HTGR WASTE GENERATION AND MANAGEMENT IN THE FRAMEWORK OF EURAD-2 WP4 FORSAFF

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OUTLINE

1. EURAD 2
2. FORSAFF
3. WASTE STREAM
4. WASTE MANAGEMENT

eurad 2

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 LLW
  - 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

European Partnership for Radioactive Waste Management under EURATOM

- **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

WP9 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

FRAMEWORK

Type

Strategic study

Partners

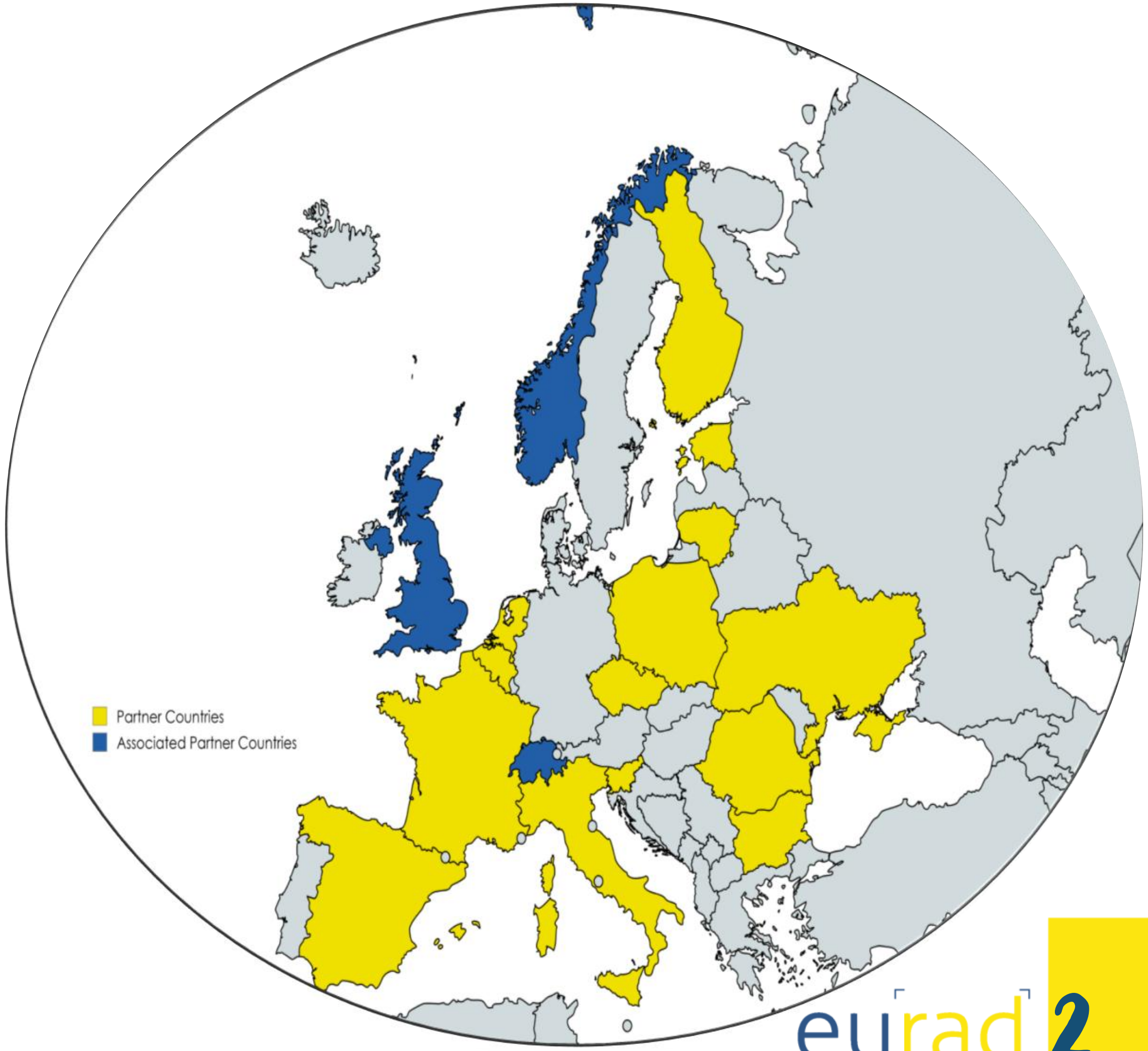
- 25 EC-funded partners
  from 14 countries
- 4 Non-EU associated partners
  from Norway, United Kingdom and Switzerland
- Effort ~ 10% WMOs, 60% Res and 30% TSOs

