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Executive Summary

Despite the high level of interest in deploying Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs), related radioactive waste management (RWM) considerations have not kept pace. Waste management implications are frequently underrepresented in deployment planning or deferred altogether, despite these technologies introducing novel fuels, coolants, and structural materials that generate waste streams beyond the scope of existing waste management infrastructures and regulatory frameworks. The Waste Management for SMRs and Future Fuels (FORSAFF) Work Package (04) of the European Partnership on Radioactive Waste Management-2 (EURAD-2) addresses this gap, examining RWM across four reactor technology groups — Light Water Small Modular Reactors (LW-SMRs), High-Temperature Gas-Cooled Reactors (HTGRs), Liquid Metal Fast-spectrum Reactors (LMFRs), and Molten Salt Reactors (MSRs) — through waste stream characterisation, waste management strategy, regulatory frameworks, and stakeholder engagement.

The central FORSAFF finding is that waste management requirements should be defined and understood during the reactor design phase, so that material and design choices can be optimised accordingly and incompatibilities with available management and disposal pathways are identified before commitments are made. Failure to act early risks future legacy waste generation, cost increases from bespoke treatment solutions, licensing delays, and loss of public confidence. LW-SMR waste streams are qualitatively similar to those of existing large Light Water Reactors (LWRs) but require dedicated assessment. AMR technologies introduce substantially more complex waste streams, e.g., irradiated graphite and Tri-Structural Isotropic (TRISO) fuel in HTGRs, long-lived activation products and reactive coolants in LMFRs and unconventional salt-based waste in MSRs, for which characterisation data remains largely model-derived. While waste management legislation is generally technology-neutral and broadly applicable, no European country has yet developed SMR/AMR-specific licensing guidance that adequately addresses the novel waste streams these technologies will generate. Credible disposal pathways nonetheless remain among the most important prerequisites for deployment approval. Addressing these issues without unduly slowing deployment is a genuine dilemma.

FORSAFF recommends that reactor developers and national programme owners prioritise experimental waste characterisation, beginning with LW-SMRs where deployment timelines are shortest and extending to AMR families as those programmes mature. National regulatory authorities should begin targeted adaptation of licensing frameworks to address SMR/AMR-specific waste streams, supported by adequate resourcing. At the EU level, greater consistency in the regulatory treatment of novel SMR/AMR waste streams, including waste classification approaches and the conditions governing cross-border transfer for disposal, would reduce fragmentation and lower barriers to the cooperative arrangements that countries deploying only a small number of units will likely need. For such countries, whether newcomers to nuclear energy or established programmes of limited scale, joint backend solutions are likely more proportionate than dedicated national infrastructure. Member States, the European Commission, and relevant international bodies should advance the regulatory and legislative conditions needed to enable such arrangements, including clear allocation of waste ownership responsibilities and explicit provisions governing fuel or module return to the vendor's country of origin. Waste management organisations, regulators, and programme owners should institutionalise SMR/AMR-specific stakeholder engagement built around transparent communication of technical uncertainties. Finally, FORSAFF calls for sustained and coordinated European R&D investment, aligned with the EURAD Strategic Research Agenda, to close the knowledge gaps on which all of the above depend.

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List of Acronyms

Acronym	Meaning
AMR	Advanced Modular Reactor
DBD	Deep Borehole Disposal
EBS	Engineered Barrier Systems
EC	European Commission
EU	European Union
EURAD-2	European Partnership on Radioactive Waste Management-2
FORSAFF	Waste Management for SMRs and Future Fuels
HTGR	High-Temperature Gas-cooled Reactor
IAEA	International Atomic Energy Agency
LIMS	Large Inventory Member States
LMFR	Liquid Metal Fast-spectrum Reactor
LW-SMR	Light Water Small Modular Reactor
LWR	Light Water Reactor
MSR	Molten Salt Reactor
PEP	Pathway Evaluation Process
R&D	Research and Development
RWM	Radioactive Waste Management
SIMS	Small Inventory Member States
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
SRA	Strategic Research Agenda
TRISO	Tri-Structural Isotropic
WENRA	Western European Nuclear Regulators Association

1. Introduction

Small modular reactors (SMRs) and advanced modular Generation IV reactors (AMRs) are attracting growing interest across Europe and globally as flexible contributors to low-carbon energy systems. Their potential advantages, e.g., modularity, passive safety features, scalable deployment, and applicability to industrial heat and hydrogen production, have led a growing number of Member States to include SMR/AMR options in national energy strategies. A range of reactor designs is currently under development worldwide, with selected projects aiming for deployment already in the 2030s.

