Topical Session 7 - Ensuring safe final disposal

Lena Z Evins (SKB), WP8 Sarec & Madalina Wittel (Nagra), WP17 CSFD

EURAD-2 Annual Event N°1

9 – 11 September 2025, Bologna, Italy

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AGENDA

Time	What	Who
1630-1700	Welcome, Introduction & Joint presentation: Safe final disposal	Lena Z Evins (SKB, SE), Madalina Wittel (Nagra, CH)
1700-1715	Spent nuclear fuel leaching experiments to investigate radionuclide release under representative repository conditions	Thierry Mennecart (SCK CEN, BE), WP8 participant
1715-1730	Experiments supporting criticality safety	Anna Alvestav (SKB, SE), WP17 participant
1730-1740	***Short Break***	
1740-1810	Panel discussion - How do we ensure safe final disposal?	Mats Jonsson (KTH, SE) , Crina Bucur (Raten, RO), Florian Voigts (BGE, DE), Marjan Kromar (IJS, SI) , Maarten van Geet (Ondraf, BE), Adrien Feuerle (ANDRA, FR)
1810-1820	Summary report from rapporteur	Virginie Solans (Nagra, CH)
1820-1830	Concluding remarks	Lena Z Evins (SKB, SE), Madalina Wittel (Nagra, CH)

INTRODUCTION: ENSURING SAFE FINAL DISPOSAL

- **Safe final disposal: a core goal for the full range of inventories**
  - Low & Intermediate Level Waste
  - High Level Waste (HLW) -> WP8 and WP17 focus on HLW, specifically, spent fuel

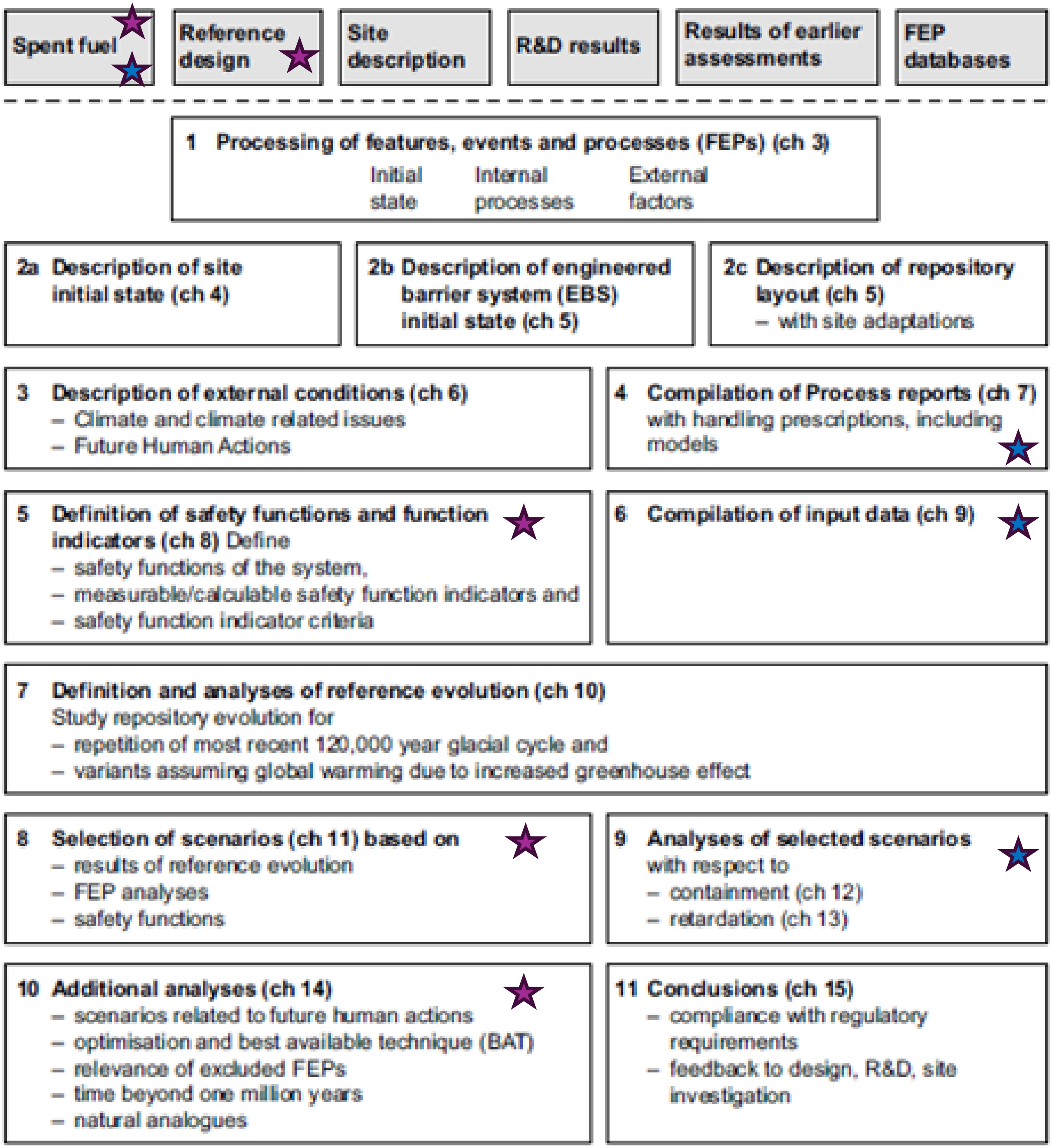
- **Typically ensured by developing disposal concepts based on multiple barrier systems**
  - Inventory and waste type steering disposal concept and barrier system
  - The waste form itself
  - Containers
  - Buffer material
  - Bedrock / Host rock

