SMALL AND ADVANCED MODULAR REACTOR WASTE GENERATION AND MANAGEMENT IN EURAD-2 WP4 FORSAFF

Timothy Schatz, VTT

Co-funded by the European Union under Grant Agreement n° 101166718

EURAD 2

European Partnership for Radioactive Waste Management under EURATOM

- Continuation of the efforts of EURAD and PREDIS. Key goals:

  - support EU Member States in developing and implementing national R&D programs for safe long-term radioactive waste management
  - develop and consolidate knowledge for the safe start of operation of DGRs for SNF, HLW, and other waste
  - maintain a knowledge management system that enhances transfer of knowledge between organisations, Member States and generations

- Founding documents:

  - Vision Document: overarching vision, goals, governing principles, scope, objectives.
  - Strategic Research Agenda: scientific and technical domains and shared knowledge management needs guiding collaborative R&D priorities.
  - Roadmap: framework linking EURAD-2's research activities to clear milestones across the different phases of a generic radioactive waste management programme.

EURAD 2 STRUCTURE

- Participants: 51 beneficiary organizations (WMOs, TSOs, and REs) + 69 affiliated entities from 21 EU Member States + 22 associated partners
- Duration & Budget: 5 years (October 2024 – September 2029), ~34.4 M EUR (co-funded EC/MS)
- Work Packages:

Research & Development
scientific research and technological innovation

Strategic Studies
short-term, cross-cutting collaborative studies on complex or emerging issues

Knowledge Management
knowledge preservation and transfer between organizations, Member States and generations

EURAD 2 WORK PACKAGES

Theme
Research & Development
Strategic Study

WP1 Progamme Management Office - PMO

Programme Management

WP3 Alternative RWM strategies

WP4 RWM for SMRs and future fuels

Predisposal

WP5 Innovative characterisation techniques for large volumes

WP6 Sustainable treatment and immobilisation of challenging wastes

WP7 Waste matrices: long term performance

Engineered Barrier Systems

WP8 Release of safety relevant RN from SNF

WPG Innovative containers/ canisters materials

WP10 Hydr-Mech-Chem evolution of bentonite

WP13 HLW repository optimization including closure

Geoscience

WP11 Impact of climate change on NWM

WP12 Radionuclide mobility under perturbed conditions

Optimisation

WP14 Near surface disposal optimisation

WP15 Digital twins

WP16 High-fidelity numerical simulations of coupled processes

Safety Case

WP17 Criticality safety

WP18 Thermodynamic database

WP2 Knowledge Management - KM

FORSAFF OVERVIEW

Type

Strategic Study

Partners

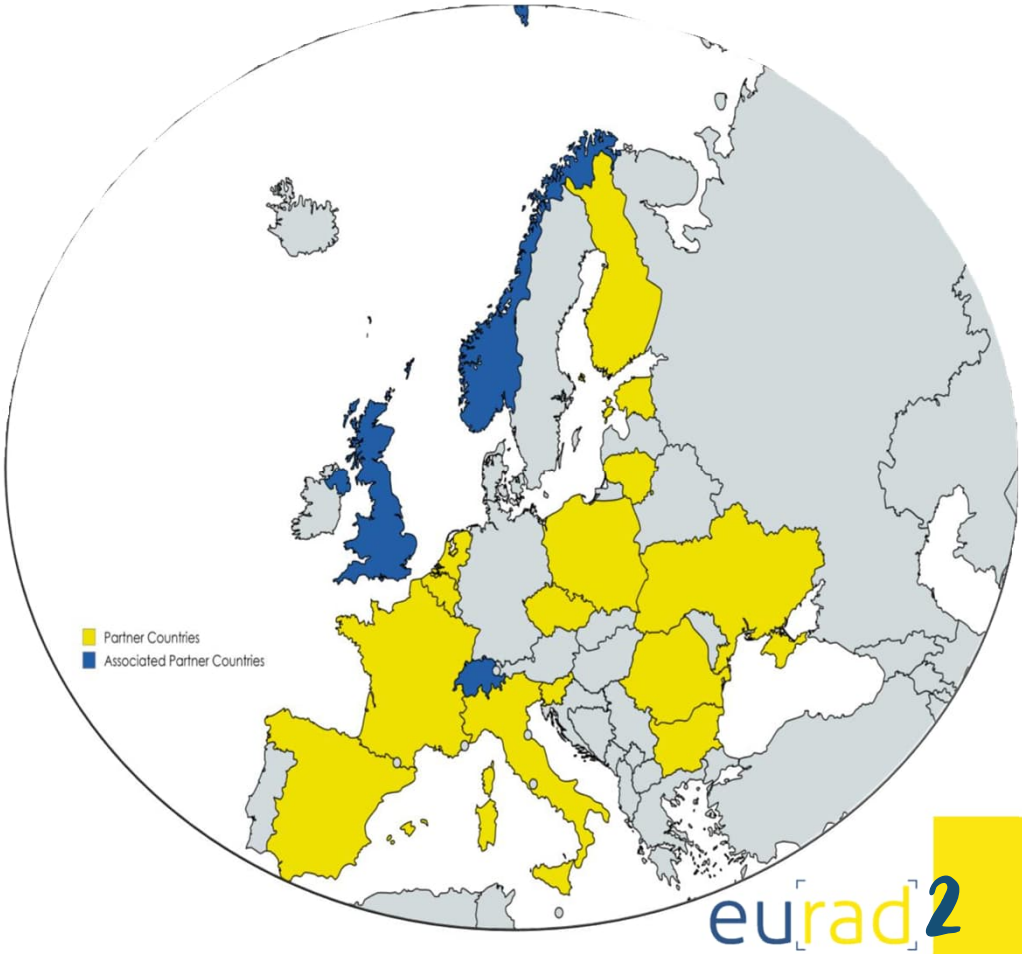
- 25 EC-funded partners
  from 14 countries
- 4 Non-EU associated partners
  from Norway, United Kingdom and Switzerland
- Effort ~ 10% WMOs, 60% REs and 30% TSOs

