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on Radioactive Waste Management

Towards Safe and Sustainable Deployment of LW-SMRs and AMRs: Identifying Knowledge Gaps in Waste Management

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Authors	**Anne Saturnin (CEA), Gabriele Magugliani (POLIMI), David Garcia (Amphos 21), Jesus Martinez (Amphos 21), Virginie Wasselin (Andra), Bérengère Cordier (Andra), Robert Mandoki (Andra), Magaly Tribet (CEA), Timothy Schatz (VTT), Sami Naumer (VTT), Josef Brinek (UJV), Paula Keto (VTT), Nadja Zeleznik (EIMV), Alan Tkaczyk (UTARTU)**
Contributors	**Francisco Alvarez-Velarde (CIEMAT), Roland Jansma (NRG), Ludovic Vaillant (CEPN), Robbe Geysmans (SCK CEN), Meritxell Martell (Merience), Réka Szőke (IFE), Haske Reiling (NRG), Gilliam Van Oudenaren (NRG), Ernestas Narkūnas (LEI), Juan García (CIEMAT), Eef Weetjens (SCK CEN), Irena Herdzik-Koniecko (INCT), Terje Tverberg (IFE), Oleksandr Soloviov (SSTC), Jan Uhlíř (CVREZ), Borys Zlobenko (SIIEG)**

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Executive Summary

The deployment of small modular light water reactors (LW-SMRs) and advanced modular Generation IV reactors (AMRs) offers a significant opportunity to contribute to the development of low-carbon energy systems. However, considerations relating to radioactive waste management (RWM) have not been developed to the same level of maturity as the reactor designs themselves.

The management of radioactive waste generated by these nuclear technologies poses challenges that require immediate, strategic attention. Addressing these challenges early on will make it possible to develop management methods compatible with existing infrastructure or to deploy new facilities capable of safely handling LW-SMR/AMR waste. In some cases, regulatory frameworks will also need to be adapted. Furthermore, a transparent and factual dialogue between all involved parties around these means of producing sustainable energy, including the Civil Society, will need to be implemented. Failing to address these topics could have numerous and far-reaching consequences, potentially resulting in significant cost increases (unavailability of suitable facilities, development of tailor-made processes, etc.), significant delays (licensing, deployment schedules) and a loss of public confidence.

This white paper identifies critical gaps in RWM strategies and related research and development (R&D) needs for LW-SMRs/AMRs to ensure that these technologies can be deployed in a safe, sustainable, timely and socially responsible manner. Four types of SMR/AMR concepts are considered here. One is based on the familiar light water (LW) technology (LW-SMRs), while the other three AMR concepts, Liquid Metal Fast Reactors (LMFR), High-Temperature Gas-cooled Reactors (HTGR) and Molten Salt Reactors (MSR), have much more limited experience.

Proposals include R&D studies on waste characterisation, which depends on the specificities of the reactor and fuel cycle. This step is the cornerstone for studying and developing LW-SMR/AMR RWM. The more comprehensive and robust the knowledge of waste generation, the more effective and reliable the identification will be for initiating waste management studies. In addition, R&D proposals for actions regarding waste management need to be adapted to the reactor and fuel cycle specific constraints. The technology readiness level (TRL), and hence the status of available knowledge, is not the same depending on the reactor concept. Waste streams from LW-SMRs are expected to be similar in nature to those arising from the deployment of large light water reactors (LWRs). For AMR technologies, especially those at a lower TRL, specific waste streams are introduced that are not fully compatible with current treatment and conditioning methods or existing recycling and disposal strategies. The proposed R&D studies are important for developing safe and scalable treatment and stabilization processes that can address the unique challenges posed by emerging waste streams and support the long-term sustainability of waste management strategies.

R&D actions for waste characterisation and management concern LW-SMR/AMR vendors, Research Entities (REs), Technical Safety Organisations (TSOs) and Waste Management Organisations (WMOs), as anticipating potential modifications to existing facilities or the need for new infrastructure is essential to limit fragmented or customised developments that can be both costly and time-consuming.

The deployment of LW-SMRs/AMRs could also require adjustments to existing national regulatory frameworks, as well as the development of EU-level regulations and international guidelines. Case studies are proposed based on current knowledge in the area of cross-border transport of radioactive materials, integrating technical, safety, safeguards, and societal engagement aspects. The work should focus initially on LW-SMRs and then progress to other reactor types. The issue of fuel take-back policies merits further examination in the context of existing regulatory frameworks.

Stakeholder engagement is essential in the deployment of LW-SMRs/AMRs and related RWM. To this end, proposed steps include developing engagement frameworks that address technological innovations, uncertainties, and risks; creating clear communication tools; co-producing waste management scenarios with stakeholders, particularly on transport and centralised versus decentralised storage; and establishing governance mechanisms that define responsibilities, financing and equity across generations and regions.

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1. Introduction

Today, a growing number of companies are developing LW-SMRs and AMRs [1]. Their applications can extend beyond electricity generation to other forms of energy such as heat, cogeneration or hydrogen production. These reactors are based on diverse technical concepts, with specific technological characteristics that influence the generation and management of radioactive waste throughout the entire fuel life cycle including both operation and decommissioning.

Various LW-SMR/AMR designs exist and many of them are based on light water (LW) technology. For the LW-SMR concepts, a large amount of related experience exists as the majority of the worldwide fleet is built on LW technology and more than half of the permanently shut down nuclear power plants are LWRs. Therefore, the knowledge in the management of associated waste can be considered quite mature [2]. LW-SMRs are addressed in this document together with three AMR concepts for which global experience remains very limited:

- Liquid Metal Fast Reactors (LMFR) operating in the fast neutron spectrum and using liquid coolants such as sodium, lead or lead-bismuth,
- High-Temperature Gas-cooled Reactors (HTGR) using helium as a coolant and TRISO (Tri-Structural Isotropic) fuel particles embedded in graphite pebbles or blocks,
- Molten Salt Reactors (MSR) using molten salt as both fuel carrier and coolant often at high temperatures and low pressures.

Some AMR concepts, however, use other specific combinations of coolant and fuel.