Duration

24 months (Kick-off: October 2024)

Resources

~ 1 M EUR



PARTNERS

ASSOCIATED PARTNERS

WP4 WASTE MANAGEMENT FOR SMRS AND FUTURE FUELS FORSAFF - OBJECTIVES

To develop understanding and provide recommendations on SMR deployment and supplier options with respect to nuclear waste 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

FORSAFF aims to identify knowledge gaps and provide recommendations for future research in SMR waste generation and management

FORSAFF TASK BREAKDOWN

Task 1 – Project Coordination

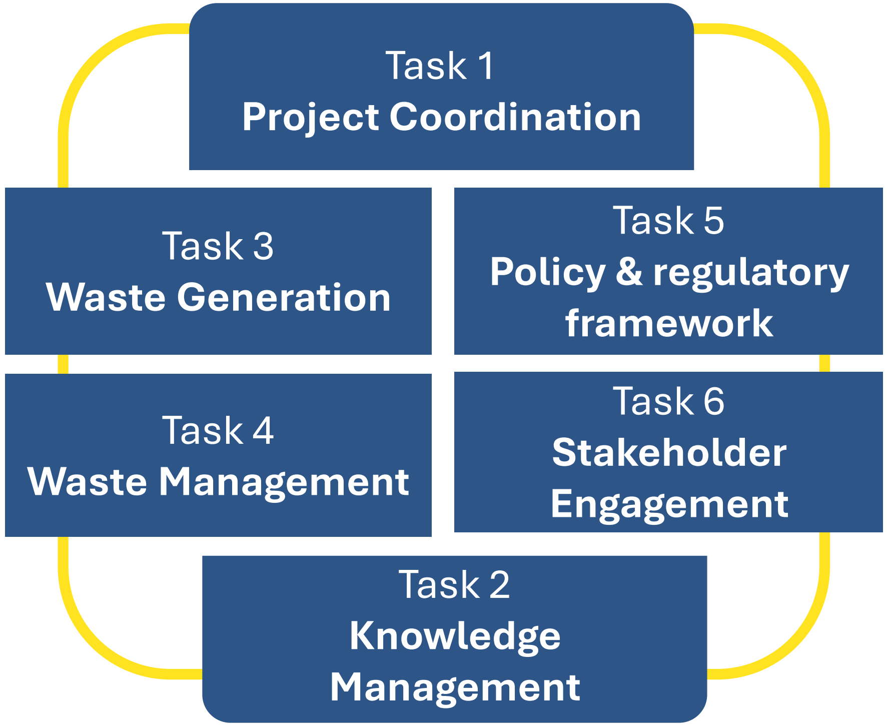
Objective: Overall management, scientific/technical coordination, monitoring and reviewing progress and outputs and dissemination/outreach of results

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

Task 3 – Waste generation

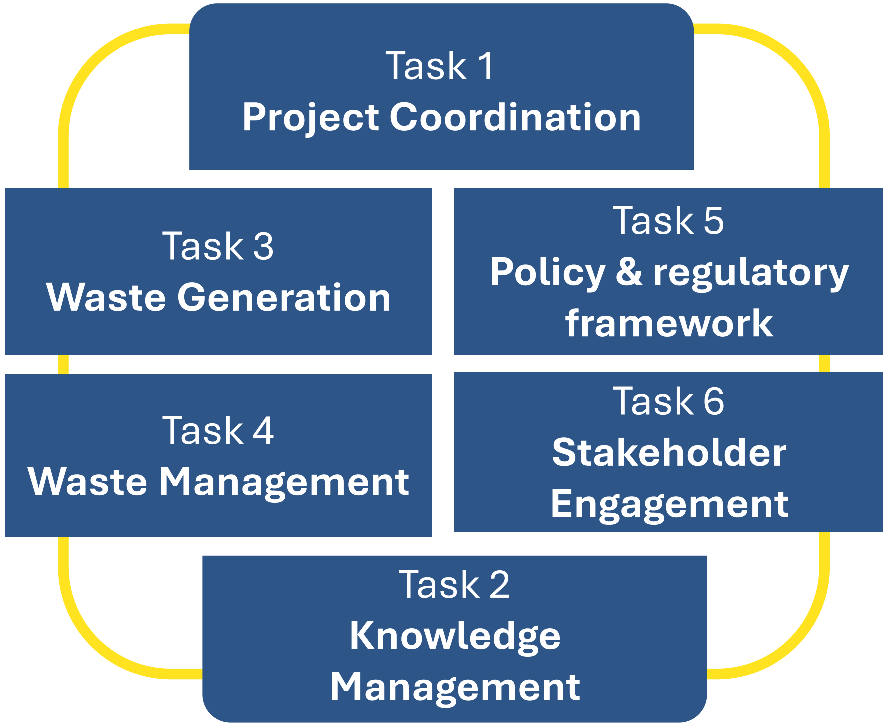
Objective: Define SMR waste inventories (including SNF or waste generated after reprocessing) and main physico-chemical-radiological properties.