Duration

24 months (Kick-off: October 2024)

Resources

~ 1 M EUR



FORSAFF PARTNERS

ASSOCIATED PARTNERS

WP4 WASTE MANAGEMENT FOR SMRS AND FUTURE FUELS (FORSAFF) - OBJECTIVES

The primary aim of FORSAFF is to identify knowledge gaps and provide recommendations for future research in SMR waste generation and management.

- Evaluate SMR waste inventories, including those related to the back end of the fuel cycle, and assess predisposal approaches and development needs in terms of anticipated waste generation across reactor designs and operating conditions.
- Review management routes for SMR wastes over a range of needs, considering both conventional as well as more recent concepts.
- Examine national policies and regulatory frameworks in the context of SMR fuel cycle and waste management as well as stakeholder perceptions and concerns.

Continue as a second wave R&D proposal over the last three years of EURAD-2

FORSAFF TASK BREAKDOWN (TASKS 1 AND 2)

Task 1 – Project Coordination

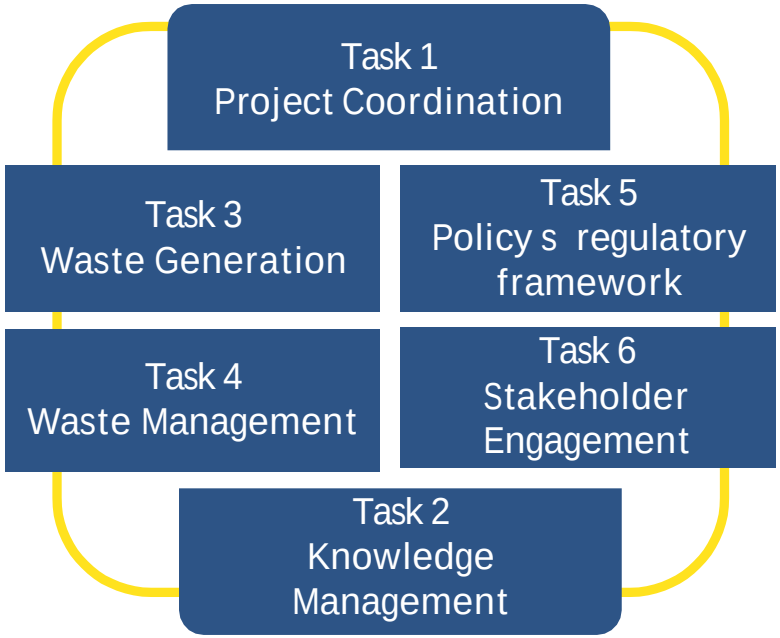
Objective: Overall management, scientific/technical coordination, monitoring and reviewing progress and outputs and dissemination/outreach of results

Subtasks: 1.1 Coordination
1.2 Dissemination
1.3 Quality Control

Task 2 – Knowledge Management

Objective: Capture knowledge relevant to the SRA topic and to contribute to knowledge transfer to the EURAD-2 community and beyond through the EURAD-2 KM programme.