The purpose of this white paper is to identify R&D challenges linked to all aspects of the management of radioactive waste from LW-SMRs/AMRs, and to propose R&D topics to address the existing knowledge gaps. It highlights the need for early and integrated planning to ensure the safe, sustainable, and socially responsible deployment of these upcoming technologies in the nuclear field, as recommended in the EURAD-2 Green Paper on ”Waste Management for SMRs and Future Fuels” [3].

Several key challenges are addressed, including waste characterisation and management throughout the entire fuel cycle, regulatory frameworks and the need for robust stakeholder engagement; a structured approach is proposed to tackle these challenges.

2. Challenge

2.1 Background

LW-SMRs/AMRs are increasingly promoted as safe, flexible and potentially cost-effective (compared to conventional, large reactors) contributors to low-carbon energy systems. However, evidence from the FORSAFF Green Paper and associated analyses indicate that RWM considerations have not been developed to nearly the same level of maturity as reactor concepts themselves. The waste management implications for LW-SMRs/AMRs are generally underrepresented or treated as extensions of existing approaches for LWR waste, despite significant technological differences, especially for AMR waste.

LW-SMR/AMR technologies will introduce novel fuels, coolants, moderators, structural materials and operational modes that generate waste streams which may differ substantially from those addressed by current waste management infrastructures and safety cases. Evidence from concept studies indicates that LW-SMRs/AMRs may generate waste streams such as irradiated graphite containing long-lived radionuclides, chemically reactive or toxic coolants (e.g., sodium, lead or molten salts), novel spent fuel forms (e.g., TRISO, salt-based fuels, advanced technology fuels) and distinct secondary waste streams associated with fuel treatment or online reprocessing concepts. These differences also pose regulatory challenges, where the existing regulatory frameworks and acceptance criteria may not fully apply.

At present, operational data from LW-SMR/AMR designs are limited or not publicly available, and waste inventories are based mainly on assumptions. This lack of data constitutes a clear evidence gap for the safe and credible management of LW-SMR/AMR-generated waste.

The waste management challenges associated with LW-SMRs/AMRs are marked by multiple, interacting uncertainties, including:

- **Waste uncertainty**: Limited knowledge of radionuclide inventories, impurity levels, chemical forms and long-term behaviour of new waste materials.
- **Fuel cycle uncertainty**: Many fast-spectrum reactor concepts are designed to operate optimally with fuels containing reprocessed actinides. However, the advanced reprocessing and fuel conditioning technologies necessary for a fully closed fuel cycle have not yet reached industrial maturity.
- **Compatibility uncertainty**: It is unclear whether existing storage designs and disposal concepts can safely accommodate these waste streams without significant modification.
- **Regulatory uncertainty**: In some countries, current regulatory frameworks and guidance are technology-specific to large, existing LWRs and may not fully cover LW-SMR/AMR-specific waste streams.

These uncertainties will make safety case development, repository planning and programme-level decision-making more complex.

The challenges of LW-SMR/AMR waste management will not be confined to reactor vendors or future operators, but rather will be shared across the entire radioactive waste community. In addition, siting of all types of LW-SMRs/AMRs used for energy, heating, or hybrid/industrial purposes may be widely geographically distributed, potentially located either near populated and residential areas as well as in very remote locations. Robust transport approaches will be needed in case of centralised management and processing facilities, whether within the country of origin, across the EU, or internationally. National programmes including regulatory frameworks and nuclear policies must ensure alignment between reactor deployment strategies and long-term waste management solutions in accordance with Waste Directive 2011/70/Euratom.

WMOs (Waste Management Organisations) must assess the acceptability of waste for disposal and ensure long-term safety. Regulators and TSO (Technical Safety Organisations) must evaluate safety cases for novel waste forms and any disposal concepts developed for wastes from these technologies.

Stakeholders and potential host communities may face increased waste transport, decentralised storage and new siting and permitting challenges.

2.2 Impacts

Failure to address LW-SMR/AMR waste management issues early on, before deployment, may result in future legacy wastes in the worst case, or significant cost increases due to the development of custom-fit treatment and conditioning technologies, expansion or redesign of storage facilities, adaptation of repository concepts and engineered barrier systems, and licensing delays linked to incomplete or evolving waste strategies. Retrofitting waste management solutions after LW-SMR/AMR deployment is likely to be considerably more expensive than early, integrated planning.

LW-SMR/AMR designs may generate larger waste volumes per unit of energy produced [4], waste forms with limited waste loading and chemically reactive or unstable wastes. These factors may challenge existing infrastructure capacities (and possible upgrades), operational safety during handling and transport and repository optimisation strategies.

LW-SMR/AMR waste streams will introduce safety challenges related to chemical reactivity hazards (e.g., sodium, molten-salt residues), uncertainties in the long-term behaviour of waste matrices, and possibly increased transport frequency associated with decentralised LW-SMR/AMR deployment. Uncertainty-driven conservatism in safety assessments may be required, potentially increasing design complexity and cost.

If LW-SMR/AMR waste issues are not resolved in a timely and effective manner, licensing and deployment schedules may be delayed, interim storage periods may be extended significantly, repository programmes may experience knock-on delays due to changing waste inventories and the regulatory adaptation processes may become reactive rather than strategic.

2.3 Rationale

Identifying and addressing LW-SMR/AMR waste management challenges proactively is essential to:

- ensure safety across the full waste lifecycle,
- avoid future legacy waste generation
- avoid fragmented and inefficient waste management pathways,
- maintain alignment between reactor deployment and national disposal strategies,
- ensure adequate funding schemes for waste and spent fuel management,
- strengthen public and stakeholder confidence in both LW-SMRs/AMRs and radioactive waste management programmes.

Early integration of waste considerations into LW-SMR/AMR designs and policy decisions supports a lifecycle approach that is central to responsible nuclear governance.

If the LW-SMR/AMR waste management challenges are addressed effectively, the benefits include:

- improved technical understanding and reduced uncertainty in waste characterisation,
- regulatory clarity and aligned approaches across LW-SMR/AMR waste management,
- optimised and cost-effective conditioning, storage and disposal solutions,
- enhanced repository readiness and long-term safety case robustness,
- increased societal trust.