INTRODUCTION: ENSURING SAFE FINAL DISPOSAL

- **What do we mean by "safe final disposal"?**
  And how do we know when a design is safe enough?
  - There can be many interpretations aiming to deliver the same thing: ultimately, a deep geological repository (design) that encapsulates the current radioactive waste and ensures the safety of our society today and for all future generations:
    - For example, ALARA / ALARP principles, e.g. when design or administrative measures are defined
    - Best available technology can be targeted and demonstrated e.g. when designing specific technical barriers
    - Etc.
- **Safety must be ensured both during the operational and in the post-closure phase**
- **Long-term evolution of the repository system – can be a challenge**
  - Long lived radioactive waste require assessment over long time period
  - Main focus for both WP8 and WP17 are when canisters fail – far in the future
  - Repository needs to be designed to protect the canister (and other barriers)
  - Many different areas involved: materials science, geology, hydrochemistry, …

EXAMPLE OF A TYPICAL SAFETY ASSESSMENT

- **The safety assessment for a deep geological repository comprises many different aspects**
- **Different parts of the assessments**
  - Internationally recognized steps of a safety assessment:
  - **WP8** mainly involved in consequence calculations
    (part of the scenario analyses)
    – consequence of barrier failure, radionuclide transport calculations
  - **WP17** (including what-if scenarios)
  - Criticality (**WP17**) also closely involved with reference design