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



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FORSAFF TASK BREAKDOWN

Task 5 – Policy and regulatory framework

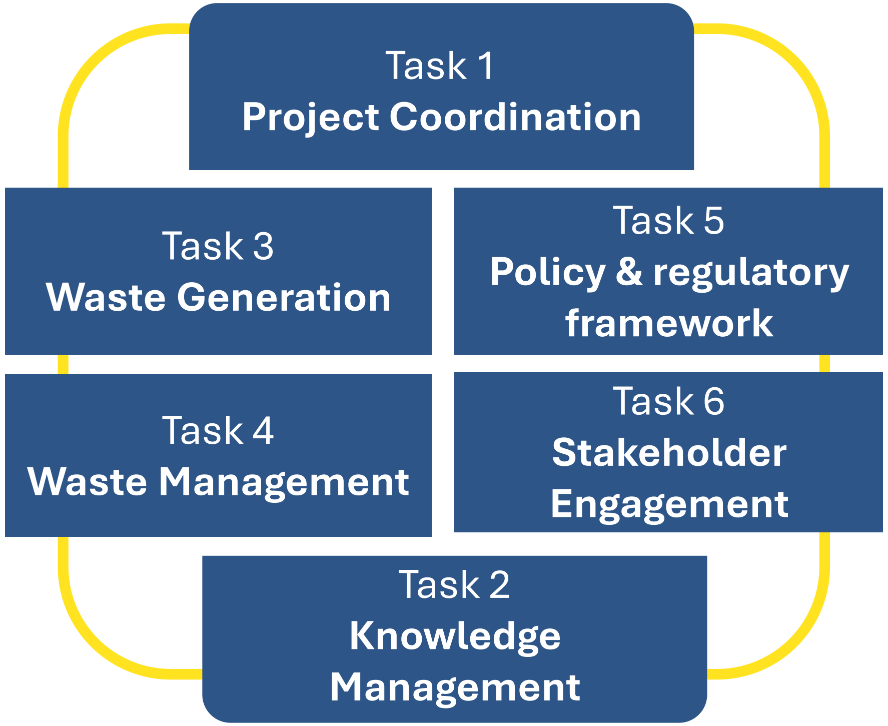
Objective: Determine needs to adjust national policies and regulatory frameworks to support SMR fuel cycle and waste management.

