Finally, the IAEA project on Challenges, Gaps and Opportunities for managing SNF from SMRs identifies viable ways to manage SMR SNF and identifies key parameters for designing backend programmes (https://www.iaea.org/projects/crp/t13021).

The OECD Nuclear Energy Agency (OECD-NEA) also has multiple ongoing SMR-related programmes. The Expert Group on Small Modular Reactors aims to identify knowledge gaps and recommendations to address the gaps on the technology readiness level of SMR designs. In addition, the NEST SMRs project aims to integrate existing SMR research projects from individual participating organisations into a broader and more impactful programmes (https://www.oecd-nea.org/jcms/pl_24326/nest-small-modular-reactors-smrs). Finally, the Joint Project on Waste Integration for Small and Advanced Reactor Designs (WISARD) aims to comprehensively investigate SMR fuel characteristics, treatment & recycling, storage, transportation and final disposal topics (https://www.oecd-nea.org/jcms/pl_86832/joint-project-on-waste-integration-for-small-and-advanced-reactor-designs-wisard). The goal is to identify and address possible future issues already during the SMR design phase. Although some of these actions are not publicly open, efforts are being made to foster discussions between the different partners involved in FORSAFF to avoid duplicity and work in a collaborative environment.

8. Recommendations and Conclusion

The deployment of SMRs could offer promising contributions to low-carbon energy systems, particularly through their flexibility, modularity, and safety features. However, their widespread adoption must be matched by robust, adaptive, and forward-looking radioactive waste management strategies. The diversity of SMR technologies introduces new waste challenges that cannot be addressed through legacy solutions alone.

Effective management of these waste streams requires early and sustained attention across the full lifecycle of SMRs (i.e. from design and operation to decommissioning and disposal). Technical innovation, regulatory reform, and stakeholder trust are critical enablers of this process. In particular, the success of SMR deployment in Europe and beyond will depend not only on technological readiness but also on the social and institutional frameworks supporting responsible and transparent waste management.

The FORSAFF WP's preliminary findings contribute essential groundwork for these efforts, highlighting both knowledge gaps and actionable pathways forward. Continued interdisciplinary collaboration, underpinned by strong regulatory guidance and inclusive public dialogue, will be key to ensuring that SMRs fulfil their potential as a sustainable energy solution.

Based on the comprehensive analysis presented in the Green Paper D4.2 on waste management for SMRs, the following recommendations are proposed to guide future actions and policy development in this area:

- **Integrate Waste Management Early in SMR Design and Deployment:** It is essential that waste management considerations are integrated from the earliest stages of SMR development. Designers and developers must collaborate closely with waste management experts to ensure that waste streams, particularly novel or complex ones, are identified, characterized, and addressed through appropriate predisposal and disposal strategies or R&D actions. This proactive approach will minimize technical, regulatory, and financial challenges arising later, as well as relevant environmental and safety requirements.
- **Develop Technology-Specific Waste Characterization Frameworks:** Given the diversity of SMR technologies and their unique waste profiles, generic waste management models are insufficient. Tailored waste stream assessments should be conducted for each SMR type, with a focus on specific fuel cycles, coolant types, activation products (which impact waste categorization), and operational modes. These studies should include experimental data where possible, and simulations should be validated against real-world conditions to reduce uncertainty.
- **Accelerate R&D on Treatment, reprocessing and Disposal of Non-standard Waste:** SMRs, particularly MSRs and LMFRs, introduce waste streams (e.g., molten salts, activated metals, and graphite) that are not fully compatible with existing disposal strategies. Focused R&D should be supported to develop safe, scalable treatment and stabilization techniques for these waste types, including thermal treatment for graphite, chemical conversion for salt residues, and advanced encapsulation for volatile fission products.
- **Update Regulatory and Policy Frameworks to Reflect SMR Specificities**: Regulatory bodies must review existing frameworks / legislation or develop new guidelines to address the distinctive challenges posed by SMRs, particularly Gen IV designs. This includes re-evaluating licensing, transport, storage, and decommissioning procedures, as well as updating WAC to accommodate chemically and radiologically novel waste types. International harmonization of these updates is also important to ensure safety and interoperability.

- **Strengthen Stakeholder Engagement and Transparency Mechanisms:** Public concerns about safety, long-term waste management, environmental impacts and regulatory oversight must be addressed through transparent, accessible, and engagement strategies. Best practices from other nuclear projects should be adapted to the unique context from the outset of SMRs.
- **Foster International Collaboration on SMR Waste Management**: The complexities of SMR waste demand international cooperation to share knowledge, avoid duplication, and build consensus on best practices. Collaboration should be strengthened through existing platforms such as the IAEA, NEA, and European Commission initiatives. Joint R&D programs, harmonized regulatory dialogues, and coordinated stakeholder involvement will support a coherent global approach.