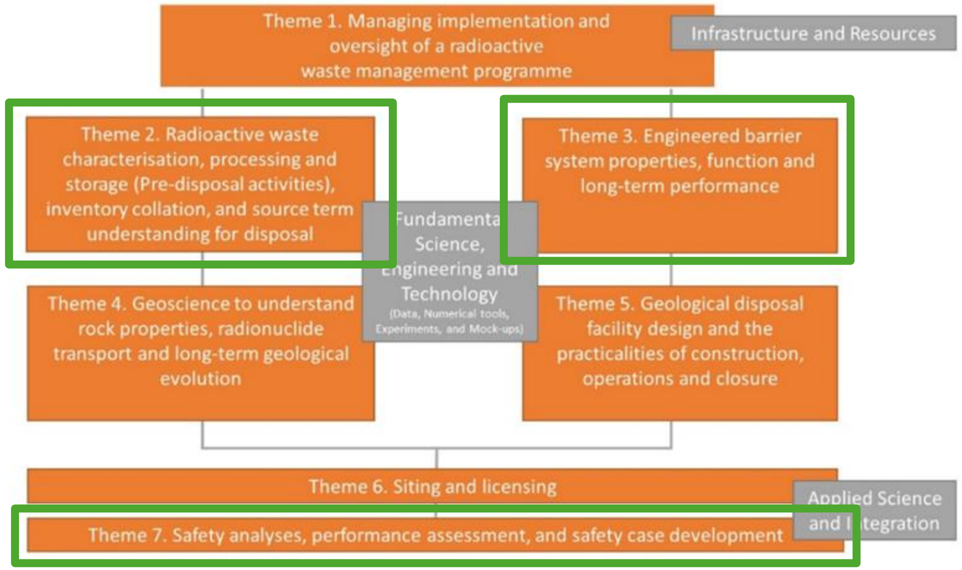


INTRODUCTION: ENSURING SAFE FINAL DISPOSAL

- **Regulatory requirements**
  - International level – similarities, differences
  - Requirements coupled to different regulatory strategies
  - “Safety Case” vs “Safety Assessment”
  - Requirements connected to different aspects of the safety assessment

- **Connection to EURAD-2 SRA Themes**
  - WP8 & WP17 relate to both **Theme 2** - Radwaste characterisation & source term understanding, and **Theme 3** : Engineered Barrier Systems & long-term performance
  - Another connection is to **Theme 7** - Satefy analyses & safety case, and this connection is what our session today will explore

Overview of EURAD-2 SRA Themes



SAREC - RELEASE OF SAFETY RELEVANT RADIONUCLIDES FROM SPENT NUCLEAR FUEL UNDER DEEP DISPOSAL CONDITIONS

Barrier processes (eg corrosion)

→ Failed barriers

→ **Release from fuel & canister**

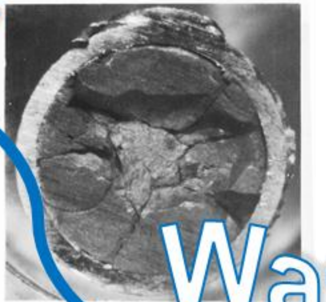
→ Transport through rock

→ Surface transport

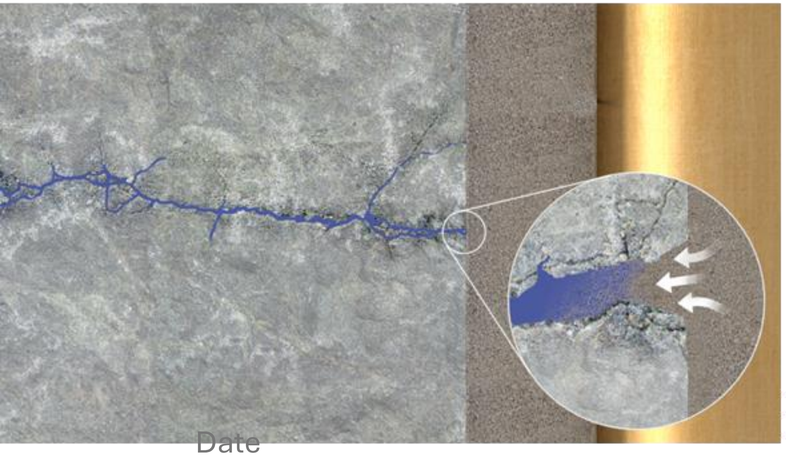
→ Dose

→ Risk

Water



Water +



SAREC - MAIN RESEARCH TOPICS AND TASKS

- Improved quantification and mechanistic understanding of the release of safety relevant radionuclides, covering most representative types of SNF.
- Clarification of fuel evolution both prior and posterior to contact with groundwater to better predict the radionuclide source term for post-closure safety assessment

	Task title
1	Management/coordination of the WP
2	Knowledge Management
3	IRF/FGR Performance of Spent Nuclear Fuel
4	Role of Grain Boundaries in Spent Fuel Corrosion
5	Studies on Model Materials
6	Mechanistic modelling