Despite this momentum, one critical dimension has not kept pace with the front-end enthusiasm, namely radioactive waste management (RWM). As documented in the FORSAFF Green Paper (Deliverable 4.2) and White Paper (Deliverable 4.3), radioactive waste management considerations for light water-SMRs and AMRs have not been developed to the same level as the reactor designs themselves [1,2]. Waste management implications are frequently underrepresented in deployment planning, treated as extensions of established approaches for conventional large light water reactors (LWRs), or deferred to a later stage. This is despite the fact that SMR/AMR technologies introduce novel fuels, coolants, moderators, structural materials, and operational modes that generate waste streams which may differ substantially from those that current management infrastructures and regulatory frameworks were designed to handle.

Failure to address these challenges early carries potential consequences such as future legacy waste generation, significant cost increases from bespoke treatment and conditioning solutions, delays to licensing and deployment schedules, and loss of public and regulatory confidence in both the technologies and the waste management programmes that must support them. Conversely, proactive and integrated waste management planning reduces long-term risk and cost, enables alignment between reactor deployment and national disposal strategies, and provides the evidentiary basis needed for credible, licensable waste management programmes. Early integration of back-end considerations into the SMR/AMR design process also opens the possibility to optimise reactor design and material selection from a disposal perspective.

Waste Management for SMRs and Future Fuels (FORSAFF) is a Strategic Study work package of the European Partnership on Radioactive Waste Management-2 (EURAD-2). Its overarching objective is to identify and describe the radioactive waste management challenges associated with LW-SMR and AMR operations, and to develop strategic guidance on waste characterisation priorities, waste management approaches, regulatory adaptation needs, and stakeholder engagement frameworks needed to ensure that these technologies can be deployed safely, sustainably, and in a socially responsible manner.

FORSAFF focuses on four reactor technology groups considered most relevant in terms of development status, deployment potential, and distinct waste management implications:

- Light Water SMRs (LW-SMRs), whose waste streams are broadly similar to those of existing large LWRs, though specific design features, i.e., smaller core geometries, higher fuel enrichments, and advanced fuel types, introduce uncertainties that warrant dedicated attention;
- High-Temperature Gas-cooled Reactors (HTGRs), which generate large volumes of irradiated graphite and use TRISO fuel particles whose high chemical and structural stability creates distinct challenges for conditioning, reprocessing, storage and disposal;
- Liquid Metal Fast Spectrum Reactors (LMFRs), which operate using chemically reactive coolants and in fast neutron spectra that generate long-lived activation products at activity levels not typically encountered in thermal reactor fleets; and
- Molten Salt Reactors (MSRs), which generate the most non-standard waste streams of any reactor family currently under development, including chemically reactive salt-based residues, volatile fission products, and complex secondary waste from online reprocessing operations.

This final deliverable draws on the full outputs of FORSAFF, synthesising findings across the technical, regulatory, and societal dimensions of SMR/AMR radioactive waste management.

The timing of FORSAFF is relevant. LW-SMRs are expected to enter the market in the 2030s, and several Member States are already in active planning or legislative development processes. For most AMR concepts, deployment timelines extend into the 2030s and beyond, but the R&D investments needed to provide effective back-end solutions should start now if they are to be available when needed. Once designs are locked in and deployment commitments made, the options for optimising waste management solutions narrow considerably.

This deliverable is addressed to the broad community of decision-makers who will shape SMR/AMR deployment across Europe: Member State governments and ministries considering nuclear energy options; reactor vendors and developers whose design choices will largely determine the characteristics of the resulting radioactive waste; waste management organisations responsible for accepting, storing, and disposing of the waste these technologies will generate; national regulatory bodies who must adapt or build frameworks capable of licensing novel waste management approaches; and European Commission officers overseeing the coherence of nuclear governance across the EU.

2. Key Findings

2.1. Generic Applications

The findings of FORSAFF across the four complementary areas are relevant to all Member States, regardless of nuclear programme maturity.

Informing waste management R&D needs: Systematic characterisation of SMR/AMR waste source terms, catalogued by origin and physico-chemical-radiological properties, provides an early basis for identifying which pre-treatment, conditioning, storage, transportation and disposal technologies will be required. The synthesis of waste management strategy and cross-cutting lessons reinforces the need to embed back-end considerations from the earliest stages of reactor design: the nature of waste is directly shaped by fuel type, structural materials, and operating conditions, and misalignment with available management pathways creates avoidable downstream problems.