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

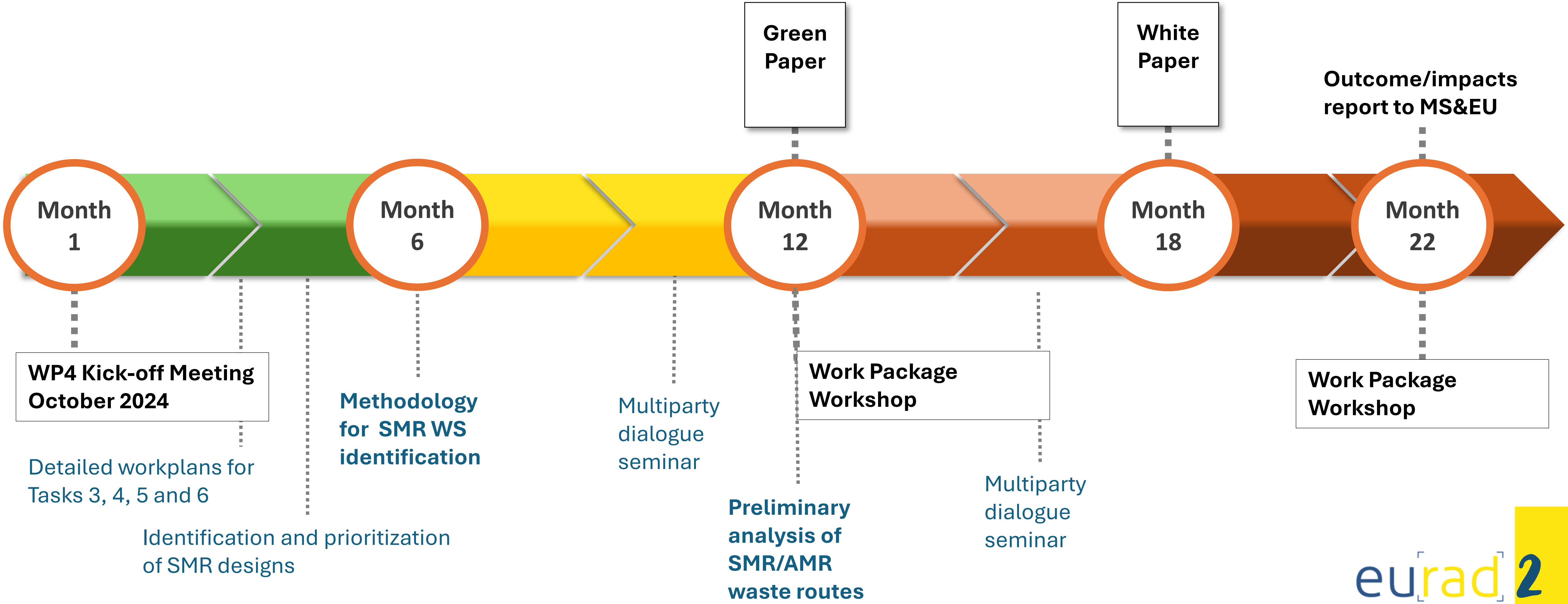
Task 6 – Stakeholder engagement

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



TIMELINE AND DELIVERABLES



FORSAFF TASK 3 – WASTE GENERATION

Lead: Polimi and CEA | **Partners:** Amphos 21, Andra, NRG, PSI, SIIEG, VTT, UTARTU

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

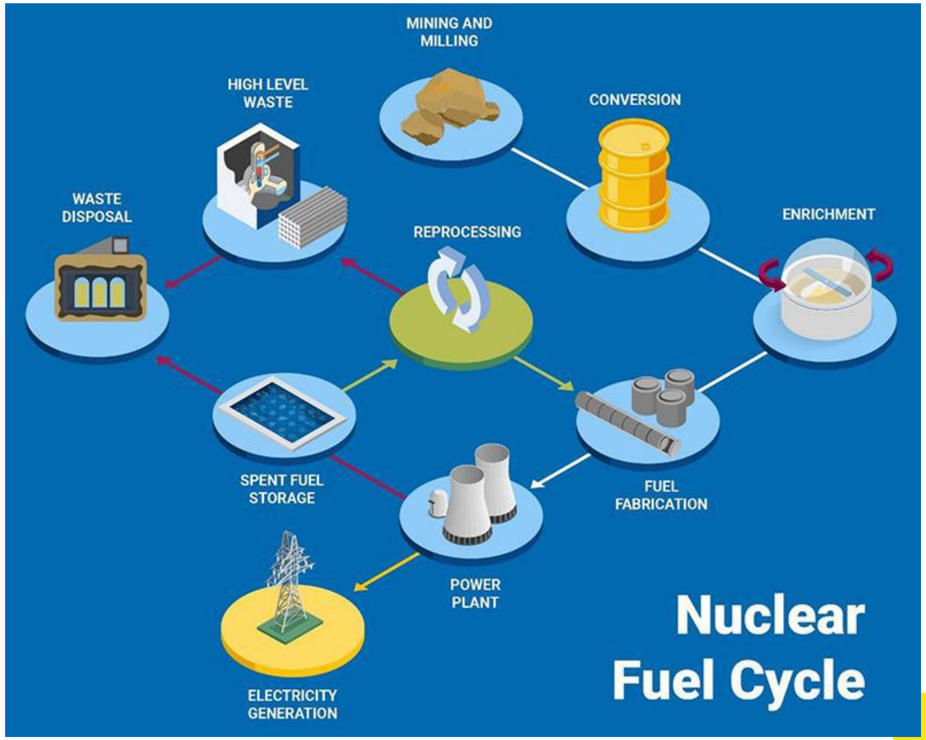
- **Subtask 3.1: Methodology for waste stream identification**
  Investigate and define overall waste inventories arising from SMRs; develop a common methodology for waste stream identification based on key waste descriptors (volume, mass, activity, etc.)
- **Subtask 3.2: Waste inventory and main characteristics**
  Identify the most significant properties impacting SMR waste management; discuss with SMR designers via formation of an End-user group
- **Subtask 3.3: Spent fuel inventory and management**
  Investigation of main characteristics of spent fuel and specific reprocessing waste generated from selected SMR designs; consider less conventional fuel types (thorium, HALEU, molten salts, TRISO)