Subtasks: 2.1 Knowledge Capture,
2.2 Knowledge transfer



FORSAFF TASK BREAKDOWN (TASKS 3 AND 4)

Task 3 – Waste Generation

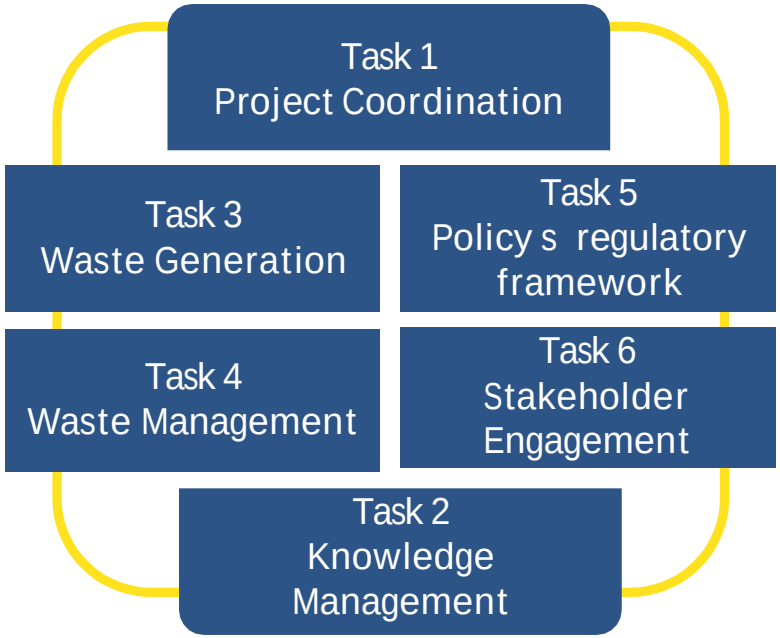
Objective: Define SMR waste inventories (including SNF or waste generated after reprocessing) and main physico-chemical-radiological properties.

Subtasks: 3.1 Methodology for waste stream identification
3.2 Waste inventory and main characteristics
3.3 Spent fuel inventory and management

Task 4 – Waste Management

Objective: Assess predisposal approaches and development needs in terms of anticipated waste generation across SMR designs and operating conditions including characterisation. Explore spent fuel reprocessing options. Examine disposal routes for SMR wastes across a range of deployment needs, disposability issues and waste acceptance criteria.

Subtasks: 4.1 SMR waste predisposal and disposal
4.2 SMR spent fuel reprocessing
4.3 Characterisation techniques and modelling methods for SMR waste



FORSAFF TASK BREAKDOWN (TASKS 5 AND 6)

Task 5 – Policy and Regulatory Framework

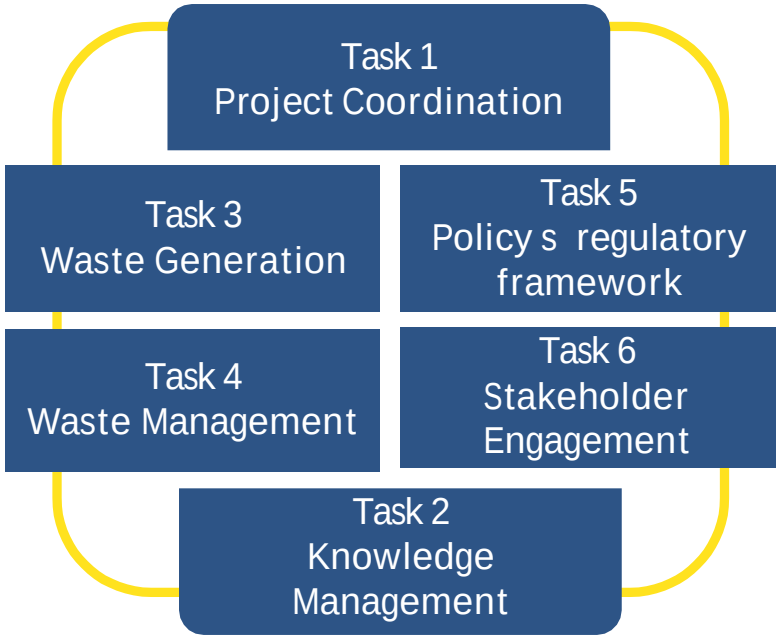
Objective: Determine needs to adjust national policies and regulatory frameworks to support SMR fuel cycle and waste management.