Supporting regulatory adaptation: Reliable waste stream data enables Member States to adapt regulatory frameworks proactively rather than reactively. The review of regulatory and institutional frameworks confirms that no European country has yet established a fully SMR/AMR-specific licensing and waste management framework. Open questions about how existing frameworks apply to emerging technologies contribute to overly conservative regulatory assumptions that increase both complexity and cost.

Enabling credible back-end planning: A demonstrably credible waste management programme covering characterisation, storage, transport, final disposal, and, where applicable, spent fuel reprocessing, is identified as among the most important enablers of SMR/AMR deployment. For Member States with limited fleet ambitions, developing dedicated national infrastructure may not be proportionate, increasing the potential relevance of shared or regional solutions. These arrangements require further development at regulatory and policy levels.

Strengthening public confidence through early engagement: Stakeholder engagement improves the credibility and robustness of waste management pathways by raising concerns at a stage when they can still meaningfully influence decisions. This further reinforces uncertainty management as a persistent challenge, with structured engagement providing an essential forum for transparent communication of uncertainties to regulators, communities, and decision-makers.

2.2 General Trends

2.2.1. Waste stream characterisation

Waste generation assessments were structured around four main reactor families, Light Water Reactors (LWRs), Liquid Metal Fast-spectrum Reactors (LMFRs), High-Temperature Gas-cooled Reactors (HTGRs), and Molten Salt Reactors (MSRs), reflecting common waste generation pathways within each family. Spent fuel and reprocessing inventories were assessed separately.

Operational waste and activated materials:

- LWRs: SMR variants are expected to produce waste qualitatively similar to existing pressurised and boiling water reactor fleets, though smaller core sizes with higher surface-to-volume ratios may increase neutron leakage and relative material activation. Higher burn-up, higher-enrichment fuels and modified fuel geometries may have implications for waste classification, storage performance, and repository design.

- HTGRs: Large inventories of irradiated graphite components will arise at end-of-life, with C-14, H-3 and Cl-36 (mainly produced through activation reactions involving impurities) likely dominating the activity. Disposability will depend significantly on operational temperatures, and dedicated management solutions will be required.

- LMFRs: The fast neutron spectrum combined with non-standard structural materials generates long-lived activation products not typically encountered at such activity levels in thermal reactor fleets. The chemical toxicity and/or reactivity of certain coolants (lead and sodium) may require dedicated waste treatment solutions.

- MSRs: Online fission product removal in certain designs generates concentrated, high-activity waste on-site; the chemical reactivity of molten salt coolants presents further dedicated management challenges.

Spent fuel and reprocessing:

- LW-SMRs: Higher burnups and novel assembly geometries may require adaptations to radionuclide inventory estimation methodologies and transport regulations.

- HTGRs: High physico-chemical stability of spent TRISO fuel may limit conventional reprocessing approaches; lower thermal power densities require larger core volumes and may lead to comparatively larger volumes of spent fuel and associated graphite materials.

- LMFRs: Closed fuel cycle operation involves large plutonium inventories with significant criticality safety implications at fuel fabrication and reprocessing facilities.

- MSRs: For some concepts, fuel processing or reprocessing may be integral to reactor operation, whereas other designs may rely on a once-through fuel cycle. Fluoride-salt fuels are incompatible with industrially mature hydrometallurgical reprocessing; alternatives such as pyroprocessing introduce substantial uncertainties regarding radiological properties of vitrified and secondary waste streams.

A cross-cutting challenge across all AMR families is the limited operational experience available which further translates into significant uncertainties in material impurity content and activation product estimates. Moreover, the potential for modular component reuse or vendor take-back, which could substantially reduce the volumes of activated materials requiring disposal, has not yet been fully integrated into assessments, as uncertainties remain regarding the regulatory and practical applicability of such approaches. It is also worth noting that certain AMR concepts, particularly those designed to operate on closed or partially closed fuel cycles, offer potential advantages from a waste minimisation perspective, including reduced generation of long-lived radiotoxic waste. Whether these potential benefits are realised in practice depends on the maturity of the associated fuel cycle technologies and on the full lifecycle waste implications being properly accounted for at the design stage.

2.2.2. Cross-cutting waste management strategy

The synthesis of findings across FORSAFF highlights several consistent themes, revealing overarching strategic lessons for SMR/AMR waste management.