FORSAFF TASK 3 – WASTE STREAM IDENTIFICATION

Safe and efective waste management strategies require knowledge of waste streams, their characteristics and magnitude

Identification of waste streams associated to SMR/AMR

- For four SMR/AMR technologies
  - Light Water Reactors
  - Lead cooled Fast Reactors
  - Molten Salt Reactors
  - **High Temperature Gas cooled Reactors**
- Looking at all life stages of the nuclear fuel cycle including reprocessing activities, and those of the reactor, from operation to decommissioning



FORSAFF TASK 3 – WASTE STREAM IDENTIFICATION

Fuel Cycle Front-end operations

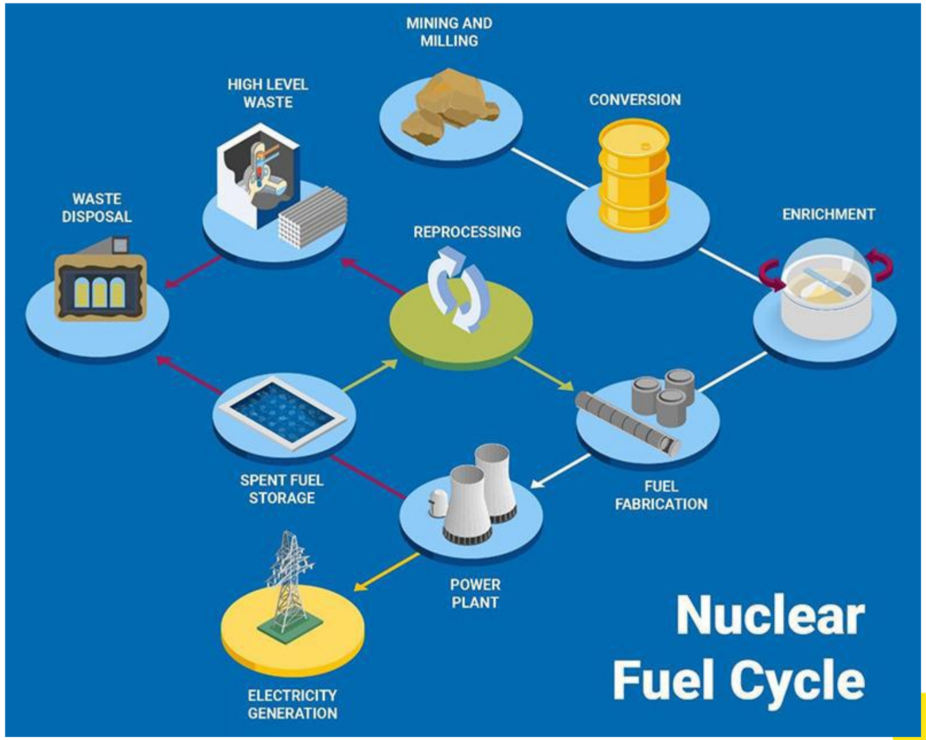
- Mining, milling, conversion enrichment, fuel fabrication… Waste streams for new fuel types?