Overall, by addressing LW-SMR/AMR waste management challenges early, many of the uncertainties identified above, e.g., unknown waste characteristics, regulatory gaps, and potential inefficiencies in treatment, storage, and disposal, can be reduced, thereby lowering long-term risk, cost, and programme complexity for the entire nuclear community.

2.4 Relevance to EURAD-2 Strategic Research Agenda (SRA)

The challenges of LW-SMR/AMR radioactive waste management directly align with several priority areas of the EURAD-2 Strategic Research Agenda [5], including addressing integration of new waste streams into national disposal programmes and future waste streams and strategies (Theme 1: Programme Management and Implementation, Roadmap Domain 1.5.1: Integrated waste management routes and strategic options); defining SMR/AMR waste streams, characterising new fuels/materials, and conditioning into acceptable waste forms (Theme 2: Predisposal, Roadmap Domains 2.1.1: Inventory, 2.1.2: Waste Characterisation); safety and risk assessment of spent fuel (SF) management and disposal operations, including new upcoming designs (Theme 3: Engineered Barrier Systems, Roadmap Domain 3.1.1: SNF)).

Addressing LW-SMR/AMR waste challenges within current and future EURAD programmes therefore contributes directly to the SRA's overarching objective: the safe, sustainable and socially responsible management of radioactive waste in Europe, now and in the future. In addition, such work would complement the Strategic Action Plan of the European Industrial Alliance on Small Modular Reactors, particularly with regard to the challenges, key objectives, and tasks identified by Technical Working Group N°7 on "Securing Existing & Advanced Fuel Supplies & Waste Management" and TWG N°2 on "Excelling in Research and Technology for SMRs and AMRS" [6].

3. Proposed way forward

The challenges associated with managing LW-SMR/AMR waste must be addressed as soon as possible across multiple R&D areas. Studies should focus on (i) waste characterisation, (ii) potential methods for managing waste throughout the fuel cycle, (iii) the adaptation or development of regulatory and policy frameworks, and (iv) strengthening stakeholder engagement and transparency mechanisms. In some cases, this may also include the benefits of establishing international collaborations on SMR/AMR waste management.

3.1 Waste characterisation studies

Actions consist of identifying the waste sources and the types, quantities, and physical and chemical forms of the radionuclides present in the reactor and the associated fuel cycle. Waste is primarily generated through fission, neutron activation, material contamination, corrosion and/or erosion, dispersion and decontamination activities. Accordingly, waste assessment depends on the specific characteristics of the reactor and fuel cycle. More generally, waste identification and characterisation studies concern:

- Nuclear fuel: assessment of radionuclide inventories and estimation of the physical and chemical form of elements in order to anticipate their management in solid or liquid phases (e.g., accumulation of insoluble species) and in the gaseous phase (e.g., aerosols likely to settle).
- Fuel assemblies and core components/structures: depending on the reactor concept, evaluation of activity generated by neutron activation during operation, corrosion resistance of structures during operation and storage and the need for washing/decontamination after fuel unloading, etc.
- Coolant: depending on the reactor concept, knowledge of its initial composition before neutron activation studies and possible fuel assembly leakage and the resulting contamination in the coolant (actinides, fission products, activation products from corrosion/erosion of structures). These data inform the specification of source terms needed, for example, in the design of solid traps.
- Treatment and conditioning of discharges (gaseous/liquid) during operation and/or reprocessing activities, depending on reactor concept and local regulatory requirements.

A robust understanding of materials composition, including impurities, and relevant properties is essential for accurately determining source terms. This approach helps minimise unexpected waste management consequences such as the generation of long-lived or otherwise problematic radionuclides arising from activation or contamination. Identification of the non-radiological, physico-chemical characteristics of contaminated matrices, such as flammability, toxicity and reactivity with air and water, is also of paramount importance to assess the applicability of existing RWM technologies and for determining whether additional R&D actions are required.

The more comprehensive and robust the knowledge of source terms, the more effective and reliable the identification of waste categories and properties will be for initiating waste management studies irrespective of the specific LW-SMR/AMR design. Today the main difficulties are associated with AMRs, for which the lack of empirical or experimental data is more prominent. R&D actions should consider experimental data acquisition where possible, and simulations should be validated against real-world conditions to reduce uncertainties.

3.2 Waste management studies

Identifying and characterising LW-SMR/AMR waste and limiting uncertainties in LW-SMR/AMR waste management throughout the entire fuel cycle (treatment and conditioning, reprocessing, storage, transportation and disposal) requires additional R&D studies depending on the technology (LWR, HTGR, LMFR, MSR). Appendix C presents relevant examples of back-end challenges and corresponding R&D needs identified for the different LW-SMR/AMR technologies, as described in the following paragraphs.

The fuel cycle of LW-SMRs is rather well understood and the expected waste streams are similar in nature to those arising from large LWRs. However, some LW-SMR designs specify higher enrichments, higher burnup levels, advanced fuel technologies (e.g., accident-tolerant fuels, mixed-oxide fuels, or other innovative fuel compositions) as well as novel fuel geometries. In addition, smaller cores are expected to result in higher activation of structural materials. These peculiarities warrant a review of established predisposal and disposal practices. Addressing identified knowledge gaps (Table C-1) will enable the safe integration of LW-SMR waste streams into established large LWR waste management frameworks, as well as into emerging national programmes in countries that lack waste management infrastructure. Improved conditioning and enhanced waste form performance should reduce environmental release risks and repository impacts, taking into account the LW-SMR specific characteristics. Minimising uncertainties in the long-term performance of storage options under normal and abnormal conditions will help prevent bottlenecks in the implementation of back-end programmes and final disposal solutions. Developing reliable High-Level Waste (HLW) characterisation techniques will contribute to make licensing processes more efficient and robust by reducing uncertainties in waste classification and properties. Finally, deep geological repositories may not be the most economically feasible disposal option for countries envisaging the deployment of a limited number of SMR/AMR units. In these cases, deep borehole disposal may be a more suitable and flexible alternative. However, further assessments are required to unlock this alternative as a viable, cost-effective route for these countries.