- Early integration of waste management: Waste management should be considered from the very beginning of reactor design, not treated as a downstream issue. Fuel types, structural materials, and operating conditions directly determine what waste will need to be managed; if the outcomes of these design decisions are not aligned with existing waste management and disposal pathways, unnecessary technical and regulatory challenges can arise. For designs that have already progressed beyond the point where material or fuel choices can be revisited, the priority shifts from optimisation to early and rigorous characterisation of the resulting waste streams, so that appropriate management and disposal pathways can be identified and developed in parallel with the remaining design and licensing work. Early integration of back-end considerations can also help realise the waste minimisation potential of certain AMR concepts, for instance those capable of actinide recycling, which may otherwise be forfeited if fuel cycle decisions are deferred.

- Waste characterisation as a cornerstone: A sound understanding of waste streams, including radionuclide inventory, chemical composition, and physico-chemical properties, is the fundamental building block of any effective waste management strategy. For most AMR concepts, however, this data remains largely model-derived rather than experimentally validated, a gap that requires targeted research investment.

- Pervasive and interacting uncertainties: Waste management planning for SMRs and AMRs is subject to multiple layers of uncertainty spanning waste composition and long-term behaviour, fuel cycle configuration, reprocessing strategy, and compatibility of existing storage and disposal systems with new waste forms. These uncertainties interact and compound one another, often leading to conservative assumptions that, while necessary from a safety perspective, increase programme complexity and cost. The strategic response is not simply to accept this burden, but to prioritise targeted R&D that reduces the most consequential uncertainties early, in particular, experimentally grounded waste characterisation data for the designs closest to deployment, while adopting adaptive management frameworks that allow assumptions to be revisited and refined as knowledge matures, rather than locking in conservative positions that may prove unnecessarily restrictive.

- Increasing diversity of waste streams: The range of waste materials and forms associated with AMRs, i.e., irradiated graphite, chemically reactive liquid metal coolant residues, molten salts, is substantially broader than for conventional reactor systems, requiring technology-specific waste management approaches rather than standardised solutions.

- Deep geological disposal remains the reference endpoint: Despite the introduction of novel waste types, deep geological disposal remains the reference solution for high-level and long-lived waste. Adapting repository concepts to accommodate new waste characteristics requires further research on long-term behaviour and interactions with engineered and natural barriers. As an alternative, deep borehole disposal may offer flexibility for countries with small inventories for which a dedicated deep geological repository may not be proportionate. However, this requires further technical and regulatory development, and should be considered in the context of each Member State's primary obligation to make demonstrable progress on implementing its national radioactive waste management programme.

- Distributed deployment and infrastructure strategy: The modular and potentially decentralised nature of SMR/AMR fleets increases the strategic importance of transport systems and intermediate storage solutions and raises questions about the appropriate balance between centralised and decentralised national waste management infrastructure. For Member States with limited fleets, shared or regional solutions may be more proportionate than dedicated national facilities.

- Coordinated European R&D: Advancing knowledge on waste characterisation, treatment technologies, storage and transport, and disposal performance will be essential to reduce uncertainties and support safe implementation, in alignment with the EURAD Strategic Research Agenda.

2.2.3. Regulatory frameworks and back-end solutions

SMR/AMR waste management across Europe is currently governed by the existing Euratom framework, principally the Waste Directive (2011/70/Euratom), the Basic Safety Standards Directive (2013/59/Euratom), and the cross-border transport Directive (2006/117/Euratom), alongside IAEA SSR-6, the Joint Convention, and WENRA reference levels. No SMR/AMR-specific legislation yet exists, and the maturity of national-level adaptation varies considerably across Europe. This creates a range of regulatory and policy considerations that will influence the deployment of SMR/AMR technologies.

- Spectrum of adaptation maturity: Technology-neutral frameworks in countries such as France and Belgium can accommodate SMRs/AMRs through guidance and project-specific conditions. Finland and Sweden are actively updating their systems for new nuclear projects, while Estonia is building an entirely new legislative architecture. No single regulatory pathway will suit all Member States.

- Back-end credibility as a licensing prerequisite: Clearly defined waste management responsibility and a credible disposal pathway are important enablers for SMR/AMR deployment. Countries with advanced final disposal programmes at the time of writing, e.g., France (Cigéo construction licence submitted), Finland (ONKALO® under operational licence review), and Sweden (SKB construction licence granted in 2022) are perhaps best positioned. The absence of a final disposal solution may introduce additional complexity for deployment.