Fuel Cycle Back-end operations (disposal and reprocessing)

- Physico-chemical properties: mass, volumes, activities, BU, thermal loads, inventories, unconventional hazardous mats.,
- Form, process wastes, reprocessing methods…

Reactor Operation and Decommissioning

- All source terms, peculiarities (flammability, toxicity…)
- Innovative and unusual materials → RN inventories



FORSAFF TASK 3 – WASTE STREAM IDENTIFICATION

Data Table per reactor family. Sections:

- General characteristics: description of the reactor technology and main technical aspects
- Nuclear fuel cycle: front-end and back-end, reprocessing or direct disposal
- Operational and decommissioning wastes

Three stage approach to WS characterisation

1. General characteristics
2. Qualitative and quantitative assessment of waste streams and their relevance, parameters, uncertainties
3. Uncertainty reduction and knowledge gap identification

GENERAL CHARACTERISTICS					
#	Parameter	Unit and description	Value	Uncert. H/M/L	Ref.
G1	Reactor technology				
G2	Type of energy produced	Electrical, thermal, mixed			
G3	Thermal power and power density	MWth, MWth/m^3			
G4	Electrical power	MWe			
G5	Neutron spectrum	Thermal, fast			
G6	Coolant	Type, chemical composition, volume, mass			
G7	Moderator	Type, chemical composition, volume, mass			
G8	Expected operational life	Years			
NUCLEAR FUEL CYCLE: FRONT-END, BACK-END AND ASSOCIATED WASTE					
#	Parameter	Unit and description	Value	Uncert. H/M/L	Ref.
F1	Fuel type and chemical composition				
F2	Fuel properties	Liquid/solid in normal conditions; arrangement (assembly/fuel			

FORSAFF TASK 3 – HTGRS GENERAL CHARACTERISTICS

General Table

- HTGRs: Pebble Bed and Prismatic Blocks
- Electricity and heat production
- Thermal and electric power flexibility depending on the model and application, from micro-modular to large HTGR concepts (up to 1,200 MWth, 300 MWe)
- Thermal neutron spectrum
- Coolant: high purity Helium gas
- Moderator: solid graphite
- Expected operational life: 20-60 years

Parameter	Unit and description	Value
Reactor model		High-Temperature Gas-Cooled Reactor (HTGR) (two configurations: pebble bed and prismatic block)
Type of energy produced	Electrical, thermal, mixed	Electricity, thermal, mixed
Thermal power and power density	MWth, MWth/m^3	Thermal power: < 200 MWth (exp. and micro-modular designs); < 600 MWth (modular designs); < 1250 MWth (large HTGR concepts) Power densities: 2-14 MWth/m^3
Electrical power	MWe	up to 300 MWe (per unit)
Neutron spectrum	Thermal, fast	Thermal
Coolant	Type, chemical composition, volume, mass	Gas, helium (>99.99 %), 10-30 m^3, ~50-200 kg (depending on core type)
Moderator	Type, chemical composition, volume, mass	Solid, graphite (pure carbon), ~50-150 m^3 (depending on core type),
Expected operational life	Years	20-60

FORSAFF TASK 3 – HTGRS ONGOING WORK

Fuel cycle – front end

- **Mining & Milling**: Possible waste streams are not SMR specific and depending on fuel composition: Uranium / Thorium / Plutonium from reprocessing (UOX, MOX…)
- **Fuel manufacturing:** process and operating waste (filters, glove boxes, equipment …)
- **Long-lived or specific RN:** depending on fuel composition (U, Pu, Th…)

Fuel cycle back-end (direct disposal option)

- **Long-lived or specific RN:** long-lived fission products (Cs, I, Ag, Sr, Te), long-lived and/or mobile activation products (C-14, Cl-36), mechanical stressors (T, C-14, Kr-85)

Fuel cycle back-end (reprocessing option)

- **Waste after processing waste:** An, FPs in nitric solution, activated SiC, carbonaceous waste, graphite structural waste.
- **Process waste**: induced waste, depending on equipment and tools

FORSAFF TASK 3 – HTGRS ONGOING WORK

Operational waste

- **Components:** Helium purification systems, air filters, housekeeping waste, secondary circuit water filtration resins, conventional process waste, instrumentation and controls
- **Long-lived RN:** Graphite (Cl-36, C-14, H-3) and irradiated/contaminated steel components (Co60, Ni-63, Ni-59, Mo-93, Tc-99, Nb-94)

Decommissioning waste

- **Contaminated materials and decontamination wastes**: graphite, activated and contaminated metals, concrete (Ca-41).