HTGRs use helium as a coolant and TRISO fuel particles embedded in graphite pebbles or blocks. Its characteristics yield two main design-specific waste streams: chemically robust spent TRISO particles and high volumes of irradiated graphite. Addressing research needs in treatment, conditioning and/or reprocessing of TRISO and graphite waste, described in Table C-2, will represent a step forward in terms of safety, waste volume reduction, and long-term performance, as well as enabling possible actinide recovery. For storage and transport, gaining knowledge on long-term pond-aging and dry-cask performance for TRISO fuel and irradiated graphite will help define wet and dry storage strategies. Improving experimental, non-destructive measurement methods will enhance the reliable characterisation of waste streams activity levels, enabling the routing of graphite and TRISO wastes to the most appropriate disposal options. This approach avoids overly conservative assumptions while maintaining safety. Safe and scalable volume reduction techniques can help minimise repository footprints. Leaching and interaction data for graphite and TRISO with glass, ceramic matrices and bentonite will support robust safety cases for both surface and deep geological facilities.

LMFRs operate in the fast neutron spectrum and can use oxide, nitride or metallic fuels. Coolants include liquid sodium, lead or lead-bismuth eutectic. Back-end challenges for LMFRs stem not only from their characteristic spent fuel inventory profile but also from the high chemotoxicity, radiotoxicity, and reactivity of the coolants used, as well as from the volume and complexity of the coolant-contaminated structural components (Table C-3). Increasing the Technology Readiness Level (TRL) of LMFR waste treatment and conditioning processes is necessary. These processes are typically envisioned for plutonium or minor actinide management and support closed fuel cycles. Thus, R&D on aqueous or possibly pyrochemical processes will help make actinide recycling possible, improve resource utilisation, and further reduce long-term radiotoxicity and heat load in geological repositories. Disposing LMFR HLW in geological repositories requires a better understanding of their long-term behaviour in realistic geochemical environments for the implementation of the required design adaptations and the development of robust safety cases. At the same time, disposal of Intermediate and Low Level Waste (ILW/LLW) streams will be made more feasible if the potential for leakage is minimised, such as through the treatment and conditioning of LMFR effluents (see Table C-3), using improved methods that minimise volume increase [7].

MSRs use liquid fuels based on fluoride or chloride salts, which also serve as coolant for the fuel circuit. They can be operated in either the thermal or fast neutron spectrum, with graphite serving as the moderator in the thermal spectrum. On-line recycling is possible for this type of reactor through pyrometallurgical treatments, meaning that reprocessing is typically an integral part of the reactor system. Pyrochemical and pyrometallurgical separation methods in particular are being proposed and studied for the reprocessing of MSR liquid fuel. MSRs generate unconventional waste streams dominated by activated fluoride or chloride salts containing fission products. Additional MSR wastes include metal alloys resulting from pyrometallurgical reprocessing containing soluble and insoluble fission products, noble metals, and radioactive gases such as tritium and other volatile radionuclides, as well as salt-contaminated structural materials (primarily nickel alloys) and in thermal neutron designs, structural graphite. Integration of spent fuel salt treatment using a hydro-metallurgical reprocessing scheme was also recently proposed [8]. Table C4 outlines R&D actions addressing technical challenges related to radioactive gases and volatile radionuclides from the MSR fuel circuit, radioactive waste arising from pyrochemical, pyro- and/or hydro-metallurgical reprocessing methods and the decontamination of structural materials exposed to high temperatures or oxidising atmospheres.

All of the R&D actions for waste characterisation and management concern LW-SMR/AMR designers, REs and TSOs and WMOs through the systematic sharing of data and studies. The management of radioactive waste must take into account the safety constraints of existing or future treatment, conditioning, storage and disposal facilities. Studies must begin sufficiently early ahead of the planned deployment in order to anticipate, as accurately as possible, any modifications to existing facilities or the creation of new ones. Early planning is particularly beneficial in avoiding customised developments and late-stage solutions that are costly in terms of both time and money.

3.3 Regulatory and policy issues

In addition to technical aspects, the safe and cost-effective deployment of SMRs/AMRs requires a new or updated policy and regulatory framework for RWM over the next 3-5 years:

- An appropriate and robust regulatory framework for RWM needs to be established for countries considering LW-SMR/AMR deployment without a prior nuclear program,
- Adjustment of existing national regulatory frameworks to address the unique features/technologies of LW-SMRs/AMRs and their waste management (with a focus on the more mature technological concepts),
- Optimisation of LW-SMR/AMR licensing processes, including strategies such as pre-application engagements and vendor design reviews, to identify potential regulatory issues and align the safety case / safety assessment with regulatory expectations before a formal license application is submitted. Incorporating RWM considerations during the LW-SMR/AMR licensing process is essential to ensure that viable waste management pathways are established for the specific reactor type,
- Harmonisation of RW transport regulations, by aligning national requirements with EU-level legislation and internationally recognised best practices, thereby optimising the safe, efficient, and legally robust transport of LW-SMR/AMR waste,
- Assessing potential options for returning fuel or reactor modules to the fuel manufacturer ("take-back" approaches) and evaluating models of private and state ownership with respect to compliance with EU regulatory expectations.

These strategies should involve all key stakeholders, including regulators and TSOs, REs, LW-SMR/AMR vendors, license applicants/licensees, WMOs and civil society organisations and/or the public. An important aspect to address during the pre-application engagements is the clear allocation of future roles and responsibilities among stakeholders in LW-SMR/AMR waste management activities.

Sharing information and feedback regarding LW-SMR/AMR RWM at the international level among all stakeholders would significantly support regulatory and technical decision-making. Establishing or updating a dedicated international platform to facilitate such exchanges could be highly beneficial.

Over the long term, regulations and international guidelines should evolve to comprehensively address waste management for AMRs. This includes developing guidance on pre-disposal handling, encapsulation, and final disposal across diverse geological conditions to ensure that radioactive waste from these reactors can be managed safely and effectively.