9. References

Beattie, T., Andersson, J., Bruggeman, C., Chapman, N., Grambow, B., Knuuti, T., Theodon, L., & Zuidema, P. (2021). EURAD Roadmap, extended with Competence Matrix. Final version as of 27.09.2021 of Deliverable D1.7 of the HORIZON 2020 project EURAD. EC Grant Agreement No. 847593. Available at: http://www.ejp-eurad.eu/

Durdovic, M., Turcanu, C., Geysmans, R., Meskens, G., Perko, T., Sala Escarrabill, R., Gonçalves Oliveria, L., Zeleznik, N., Kos, D., Horvat, B., Mihok, P., Martell, M., Molyneux-Hodgson, S., Abraham, F., Mays, C., Luypaert, A. and Brabants, W. (2025) Public attitudes towards small modular reactors. An emerging research field and evidence from six countries. ECOSENS Deliverable D 1.1. Grant Agreement No 101060920 https://ecosens-project.eu/

IAEA (International Atomic Energy Agency) (2009) IAEA Safety Standards, General Safety Guide No. GSG-1. Classification of Radioactive Waste. https://www.iaea.org/publications/8154/classification-of-radioactive-waste

IAEA (International Atomic Energy Agency) (2016) Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), IAEA, Vienna

IAEA (International Atomic Energy Agency) (2019) Waste from Innovative Types of Reactors and Fuel Cycles, IAEA Nuclear Energy Series No. NW-T-1.7, IAEA, Vienna. https://www.iaea.org/publications/12226/waste-from-innovative-types-of-reactors-and-fuel-cycles

IAEA (International Atomic Energy Agency) (2021) Technology Roadmap for Small Modular Reactor Deployment, IAEA Nuclear Energy Series No. NR-T-1.18, IAEA, Vienna. https://www.iaea.org/publications/14861/technology-roadmap-for-small-modular-reactor-deployment

IAEA (International Atomic Energy Agency) (2022) Small Modular Reactors: A New Nuclear Energy Paradigm, IAEA, Vienna https://nucleus.iaea.org/sites/smr/SitePages/HomeSmrPlatform.aspx

IAEA (International Atomic Energy Agency) (2023a) Applicability of IAEA Safety Standards to Non-Water Cooled Reactors and Small Modular Reactors, Safety Reports Series No. 123, IAEA, Vienna. https://www.iaea.org/publications/15228/applicability-of-iaea-safety-standards-to-non-water-cooled-reactors-and-small-modular-reactors

IAEA (International Atomic Energy Agency) (2023b) Considerations for the Back End of the Fuel Cycle of Small Modular Reactors, IAEA-TECDOC-2040, IAEA, Vienna. https://www.iaea.org/publications/15519/considerations-for-the-back-end-of-the-fuel-cycle-of-small-modular-reactors

IAEA (International Atomic Energy Agency) (2024a) Small modular reactor technology catalogue, Vienna. https://aris.iaea.org/Publications/SMR_catalogue_2024.pdf

IAEA (International Atomic Energy Agency) (2024b) Nuclear Power Reactors in the World, Reference Data Series No. 2, IAEA, Vienna

Kim, T.K., Boing, L., Halsey, W. & Dixon, B. (2022) Nuclear Waste Attributes of SMRs Scheduled for Near-Term Deployment. Nuclear Fuel Cycle and Supply Chain. Prepared for U.S. Department of Energy Systems Analysis and Integration, ANL/NSE-22/98. https://sai.inl.gov/content/uploads/29/2024/12/smr_waste_attributes_report_final.pdf

Li, J., Dunzik-Gouga, M. L., & Wang, J. (2017). Recent advances in the treatment of irradiated graphite: A review. Annals of Nuclear Energy, 110, 140–147. https://doi.org/10.1016/j.anucene.2017.06.040

NEA (Nuclear Energy Agency) (2024) The NEA Small Modular Reactor Dashboard: Second Edition. OECD 2024, NEA No. 7671

Tromans, S., Corkhill, C. & Joyce, M. (2024) Development of small modular reactors and advanced modular reactors – Implications for the management of higher activity wastes and spent fuel. CoRWM (Committee on Radioactive Waste Management) Position Paper. https://assets.publishing.service.gov.uk/media/65c26c9ca6838e000d49d589/corwm-smr-and-amr-position-paper.pdf

UNECE (1998) Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters was adopted on 25th June 1998. https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-13&chapter=27

Wells, B.E., Phillips, N.R., Geelhood, K.J. (2021) TRISO Fuel: Properties and Failure Modes. Pacific Northwest National Laboratory. PNNL-31427