FORSAFF TASK 4 – WASTE MANAGEMENT

Lead: Amphos 21 and Andra | **Partners:** CEA, CIEMAT, CVR, GSL, IFE, INCT, LEI, NWS, POLIMI, TVO, PSI, RATEN, SCKCEN, SSTCNRS, SURO, VTT, UTARTU

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.

- **Subtask 4.1: SMR waste predisposal and disposal**
  Investigate predisposal and disposal management options for SMR wastes; identify pre-disposal / disposal route needs.
- **Subtask 4.2: SMR spent fuel reprocessing**
  Assess current reprocessing technologies with respect to SMR SNFs; identify reprocessing needs.
- **Subtask 4.3: Characterisation techniques and modelling methods for SMR waste**
  Evaluate waste characterisation methods and modelling tools for SMR wastes; identify characterisation needs (both experimental and modelling techniques)

FORSAFF TASK 4 – METHODOLOGY

Task 4.1 SMR waste predisposal and disposal

- Identification of Waste Streams and comparison (Task 3)
- Identification of pre/disposal methods
- For each WS and SMR: treatment, conditioning, transport, storage and disposal options

Task 4.2 SNF reprocessing for SMR designs

- Identify existing reprocessing techs and applicability
- Pyroprocessing
- Solvent extraction method

Task 4.3 Characterisation / modelling for SMR waste

- Experimental methods for waste characterization
- Modelling codes for waste characterisation

T.4.1. SMR Waste Predisposal and disposal
Section A) Identify Waste Streams(WS) and compare with identified WS in Task 3 methodology
Section B) Identification of Pre-/Disposal methods
Section C) For each WS of each SMR family complete Treatment/conditioning/transport/Storage/Disposal (+References)
Section D)Assess Infrastructure and Research Needs for Newest Waste Materials

T.4.2. Spent fuel reprocessing from SMR designs
Section A) Identify Existing Reprocessing Technologies Suitable for Each Targeted Fuel Type
Section B) Pyroprocessing
Section C) Solvent Extraction Method
Section D) Evaluate Reprocessing Options for LWR and LMFR (ALFRED Reactor Basis)

FORSAFF TASK 4 – ONGOING WORK

Task 4.2 SNF reprocessing for SMR designs and fuel type

- Pyroprocessing for HTGRs: low technology readiness level, not much knowledge accumulated
- Aqueous solvent extraction methods for HTGR: R&D stage, potential implementation after oxidation of graphite and filtration of insoluble, further investigation needed.

➢ Gaps and issues identified relate to the lack of literature for reprocessing for SMRs

Task 4.3 Characterisation / modelling for SMR waste

- Most experimental methods under study could be already applicable to SMRs but some are undergoing a closer inspection (Radiological/Destructive/radiochemistry, scaling factors, Non-radiological/Wigner energy)
- Modelling methods (particle transport codes, chemical and geochemical codes, Multiphysics, environmental impact assessment): gaps in data (libraries and experimental) due to the presence of new materials.

THANK YOU FOR YOUR ATTENTION

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

Abstract

The European Partnership on Radioactive Waste Management (EURAD) is a collaborative programme funded by the European Commission (EC), aiming to support "*safe Radioactive Waste Management, covering all phases including predisposal and disposal, through the development of a robust and sustained science, technology and knowledge management programme*", as stated in the EURAD Vision Statement. The first phase of the joint programme ran from 2019 to 2024 and is now being continued by a second phase, known as EURAD-2. This paper provides an overview of EURAD-2 Work Package 4: Waste Management for Small Modular Reactors and Future Fuels (FORSAFF), whose objective is to identify knowledge gaps and provide recommendations for future research regarding Small Modular / Advanced Modular Reactors (SMR/AMR) waste generation and management. This paper presents ongoing FORSAFF activities focused on i) identifying SMR/AMR waste inventories including spent fuel or waste generated after reprocessing (Task 3) and ii) assessing SMR/AMR waste predisposal and disposal strategies, spent fuel reprocessing, characterisation methods and modelling tools for SMR/AMR waste (Task 4).

1. INTRODUCTION

Small Modular Reactors are being developed to help meet growing global energy demands. While they offer

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