- Solutions for newcomers or programmes of limited scale: Multinational repository arrangements may offer a more proportionate pathway than dedicated national infrastructure, though realising this option would first require a shift in the host country's policy on waste imports for disposal and in user countries' policies on waste exports, both of which would then necessitate amendment of relevant legal acts. Deep borehole disposal may offer an alternative national pathway for countries with limited waste inventories, though further technical and regulatory development is required.

- Multinational and shared solutions for SIMS: Multinational repository arrangements or deep borehole disposal may offer more proportionate pathways, though realising these options would first require a shift in national policy on waste imports for disposal, which in most cases would then necessitate amendment of relevant legal acts.

- Consent-based siting: Involving well-informed and willing host communities has proven essential for sustaining public trust and political support for both reactor and repository siting and is recommended as a cornerstone of deployment strategies.

- Regulatory resourcing: Regulatory bodies must be adequately resourced to manage multi-technology licensing in parallel with existing programmes, as simultaneous review of multiple novel reactor designs risks overwhelming national regulators that have not yet expanded their technical capacity.

2.2.4. Stakeholder engagement

FORSAFF examined how stakeholder engagement can be structured and integrated into SMR/AMR waste management decision-making across the full project lifecycle. The principal finding is that engagement must begin early and be maintained throughout technical, regulatory, and policy processes; not treated as a downstream communication exercise.

Other key findings fall into three interconnected themes:

- Engagement allows technical assumptions about waste characterisation, treatment, transport, storage, disposal, and financing to be tested against regulatory, operational, and societal expectations before they become embedded in programme commitments, thereby reducing the risk of late-stage delays and rework.

- Engagement provides a framework for transparent discussion of the uncertainties associated with SMR/AMR waste streams, which may differ significantly from those of existing large light-water reactors, and their implications for safety, environmental protection, intergenerational fairness, and institutional responsibility.

- Engagement supports governance model development in distinct but related ways depending on deployment context. For LIMS, it is needed to assess whether existing waste acceptance criteria, transport systems, storage capacities, and disposal safety cases remain valid, while for SIMS it is essential for strategic preparedness, helping to clarify national capacities and open dialogue on shared or multinational solutions.

3. Expectations

A public FORSAFF webinar brought together a broad range of stakeholders, waste management organisations, regulators, technical support organisations, industry representatives, researchers, and civil society, to articulate their expectations of ongoing and future SMR/AMR waste management initiatives. Participants were drawn from across Europe and beyond, including LIMS and SIMS, nuclear newcomer countries, and international bodies, and included backgrounds in consultancy, R&D, and international governance.

Discussions focused on four questions: what stakeholders want and need over 5- and 10-year horizons; which project outputs are most useful; what waste management challenges remain; and how project initiatives can better support decision-making. Five clear and mutually reinforcing themes emerged.

Waste characterisation data is the most urgent near-term need. The single most consistent message was the need for reliable, experimentally grounded waste inventory and characterisation data:

- Stakeholders from waste management organisations, regulatory bodies, and technical support organisations stressed that current data for most AMR designs remains too vague, largely model-derived rather than experimentally validated, to support credible waste acceptance assessments, disposability demonstrations, or licensing decisions. This was expressed as an immediate practical constraint, not a long-term aspiration: without this data, waste management organisations cannot confirm that facilities can accept new waste types, and regulators cannot establish appropriate criteria.

- The disposability of novel materials, including irradiated graphite, spent TRISO fuel, molten salt residues, and liquid metal coolant wastes, was specifically cited as requiring dedicated evidence.

- Stakeholders also noted that vendor optimism about waste management implications should not substitute for independent, verifiable data, and that meaningful design-stage engagement with developers is needed to obtain the design-specific details on which disposability assessments depend.

- For LW-SMRs, where waste streams are qualitatively closer to existing LWR experience, a larger body of applicable knowledge already exists, making the near-term data gap less acute than for AMRs.

Back-end implications are being systematically underweighted in deployment planning. A recurring concern was that the backend of the SMR/AMR fuel cycle is being neglected in commercial and policy discourse:

- Stakeholders observed that reactor vendors tend to be optimistic about waste management implications, that deployment discussions are frequently driven by energy security and affordability rather than lifecycle considerations, and that back-end costs are often excluded from cost transparency.

- The cost differential between surface-level waste management activities and deep geological repository disposal can be very large, and this gap has systematic implications for the economic viability of SMR/AMR projects if not accounted for upfront.

- Current deployment timelines for the 2030s are too tight if waste management, decommissioning, and disposal issues are not addressed in parallel, and that optimisation opportunities will be lost if these matters are postponed.