3.4 Stakeholder engagement issues

Based on FORSAFF outcomes [3, 9-10], a key finding is that stakeholder engagement should be treated not as a parallel, one-way communication activity, but rather as a bidirectional, core component of the next R&D cycle addressing RWM for LW-SMRs/AMRs. The immediate challenge lies in the mismatch between the rapid front-end development of LW-SMRs/AMRs and the limited public availability of back-end information, including waste characterisation, conditioning routes and disposal compatibility. To address this, R&D should proceed in several steps, which may sometimes be conducted in parallel:

Step 1: Develop engagement frameworks tailored to LW-*SMR/AMR*-*specific waste challenges.* Undertake comparative research on how existing national RWM engagement approaches, developed largely for conventional reactors, should be adapted for LW-SMRs/AMRs, taking into account the potential for new waste streams, a larger number of sites, more frequent transport routes and compatibility with existing RWM pathways. The aim is to produce LW-SMR/AMR-specific RWM engagement frameworks following existing experience that explicitly address uncertainties, explain technological novelties, and respond to concerns about dispersed impacts and long-term stewardship.

Step 2: Test methods for communicating uncertainty and evidence in R&D contexts. Design and evaluate engagement tools that can communicate technical uncertainty responsibly (e.g., uncertainties about waste volumes, conditioning options, disposal compatibility, and timelines), while maintaining trust and avoiding perceptions that the risk would be minimised. This includes producing and disseminating guidance on transparency standards, evidence-sharing, and the role of independent review, which are widely recognised as important trust building measures in stakeholder engagement.

Step 3: Co-produce RWM scenarios and decision points with stakeholders. Establish participatory processes where stakeholders (host communities, transport corridor stakeholders, and civil society organisations in particular) can engage directly with different waste management and disposal approaches, and what each option means in practice, including centralised vs. distributed interim storage and implications for transport. The objective is to develop practical stakeholder involvement approaches that demonstrably influence R&D priorities and system level decisions, for example, by allowing stakeholders to provide input to scenario design, evidence review, and the definition of decision criteria, using a transparent and equitable decision process. Such processes ensure that stakeholders' perceptions, needs, expectations, and concerns are effectively incorporated

Step 4: Develop and validate governance and fairness mechanisms. Conduct R&D on governance design, including how responsibilities, long-term liabilities, and financing mechanisms can be communicated transparently and perceived as legitimate. Particular attention should be given to fairness issues (voluntariness, intergenerational responsibility, compensation arrangements, and equity across regions), as these are repeatedly highlighted as underlying drivers of public concern.

4. Call to Action

Limited knowledge exists concerning LW-SMR/AMR waste inventories and, consequently, adequate waste management for the safe and efficient deployment of LW-SMR/AMR technologies. Early and integrated planning is essential to mitigate potential risks in the fuel cycle, optimise costs, and ensure public confidence in LW-SMR/AMR technologies and radioactive waste management programmes. Addressing the waste management challenges associated with LW-SMRs/AMRs requires early and targeted consideration in R&D efforts across multiple domains.

The prioritisation of R&D actions should be guided by the deployment schedules. The following proposals are recommended for near- and longer-term focus.

LW-SMRs:

Near Term Priorities (3-5 years)

- Obtain access to input data for LW-SMR spent fuels and waste to assess their specific characteristics and how they differ from those of large LWRs, e.g., examine factors such as the effect of core size on material activation and the impact of higher enrichments and/or burnups.
- Assess the amount, composition, and radiological properties of LW-SMR spent fuels depending on the fuel cycle (reprocessing or direct disposal); adapt conditioning processes to modular assemblies; define safe and efficient transport solutions to storage or disposal facilities.
- Characterise storage behaviour of LW-SMR waste, including potential impacts on packaging and repository design.
- Develop stakeholder engagement frameworks for back-end R&D (serves both LW-SMRs and AMRs); implement participatory decision-making, scenario-based planning, and transparent governance to communicate uncertainties and integrate stakeholder input into R&D and policy.

Longer-Term Priorities (5-15 years):

- Develop comprehensive datasets on spent fuels and conditioned wastes to inform repository design, licensing, and safety assessments.
- Explore advanced partitioning and transmutation strategies to reduce long-lived radiotoxicity.
- Assess integration of SMR-specific waste streams into national spent fuel management and disposal strategies.
- Develop decommissioning and waste retrieval strategies considering modular core design and packaging.
- Investigate long-term storage and disposal solutions, including high-level waste conditioning techniques, tailored to SMR characteristics.
- Institutionalise stakeholder engagement in back-end R&D (serves both LW-SMRs and AMRs); embed participatory mechanisms in licensing and governance, develop long-term trust monitoring and ensure permanent, structured stakeholder involvement beyond individual projects.

AMRs:

Near Term Priorities (3-5 years)

- Obtain access to input data in order to develop R&D studies on waste characterisation.
- Expand knowledge base on LMFRs, HTGRs, and MSRs to better understand waste chemistry, radiotoxicity, decay heat, etc.
- Integrate lessons from international collaborations (ALFRED, MIMOSA, GENIORS, ARCAS and SACSESS) and experimental facilities to guide back-end strategies.
- Develop modelling tools for predicting radionuclide inventories, decay heat, and long-term behaviour of spent fuel and conditioned waste.
- Initiate R&D on high-level waste forms for AMRs, including compatibility with geological disposal.

Longer-Term Priorities (5-15 years):

- Develop advanced monitoring, measurement, and analytical techniques for high-temperature and chemically complex wastes.
- Study materials compatibility and corrosion in storage and disposal conditions for AMR-specific waste forms.
- Enhance modelling tools for predicting radionuclide inventories, decay heat, and long-term behaviour of spent fuel and conditioned waste.
- Advance R&D on high-level waste forms for AMRs, including compatibility with geological disposal.
- Explore novel fuel cycles to reduce waste volumes and radiotoxicity while maximising resource utilisation.
- Validate waste characterisation, conditioning, and storage methods through pilot-scale demonstrations.