Subtasks: 5.1 Establish policy and regulatory framework insight,
5.2 Adequacy of existing policies

Task 6 – Stakeholder Engagement

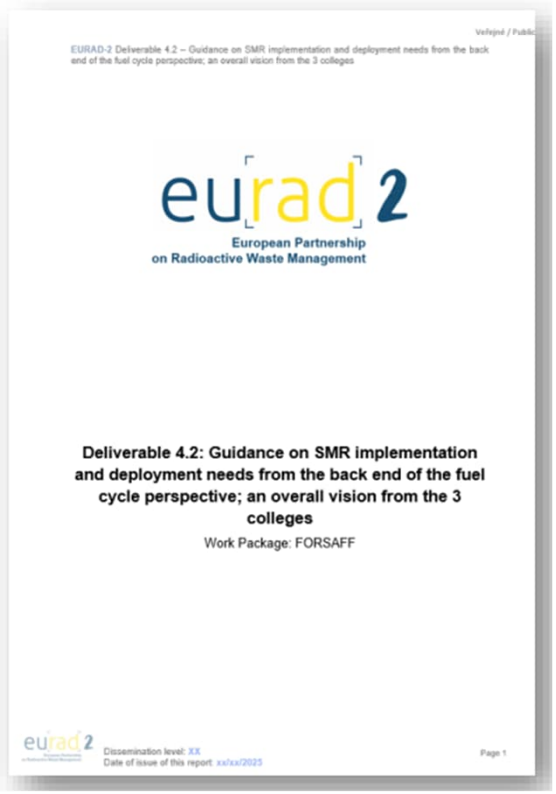
Objective: Identify stakeholder perceptions and concerns related to SMR waste management and develop recommendations for transparent information exchange and dialogue.

Subtasks: 6.1 Stakeholder perceptions and concerns
6.2 Multiparty dialogue seminars



DELIVERABLE 4.2 - GUIDANCE ON SMR IMPLEMENTATION AND DEPLOYMENT NEEDS FROM THE BACK END OF THE FUEL CYCLE PERSPECTIVE

- Green Paper
  - What do we think should be done?
    - Challenges
    - Gaps
    - Uncertainties



DELIVERABLE 4.4 - IDENTIFICATION OF KNOWLEDGE GAPS FOR FUTURE R&D ACTIVITIES

- White Paper
  - How do we think it should be done?
    - relative to addressing the challenges, gaps and uncertainties highlighted in FORSAFF Green Paper
- *in development*

SPENT FUEL AND WASTE CHARACTERIZATION

Radionuclide inventory and source-term calculations

- Determine the inventory of radionuclides in SMR/AMR spent-fuel under various burn-ups, enrichments and power densities. The work requires full-core 3-D numerical calculations, validation with experimental data and improved nuclear-data libraries. Efforts also include cross-verification of codes and uncertainty propagation studies.

Impurity and structural material effects

- Study the influence of impurities in SMR fuel, cladding and reactor structures on the activation products in spent-fuel. Similar work is needed to understand the effect of new cladding alloys and accident-tolerant fuels on radionuclide inventory.

TRISO fuel and irradiated graphite

- Develop methods to quantify radionuclide inventory within TRISO kernels and graphite layers, assess PyC/SiC integrity and determine contamination heterogeneity in bulk graphite. Complementary studies to optimise dissolution techniques for TRISO fuels using molten KOH or HF/HNO_3 and perform micro-deposition/ alpha-spectrometry for trace-level isotopic analysis.

Advanced fuels and coolants

- Characterise advanced fuels by microstructural and chemical analyses; determine long-term stability under air ingress, humidity and heat loads; analyse coolant activation products (e.g., Po-210 in lead–bismuth coolants). Characterise halide-rich molten-salt waste to mitigate matrix effects and improve analytical accuracy.

FUEL TREATMENT AND REPROCESSING

Advanced separation techniques

- Develop actinide/lanthanide separation methods to enable partitioning and transmutation; optimise extraction of uranium and thorium from HTGR reprocessing and demonstrate the process at scale; adapt existing reprocessing plants for new SMR waste forms by predicting feed isotopic compositions.

On-line/off-line reprocessing of molten salt fuels

- Describe technologies for preparing fresh liquid fuel from spent LWR MOX fuel and implement on-line and off-line pyrochemical reprocessing of MSR Th-breeder and actinide-burner fuels.

Pyrochemical reprocessing of fast breeder fuels

- Develop dry pyrochemical technologies for sodium-cooled fast-breeder reactors (LMFBRs), including characterisation of resulting waste streams and immobilisation methods.