Useful outputs are those that directly support decisions, not those that remain academic. There are clear distinctions between research outputs that advance knowledge and those that translate into decision support:

- Publicly accessible waste inventory benchmark cases and assessment approaches for non-LWR designs, quantitative data on repository compatibility and techno-economic performance, practical implementation roadmaps and deployment scenarios relevant to specific national or regional contexts and evidence from demonstration projects and pilot facilities that theoretical concepts can function under real operating conditions were identified as valuable project outputs.

- Decision-makers should have an understanding of the full infrastructure picture, not just waste characterisation, but the storage, transport, regulatory, and financing architecture that surrounds it.

- Alignment both of regulatory frameworks across EU Member States and of design standards such as fuel specifications was identified as a valuable enabler that projects could actively support.

Newcomer countries face qualitatively different challenges that require dedicated attention. The position of countries without established nuclear infrastructure was addressed:

- SMR/AMR deployment decisions in these countries are being shaped by national energy strategies and political considerations often with limited engagement of waste management expertise at the strategic level.

- Clear allocation of legal and financial responsibility for nuclear waste across its full lifecycle, including the respective obligations of reactor operators, vendors, and the state, and the conditions under which fuel or module return to the vendor's country of origin may be applicable, together with the governance implications of a shift from large public operators to smaller, potentially private producers, and the disproportionate burden that geological disposal costs could represent for countries deploying only a small number of units, were highlighted as key concerns.

- Newcomer contexts require tailored support, rather than generic outputs, in the form of guidance directly applicable to national decision-making on regulation, waste ownership, infrastructure planning, and financing.

Long-term knowledge continuity and governance stability are prerequisites for programme success. Concerns regarding the conditions under which SMR/AMR programmes can sustain progress over the long-time horizons required:

- Smooth, deliberate knowledge transfer between countries, between organisations, and between generations of practitioners is essential for a field where the back-end challenges of technologies deployed today will be resolved in the future. This speaks to the need for long-term, institutionalised R&D programmes rather than project-by-project investment, and for active knowledge management that continues over programme transitions.

- The reversibility of governance and decision-making processes for waste disposal is an inherent tension. While policy flexibility may be necessary and socially valued, frequent or unpredictable shifts in waste management policy create uncertainty for vendors and developers that can impede investment and programme delivery. Providing stable, predictable policy frameworks including state support and clear allocation of long-term responsibilities was identified as important for securing the sustained industry engagement on which deployment depends.

4. Evaluation of Impact

FORSAFF was designed as a Strategic Study work package, with its scope defined in relation to the EURAD-2 Strategic Research Agenda (SRA) [3]. This section assesses how the drivers and expected impact topics identified at the outset of the work package were addressed and considers the extent to which the programme has delivered on its intended contribution to the SRA's overarching objective: the safe, sustainable, and socially responsible management of radioactive waste in Europe, now and in the future.

4.1 Alignment with the EURAD-2 Strategic Research Agenda

The FORSAFF work package was mapped at inception against three SRA themes and associated roadmap domains of primary relevance. The table below summarises these drivers, describes how FORSAFF addressed them, and reflects on the degree to which the intended contribution was achieved.

SRA Theme / Roadmap Domain	Selection Basis	How addressed in FORSAFF	Assessment
Theme 1: Programme Management and Implementation Roadmap Domain 1.5.1: Integrated waste management routes and strategic options	Identified as a primary driver. SMR/AMR deployment creates a need for new or adapted waste management routes to be	FORSAFF Task 4 synthesised cross-cutting strategic lessons, including early integration of waste management into reactor design, infrastructure proportionality for SIMS, the role of deep geological	Fully addressed. The FORSAFF White Paper (D4.3) and Green Paper (D4.2) together constitute a comprehensive strategic analysis of integrated waste management routes for all four reactor technology groups. Near-