R&D studies should focus on waste characterisation, which depends on the reactor type and the specificities of the fuel cycle. This step requires data on reactor designs and used fuel inventories. Indeed, knowledge of these data and of the waste characteristics is the cornerstone for developing the LW-SMR/AMR RWM strategies. It involves in identifying source terms of radioactive waste, including nuclear material, as well as activated or contaminated components, structures and coolants. Analyses must also consider material impurities and non-radiological characteristics, as these can impact the applicability of existing RWM strategies or indicate the need for additional R&D. These studies should include experimental data where possible, and simulations should be validated against real-world conditions to reduce uncertainties.

R&D studies should also address treatment and conditioning methods for LW-SMR/AMR waste streams, potential recycling strategies, decontamination techniques for structural LW-SMR/AMR components and spent fuel reprocessing methods depending on the fuel cycle strategy. The compatibility of existing and anticipated storage, transport and disposal systems with LW-SMR/AMR waste management must be evaluated in terms of volume capacities and waste characteristics to ensure safe and efficient operation.

In the case of LW-SMRs, the expected waste streams are similar in nature to those generated by large LWRs. R&D proposals addressing different fuel cycle steps (treatment/conditioning, storage/transportation, reprocessing, disposal) will enable LW-SMR waste to be safely integrated into existing large LWR waste management frameworks. Conditioning methods and waste form performance should be enhanced to minimise environmental release risks and repository impacts, particularly in countries with established large LWR waste management systems.

For the three types of AMRs considered in FORSAFF, specific waste streams emerge that are not fully compatible with existing fuel cycle and disposal strategies. R&D studies to develop safe, scalable treatment, conditioning and storage techniques should be supported.

HTGR-type concepts require R&D proposals that cover all steps of the back end of the fuel cycle (waste treatment/conditioning, recycling, storage/transport, disposal) due to the limited information available to ensure safety, particularly with regard to the long-term behaviour of such waste and its potential interactions with Engineered Barrier Systems (EBS) and the surrounding environment. The specific characteristics of the fuel designs necessitate targeted R&D actions to optimise the waste disposal footprint.

LMFRs are marked by the need to increase the current level of technological maturity to manage, in particular, the coolant used and the components contaminated by the coolant.

MSRs generate unconventional waste streams such as salt-bearing fission products, activation products, volatile radionuclides, tritium and salt-contaminated structures. Targeted R&D studies are needed to address the design specific challenges (e.g., high temperature, corrosion) and to define appropriate waste management strategies for all steps of the fuel cycle (waste treatment/conditioning, recycling, storage/transport, disposal).

The capacity of MSR or LMFR concepts to recycle plutonium and minor actinides is a favourable feature that could improve resource utilisation and minimise HLW impact. However, additional R&D actions are needed to increase TRLs.

In summary, regardless of the type of LW-SMR/AMR, all R&D actions related to waste characterisation and management involve LW-SMR/AMR vendors, REs, TSOs and WMOs with the goal of anticipating as accurately as possible any modifications to existing facilities or the need for new infrastructure. Such foresight should be particularly beneficial in preventing customised developments that are costly in terms of both time and money.

The deployment of LW-SMR/AMRs and their associated back-end processes will require adjustments to existing national regulations and may necessitate further development of EU-level regulations and international guidelines to support consistent implementation. Future case studies, such as those examining the transport of spent fuel to centralised facilities across multiple EU countries, could provide valuable, evidence-based insights. These studies should address the regulatory framework, international guidelines, radiation safety during transport, fuel characteristics (before and after reprocessing), transport cask designs, emergency preparedness, safeguards, and societal engagement. The initial focus should be on LW-SMRs, with subsequent extension to AMR fuels and waste streams. Another topic for further study is the fuel take-back approach and its alignment with policy frameworks.

Stakeholder engagement is critical for the next R&D cycle in LW-SMR/AMR radioactive waste management. The rapid pace of reactor development contrasts with the relative immaturity of backend solutions, creating uncertainty around long-term liabilities, governance, and financing. A structured approach is needed to address technological assumptions, reduce uncertainties, and ensure transparent communication regarding the waste lifecycle, thereby strengthening the robustness and legitimacy of decision-making.

Future research should focus on developing and testing participatory governance frameworks tailored to LW-SMR/AMR waste, explicitly addressing technological uncertainty, long-term stewardship, and intergenerational fairness. Through co-designed engagement tools and stakeholder-led scenario development, such work can support informed decisions on storage, transport, and disposal while building trust and accountability.

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Appendix A. Keywords

SMR, AMR, LWR, HTGR, LMFR, MSR, characterisation, waste management, pre-disposal, disposal, safety, regulatory framework, stakeholder

Appendix B. List of acronyms and abbreviations

AAM – Alkali-Activated Materials

AMR - Advanced Modular Reactor

DGR – Deep Geological Repository

EBS – Engineered Barrier Systems

EU – European Union

EURAD – European Joint Programme on Radioactive Waste Management

FORSAFF – Strategic Study (WP) of EURAD about "Waste Management for SMRs and Future Fuels"