Access to TRISO kernels

- Further develop techniques (e.g., plasma-aided etching, molten-salt dissolution) to remove PyC and SiC coatings from TRISO particles and to manage volatile fission products and C-14 contaminated graphite.

PREDISPOSAL AND CONDITIONING

Immobilisation and encapsulation

- Develop cementitious matrices to immobilise TRISO particles and irradiated graphite while ensuring criticality safety and assessing chemical interactions between graphite and cement.

Pre-treatment of graphite

- Optimise steam-oxidation decontamination to reduce activity and enable reclassification of graphite waste; evaluate the need for pre-treatment and assess nuclide migration if graphite is disposed of without treatment.

Predisposal routes for sodium-coolant wastes

- Study conditioning of caustic NaOH solutions arising from sodium neutralisation, including sustainable matrices for direct conditioning and removal of Cs/Sr.

Management of chemo-toxic and volatile species

- Develop approaches for managing aggressive species (Cl, F, Na) in waste and trapping volatile fission products such as I, Te, Xe and Kr using sorbents.

Recycling

- Investigate technologies to recycle Pb, Cd, Bi and other metals used in advanced fuel cycles to reduce waste streams. Evaluate recycling Cl-37 in fuel salt waste to reduce enrichment costs and Cl-36 generation.

PACKAGING, STORAGE AND WASTE FORM DEVELOPMENT

Canister design and loading

- Investigate canister designs and loading strategies for LWR SMR spent fuel, including stacking short assemblies and assessing criticality.

Packaging materials and corrosion resistance

- Characterise and qualify materials for packaging irradiated graphite that resist galvanic corrosion; assess materials for packaging molten-salt waste and consider chemical conversion before disposal.

HTGR fuels and graphite

- Optimise interim storage and packaging of HTGR fuel pebbles and prismatic blocks to improve cask utilisation; develop disposal concepts that accommodate large volumes of irradiated graphite and manage H_2 and C-14 gas generation..

Spent fuel waste form development

- For MSR spent fuel, develop stable waste forms with low leach rates and experimentally demonstrate radionuclide containment; for liquid-metal fast-reactor fuel, develop waste forms that handle residual coolant and large volumes while ensuring criticality safety.

Stabilisation of used coolants

- Devise conditioning treatments to stabilise metallic coolants (Na, Pb, Bi) and demonstrate leach behaviour of toxic elements from conditioned waste forms.

DISPOSAL

Adaptation

- Assess whether existing deep geological repository concepts can accommodate SMR spent-fuel with non-standard geometries, higher heat loads and different isotopic compositions. Develop alternative disposal concepts (e.g., deep boreholes).

HALEU fuel

- Evaluate disposal of HALEU fuel, considering thermal limits, long-term degradation and post-closure criticality.

TRISO and graphite wastes

- Develop disposal concepts for bulk graphite from prismatic blocks and pebble-bed fuels, including co-disposal with fuel compacts or separate disposal.

Sodium coolant

- Investigate near-surface disposal of sodium-coolant processing effluent and compatibility with regulatory frameworks.

SYSTEM LEVEL

Siting

- Investigate whether multiple, dispersed disposal facilities are needed for widespread SMR deployment.

Safeguards and accounting

- Establish procedures for radioactive-material accounting in liquid-fueled reactors; develop data-recording systems and safeguards for pebble-bed fuels to comply with accountancy and disposal requirements.

Lack of data and conservative assumptions

- Recognise that the largest uncertainty in several topics is the lack of input data from vendors and design developers; conservative assumptions and sensitivity analyses should be used until proprietary data become available.

Governance and accountability

- Models for licensing new operators, ensuring long-term waste responsibility in decentralised SMR systems; addressing geopolitical implications of cross-border waste transport.

Societal

- Research on risk perception of decentralised SMRs and comparison with renewables. Development of transparency and dialogue frameworks to improve societal trust. Design of SMR-specific participation frameworks, comparative studies of public attitudes across EU member states, and analysis of cross-cultural engagement mechanisms.

REACTOR TECHNOLOGY AND DESIGN

Assessment of radioactive waste management and disposability technology readiness level (TRL) by reactor type (CoRWM, February 2024).

Preparation for the back-end fuel cycle of non-LWR SNF will require considerable time and effort.

LWR designs appear most likely for first deployments because they are more mature, with existing regulatory precedent (fuel, safety, operations).

R&D focused on waste management for LWR-type SMRs can have the highest near-term impact but should target specific challenges.

THANK YOU!