SRA Theme / Roadmap Domain	Selection Basis	How addressed in FORSAFF	Assessment
	integrated into national programmes.	disposal as the reference endpoint, and the strategic implications of distributed modular deployment. FORSAFF Task 5 mapped existing national and EU regulatory frameworks and identified gaps requiring adaptation. Together these tasks directly address the challenge of integrating new waste streams into national disposal programmes.	and longer-term R&D priorities are mapped explicitly to deployment schedules.
Theme 2: Predisposal Roadmap Domains 2.1.1: Inventory; 2.1.2: Waste Characterisation	Identified as a primary driver. Defining SMR/AMR waste streams and characterising new fuels and materials is a prerequisite for all downstream management decisions.	FORSAFF Task 3 developed a structured methodology for waste stream identification and inventory profiling across LW-SMRs, HTGRs, LMFRs, and MSRs, covering operational waste, activated materials, spent fuel, and reprocessing streams. Material-specific characterisation data requirements and knowledge gaps were catalogued systematically for each technology group.	Substantially addressed, with important caveats. The characterisation methodology and gap analysis are comprehensive. However, as explicitly acknowledged in D4.3, operational data from most SMR/AMR designs is absent or not publicly available, meaning that current inventories remain model-derived. The programme correctly identifies this as the most urgent near-term R&D priority rather than treating it as a resolved issue.
Theme 3: Engineered Barrier Systems Roadmap Domain 3.1.1: Spent Nuclear Fuel (SNF) - safety and risk assessment of SNF management and disposal operations, including new upcoming designs	Identified as a primary driver. Novel SNF forms from SMRs/AMRs require adapted safety assessment approaches for storage, transport, and disposal.	FORSAFF Tasks 3 and 4 identified the specific properties of SNF from each reactor family that create challenges for existing safety cases: higher burnup LW-SMR fuels affecting cask qualification and repository design; TRISO fuel's physico-chemical stability complicating reprocessing and creating	Addressed at the level of gap identification and R&D prioritisation. Full safety case development lies beyond the scope of a strategic study WP; FORSAFF scopes its contribution as providing the evidence base and R&D roadmap to support future safety case work by

SRA Theme / Roadmap Domain	Selection Basis	How addressed in FORSAFF	Assessment
		uncertainties for EBS compatibility; LMFR high-plutonium fuels raising criticality concerns; MSR salt-based fuels lacking validated disposal pathways. R&D actions targeting these gaps are compiled in the FORSAFF White Paper Appendix C.	WMOs, TSOs, and regulators.
Cross-cutting: Stakeholder Engagement and Social Dimensions	Identified as a required component of responsible deployment, including governance, transparency, and co-production of waste management scenarios.	FORSAFF Task 6 developed and delivered two multiparty dialogue seminars. These addressed uncertainties in waste characterisation and management, governance frameworks, and scenario-based planning for newcomer countries and SIMS. The FORSAFF webinar extended this engagement to a broader international community, identifying five cross-cutting stakeholder expectation themes directly relevant to future R&D and policy priorities.	Fully addressed. The seminar methodology and outcomes (Milestones MS41 and MS64) constitute records of community engagement. The FORSAFF webinar produced primary stakeholder evidence not previously available.

5. Education and Training

FORSAFF has produced a range of outputs that can serve as educational and training resources for the broader radioactive waste management community, with particular relevance to organisations and practitioners engaging with SMR/AMR waste management.

The FORSAFF Green Paper (D4.2) and White Paper (D4.3) together constitute comprehensive reference documents covering the technical, regulatory, and societal dimensions of SMR/AMR waste management across four reactor technology families [1,2]. Their structure, progressing from waste stream characterisation through management strategy, regulatory frameworks, and stakeholder engagement, follows a logical learning pathway suited to readers approaching the subject from any professional background. Both documents are publicly available and aligned with the knowledge management goals of the EURAD Strategic Research Agenda [3], supporting capacity building and knowledge transfer among Member States at different stages of nuclear programme development.

Two multiparty dialogue seminars were designed and delivered as reusable training resources for the EURAD community. Each seminar combined expert presentations, structured facilitated dialogue, and participatory methods specifically adapted to SMR/AMR radioactive waste management. Seminar 1 introduced the landscape of stakeholder concerns, policy and regulatory issues, and social-science insights, and piloted the Pathway Evaluation Process (PEP) serious-game methodology through scenario-based discussions covering SMR waste in newcomer countries, urban SMR siting, waste characterisation uncertainties, and vendor bankruptcy. Seminar 2 deepened and extended this work with a stronger focus on LW-SMRs, Small Inventory Member States, national programme case examples, and international RWM perspectives, including direct input to the validation of White Paper findings. The full seminar packages comprising facilitator guides, presentation materials, PEP scenario sets, and structured discussion outcomes are available as reusable resources for future EURAD-2 workshops, national training activities, and capacity-building exercises.