GANEX - Group Actinides Extraction

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

LW-SMR – Light Water Small Modular Reactor

MSR – Molten Salt Reactor

PUREX - Plutonium Uranium Refining by EXtraction

R&D – Research and Development

RWM – Radioactive Waste Management

SANEX - Selective Actinide Extraction

SEA – Strategic Environmental Assessments

SMR – Small Modular Reactor

SNF – Spent Nuclear Fuel

Synroc – Synthetic Rock

TRISO – Tri-Structural Isotropic

TRL – Technology Readiness Level

TWG – Technical Working Group

UC – Uranium Carbide

UOx – Uranium Oxide

WAC – Waste Acceptance Criteria

WENRA – Western European Nuclear Regulators' Association

WM – Waste Management

WP – Work Package

Appendix C. Challenges and R&D needs for LW-SMRs/AMRs

Table C-1 – LWR – Challenges and R&D needs

Technology	**Back-end activity**	**Challenge**	**R&D Undertaking**
LWR	**Treatment and conditioning**	In the vitrification process of HLW, glass-loading limits and behaviour need to be assessed, as well as the efficiency of off-gas capture of volatile radionuclides (e.g., ^{99}Tc, ^{137}Cs).	Launch pilot vitrification campaigns with high burnup UO_2, including volatile radionuclide capture systems tests.
	Treatment and conditioning	The long-term performance of cement, bitumen and advanced alternative materials (e.g., alkali-activated materials, geopolymers) for immobilisation of operational, decommissioning and end-state considerations, LLW and ILW waste needs to be better understood.	Perform experimental long-term retention, diffusion, and mechanical integrity studies on advanced waste forms (geopolymers, new cement mixes) for SMR representative L/ILW to demonstrate mechanical integrity and radionuclide retention under realistic waste loadings and temperatures.
	Storage and transportation	There is a lack of experience in dry and wet storage of LW-SMR spent fuel (which will feature different burnup levels, radionuclide inventories, mass, volumes…) in normal conditions, under environmental stress, and in accident scenarios.	For dry storage, carry out cask long-term performance tests, assess degradation mechanisms across scenarios (e.g., temperature changes and aging, SNF mechanical changes during drying, localised corrosion, weld aging), and development of monitoring strategies. For wet storage, develop guidance for multi-unit damage and mitigation strategies. Perform leak assessments, experiments in partially drained conditions, and modelling considering factors such as multi-unit interactions, geometry, and drainage levels.
	Reprocessing	Reprocessing is feasible with commercial PUREX process. Existing or advanced solvent extraction methods under development may need to be adapted to higher enrichments, higher burnup, and potentially different inventory profiles, higher in Pu.	Develop and test pilot-scale adapted PUREX process and advanced solvent extraction methods on representative HALEU and high burnup LWR fuels, explicitly addressing the performance of actinide and fission product separation (e.g. GANEX, SANEX variants), and quantifying secondary waste generation for SMR specific inventories.

Technology	Back-end activity	Challenge	R&D Undertaking
LWR	**Disposal**	HLW characteristics (e.g., radionuclide profiles and concentrations, volumes, geometries) are uncertain and this uncertainty affects disposal acceptance and safety assessments.	Develop HLW characterisation techniques (real-time assay data acquisition techniques). Perform safety assessments for different burnups, volumes, mass, compositions, and dimensions, factoring in different repository evolution scenarios.
	Disposal	Geological repositories may not be the most economically viable option for small inventories. Deep borehole disposal is an alternative but requires further investigation and demonstration.	Assess the regulatory, economic, and technical implications of implementing deep borehole disposal for LW-SMR inventories and decentralised deployment.

Table C-2 – HTGR – Challenges and R&D needs

Technology	**Back-end activity**	**Challenge**	**R&D Undertaking**
HTGR	**Treatment and conditioning**	Immobilisation of TRISO fuel particles in cementitious or glass matrices raises criticality and chemical interaction concerns. Immobilisation of graphite in cement raises chemical compatibility and mechanical integrity questions.	Conduct criticality safety assessments to identify safe design margins and loads, and assess the effect of moisture on criticality. The chemical interaction of graphite with matrix materials needs to be addressed. Study long-term durability of cementitious matrices, ^{14}C retention, thermal load compatibility, swelling and shrinkage, and micro-fracturing induced by gas release during cement setting and casting.
	Treatment and conditioning	Graphite decontamination (e.g., steam oxidation, …) and volume reduction of radioactive graphite to dispose needs to be further developed.	Optimise the steam oxidation decontamination process and assess associated activity decrease and impact on waste classification
	Storage and transportation	Wet storage in cooling ponds pose challenges such as the long-term effect of water on TRISO fuel and HTGR graphite. Prolonged exposure to varying pH and water chemistry may affect coating integrity and increase leaching of radionuclides from TRISO fuel particles. Long-term dissolution and oxidation of HTGR graphite under changing temperature and chemistry conditions are also processes that need to be better understood.	Perform long-term pond-aging experiments on TRISO particles and irradiated graphite under controlled variable pH, temperature, and chemistry conditions. These experiments must assess SiC/PyC coating degradation and leaching rates, graphite dissolution and oxidation.
	Storage and transportation	For dry storage, the main uncertainties are heat dissipation and interaction with residual moisture and gas for both TRISO fuel and irradiated graphite. In TRISO, the role of these factors on SiC/PyC coating degradation is not well understood. For graphite, existing models inadequately capture heat transfer, moisture retention, and helium fill effects, leading to uncertainties in temperature profiles and material behaviour over long periods.	Perform durability and thermal performance tests of TRISO and graphite in representative dry cask configurations, under realistic conditions of temperature, humidity, and mechanical stress (vibration, shocks). Perform CFD-informed thermal tests of graphite-loaded casks alongside an evaluation of passive and active thermal control systems.

Technology	Back-end activity	Challenge	R&D Undertaking
HTGR	**Storage and transportation**	Transportation infrastructure and tailored-made casks for pebble fuel and graphite may need to be developed. Automated pebble and graphite handling, contamination control systems and protocols do not exist.	Design and test casks and transfer systems for pebbles and graphite, including automated handlers with filtration systems to prevent dust spread.
	Reprocessing	Accessing the TRISO kernels by removing multiple SiC/PyC coatings and graphite while preserving kernel integrity is the main reprocessing challenge. Head-end methods (plasma etching, molten-salt oxidative dissolution, carbochlorination, etc.) are mostly theoretical or at an experimental stage. In addition, these processes would generate large volumes of ^{14}C contaminated graphite and complex secondary wastes.	Design and demonstrate integrated TRISO head-end processes at lab scale then extend it at pilot scale. Trials must quantify kernel exposure efficiency and integrity, propose solutions for volatile FP capture, management of ^{14}C contaminated graphite and SiC/PyC residues.
	Disposal	Segregation by waste class lacks real-world performance data on gamma/neutron sorting systems.	Perform gamma/neutron sorting tests to quantify segregation efficiency.
	Disposal	Volume reduction techniques face scale-up uncertainties and incomplete understanding of off-gas composition.	Conduct bench- and pilot-scale demonstrations of volume reduction processes, with off-gas characterisation and capture.
	Disposal	Surface and near-surface disposal require long-term data on radionuclide release from graphite wastes and on irradiated graphite degradation.	Carry out long-term leaching and graphite behaviour studies under surface and near-surface disposal conditions.
	Disposal	There is no proof that intact TRISO particles can be vitrified or sintered into ceramics while maintaining coating integrity. In addition, interactions between SiC/PyC and irradiated graphite with bentonite under repository conditions of temperature, pressure, and chemistry are poorly characterised.	Perform vitrification trials and ceramic-matrix sintering experiments to confirm coating integrity, durability, and compatibility with TRISO particles and graphite wastes under realistic thermal and mechanical loads. Perform long-term geochemical and thermo-hydro-mechanical studies of SiC/PyC and irradiated graphite interactions with bentonite.

Technology	Back-end activity	Challenge	R&D Undertaking
HTGR	**Disposal**	For large graphite inventories, volume reduction techniques must address ^{14}C bearing-gas capture and management, as well as scalability and safety.	Develop scalable processes with robust ^{14}C sequestration and off-gas treatment.

Table C-3 – LMFR – Challenges and R&D needs

Technology	Back-end activity	Challenge	R&D Undertaking
LMFR	**Treatment and conditioning**	Vitrification of HLW requires better definition of waste composition, glass loadings, and heat tolerances. Alternative matrices such as Synroc have not yet been implemented at industrial scale.	Establish reference glass compositions, maximum waste loadings, and thermal limits. Evaluate Synroc/HIP performance and increase TRL.
	Treatment and conditioning	For ILW/LLW streams (especially lead, lead-bismuth, and sodium coolants, sodium-wetted components, and liquid effluents) treatment and conditioning practices remain technologically immature. Immobilisation of decontaminated lead coolant and structural waste in alkali-activated materials and geopolymers is promising but further research is required to demonstrate their performance. For sodium processing[1], batch conversion into carbonates and tritium removal require further research and industrial scale-up, especially regarding the effects of impurities and filtration systems. Practical experience is lacking for the water-vapor treatment of large, complex sodium-wetted components. Finally, cementation of liquid effluents requires formulations that ensure low leakage. Cs/Sr extraction technologies remain at an early development stage.	Develop and test AAM (Alkali-Activated Materials) and geopolymer formulations tailored to LMFR waste streams, including long-term durability and leaching studies. For sodium coolant, research batch processing into carbonates and tritium removal, focusing on impurity effects, filtration strategies, and overall process safety. Design and conduct large mock-up trials of water-vapor treatment for large sodium-wetted and geometrically complex components. Validate decontamination efficiency and operational safety. Design and qualify cement matrices for liquid effluents, assessing leakage and Cs/Sr extraction methods from concept to pilot scale.
	Storage and transportation	The suitability of existing storage or dual-purpose casks for LMFR spent fuel, activated core components, and conditioned waste must be assessed. Interim storage of metallic sodium poses safety challenges due to its high chemical reactivity, requiring robust containment and accident management provisions. Liquid effluents from sodium processing	Qualify existing storage and dual-purpose cask designs for representative LMFR fuel and waste forms through thermal, chemical, mechanical, criticality, shielding, and leakage analyses. Where necessary, develop tailored storage system designs.

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[1] To be precised for other metal coolant processing

		require storage solutions that minimise leakage.	

Technology	Back-end activity	Challenge	R&D Undertaking
LMFR	**Reprocessing**	PUREX-based processes are applicable to oxide and nitride fuels. Advanced solvent extraction methods at intermediate TRL are also under development. Pyroprocessing is promising for metallic and nitride fuels. However, the overall TRL of fast-reactor reprocessing (especially pyroprocesses) is low. In addition, high fissile content fuels demand dedicated criticality assessments.	Advanced pyroprocessing and aqueous reprocessing from conceptual to pilot scale using representative oxide, nitride, and metallic fuels. Perform detailed criticality analyses and analyse recovery efficiency. Characterise sodium or chloride rich secondary waste streams.
	Disposal	For the direct disposal of LMFR spent nuclear fuel in geological repositories, safety questions arise from the fuel form presentation (oxide / nitride / metal), burnup histories, and high Pu content need to be considered. Design implications and associated costs to accommodate LMFR wastes in current repository concepts are not determined and quantified.	Perform criticality analyses and characterise dissolution and degradation rates of representative LMFR fuels and waste forms under expected geochemical environments. Assess the impact on repository design and costs.
	Disposal	Existing effluent conditioning processes are either vulnerable to leaks or significantly increase waste volume. This has an impact on near surface disposal of ILW/LLW.	Develop and test improved effluent conditioning methods that guarantee very low leakage, optimising resulting volumes.

Table C-4 – MSR – Challenges and R&D needs

Technology	Back-end activity	Challenge	R&D Undertaking
MSR	**Treatment and conditioning**	Reduce the residual activity of metal components for optimising disposal capacities.	Decontamination of metallic components exposed to corrosion and irradiation
	Reprocessing	Pyrochemical, pyro- and/or hydro-metallurgical separation method are proposed for MSR liquid fuel reprocessing. These technologies under development currently reach a maximum TRL of 4 and therefore require further technological research and verification. This applies in particular to pyro- or hydro-chemical reprocessing from chloride melts. Another task of reprocessing when using chloride melts is the requirement to recycle chlorine, which is enriched with ^{37}Cl in chloride MSR.	Focus on the characterisation of radioactive waste originating from electrochemical separation methods from fluoride or chloride melts, from molten salt/liquid metal extraction separation methods, and from fluoride volatility separation methods. Optimise the integration of spent fuel chloride salt treatment within a hydro-metallurgical reprocessing scheme.
	Disposal	Disposal mainly concerns the development of technologies for vitrification of fluoride- or chloride-based waste, either in the form of solidified melts or inorganic sorbents based on alkaline fluorides or chlorides.	Develop methods for vitrifying fluoride- or chloride-based waste, or verify the possibility of converting them into nitrates, for which waste vitrification methods from hydrometallurgical methods (PUREX) will then be applicable.
	Disposal	Disposal LLW and ILW from structural material and graphite decontamination will use similar technologies as from reprocessing of LWR and MAGNOX spent fuel.	Will depend on specific MSR concepts, likely to involve metal ILW compacting and LLW cementation technologies.