The FORSAFF webinar provided a further educational dimension by bringing together practitioners from waste management organisations, regulatory bodies, technical support organisations, research institutions, industry, and civil society across Europe and beyond. The structured discussions generated a primary record of current stakeholder knowledge, expectations, and concerns that complements the technical literature and can inform future training design. The webinar findings, summarised in the Expectations section of this deliverable, highlight in particular the need to build decision-makers' understanding of the full back-end infrastructure picture, not only waste characterisation, but the treatment, storage, transport, disposal, regulatory, financing, and governance architecture surrounding it, an insight that should inform the design of future educational initiatives.

6. Conclusion

FORSAFF has established the technical, strategic, regulatory, and societal foundations needed to support responsible SMR/AMR radioactive waste management in Europe. Its outputs confirm that the waste management implications of these technologies are both substantial and manageable, but only if addressed proactively, in parallel with reactor development, and with the full lifecycle in view. The window for integrated, optimised planning is open now. Several concrete research needs and recommendations follow from the work.

The most urgent near-term research need is experimentally grounded waste characterisation data for SMR/AMR designs. Current inventory assessments remain largely model-derived, and this gap is a concrete practical constraint for waste management organisations, regulators, and developers alike. Priority should be given to obtaining design-specific data from reactor vendors and initiating targeted experimental programmes, beginning with LW-SMRs where deployment timelines are shortest, and extending progressively to HTGRs, LMFRs, and MSRs as those programmes mature. This work should explicitly address material impurity content, activation product inventories, and the physico-chemical properties of novel waste forms, as these are the parameters on which disposability assessments and waste acceptance criteria depend. It should also draw systematically on the body of real-world operational and decommissioning data that already exists for predecessor technologies, including coolant removal and partial decommissioning experience from sodium-cooled fast reactors such as Experimental Breeder Reactor II, and graphite and TRISO waste stream data from HTGR programmes such as Arbeitsgemeinschaft Versuchsreaktor and Fort St. Vrain, as these sources can provide empirical grounding for modelling assumptions and help narrow uncertainties before new experimental programmes are required.

While waste management legislation is generally technology-neutral and broadly applicable, no Member State has yet developed SMR/AMR-specific licensing guidance that adequately addresses the novel waste streams these technologies will generate, and the gap between front-end reactor development momentum and back-end regulatory readiness is widening. Regulatory bodies should be supported and adequately resourced to begin this adaptation now, focusing initially on LW-SMR waste streams where the knowledge base is most mature. At the EU level, greater consistency in the regulatory treatment of novel SMR/AMR waste streams, including waste classification approaches and the conditions governing cross-border transfer for disposal. would reduce fragmentation and lower barriers to the cooperative arrangements that newcomers or programmes of limited scale will likely need.

Backend solutions for nuclear newcomer countries and limited scale programmes require dedicated development. DBD and multinational repository arrangements are attractive for countries that will not deploy large reactor fleets, but both require further technical development, regulatory frameworks, and in most cases national legislative change to permit cross-border waste transfer for disposal. Clarifying waste ownership and long-term liability arrangements, including the conditions under which vendor take-back or fuel return schemes may be applicable, is a priority for countries making technology selection decisions now.

Stakeholder engagement frameworks tailored to SMR/AMR-specific waste management challenges should be developed and institutionalised. Engagement should be structured around the actual uncertainties these technologies introduce, novel waste forms, unresolved disposal pathways, distributed deployment implications, and long-term governance questions, rather than adapted from frameworks designed for conventional large reactor programmes. Consent-based siting, transparent communication of uncertainty, and participatory scenario development should be embedded as standard practice in both reactor deployment planning and repository programme development.

Finally, the knowledge generated by FORSAFF should be sustained and extended in future EURAD cycles. The R&D priorities identified in the White Paper spanning waste characterisation, treatment and conditioning, storage and transport, regulatory adaptation, and stakeholder governance constitute a coherent programme of work that no single organisation or Member State can address alone. Coordinated European investment, aligned with the EURAD Strategic Research Agenda and complementary to the work of the EU SMR Industrial Alliance offers the most efficient path to closing the knowledge gaps that currently stand between SMR/AMR deployment ambitions and the credible, safe, and socially accepted waste management programmes they require.

7. References

[1] Saturnin, A. et al. (2026). Towards Safe and Sustainable Deployment of LW-SMRs and AMRs: Identifying Knowledge Gaps in Waste Management. EURAD-2 Deliverable D4.3.

[2] Garcia, D. et al. (2025). Guidance on SMR Implementation and Deployment Needs from the Back End of the Fuel Cycle Perspective (Green Paper). EURAD-2 Deliverable D4.2.

[3] EURAD Bureau (2023). Strategic Research and Knowledge Management Agenda.