SAREC PARTICIPATING ORGANISATIONS

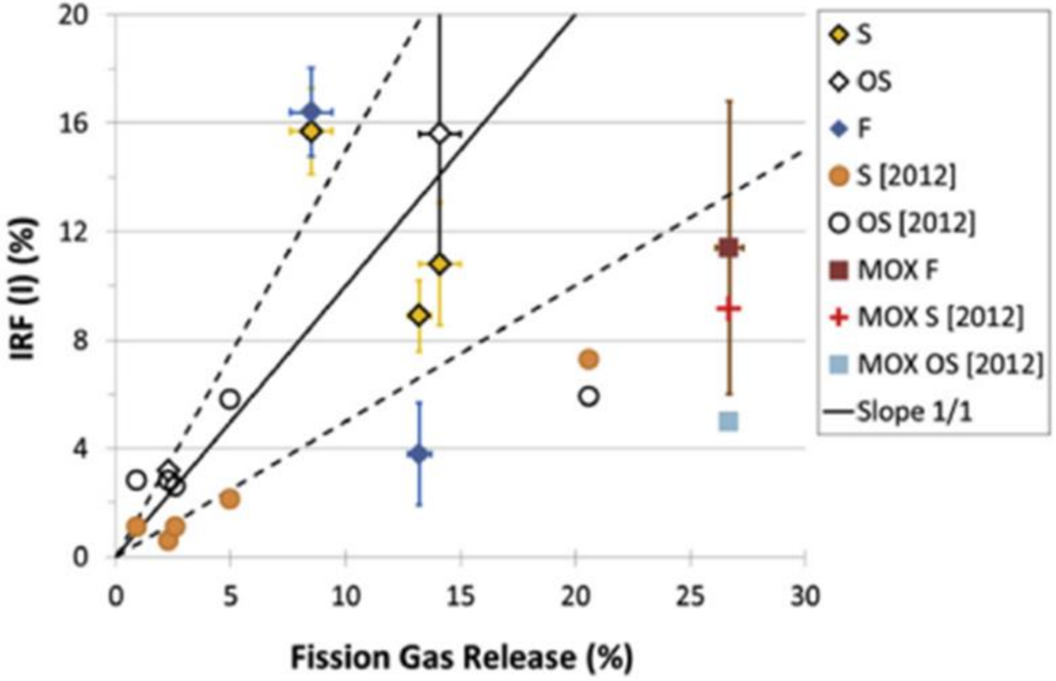
1 MGT	2 KM	3 Spent fuel	4 Grain boundaries	5 Model materials	8 Modelling
SKB	**A21**	**KIT**	**Ondraf Niras**	**Ciemat**	**KTH**
A21	Energorisk	SKB(Studsvik)	CEA	FZJ	UPC
KIT		FZJ	CNRS (ICSM)	CNRS(Subatech)	IRSN
Ondraf Niras		SCK CEN	UMONTP	KTH	ENSMP
Ciemat		Eurecat	FZJ	VTT	Energorisk
KTH		JRC Karlsruhe	HZDR	U Lancaster	VTT
			VTT	U Bristol	PSI
			U Helsinki	NWS	
			U Bristol		

SAREC – WHAT WE (THINK WE) KNOW

- Initial State-of-the-Art report: https://www.ejp-eurad.eu/publications/eurad-2-d81-sarec-initial-sota
- For a given dose rate, a certain amount of initial H_2 will supress radiolytic oxidation of the spent nuclear fuel matrix
  - Radionuclide release from the matrix is then very slow
- Most repository concepts have abundant of Fe(0) in steel or cast iron as a part of the canister - Anoxic corrosion yields H_2 and Fe(II), both keeping the radiolytic oxidation low
- Some fraction of the radionuclides will be part of the so-called ”Instant Release Fraction” (IRF)
- Normally, the IRF is a few % of the inventory of some mobile radionuclides (eg I-129, Cs-135)
- The fission gas release (FGR), the linear heat generation rate (LHGR), and the burnup (BU) are all important to know in order to quantify and understand the IRF.

SAREC – RELEVANT GAPS TO FILL (A SELECTION)

- Relation between release of fission gases to the gap & during leaching
- Effect of grain boundaries, dopants and leaching environment on radionuclide release
- Full picture of the different surface-mediated reaction related to the hydrogen effect
- Effect of iron-based materials in the near field
- Dopants effect of surface-mediated redox reactions
- Dopants effect on atomic and micro-scale spent fuel pellet structure
- Effect of potential secondary phases
- Consensus regarding radionuclide release models
- A joint database populated with experimental results and relevant metadata.



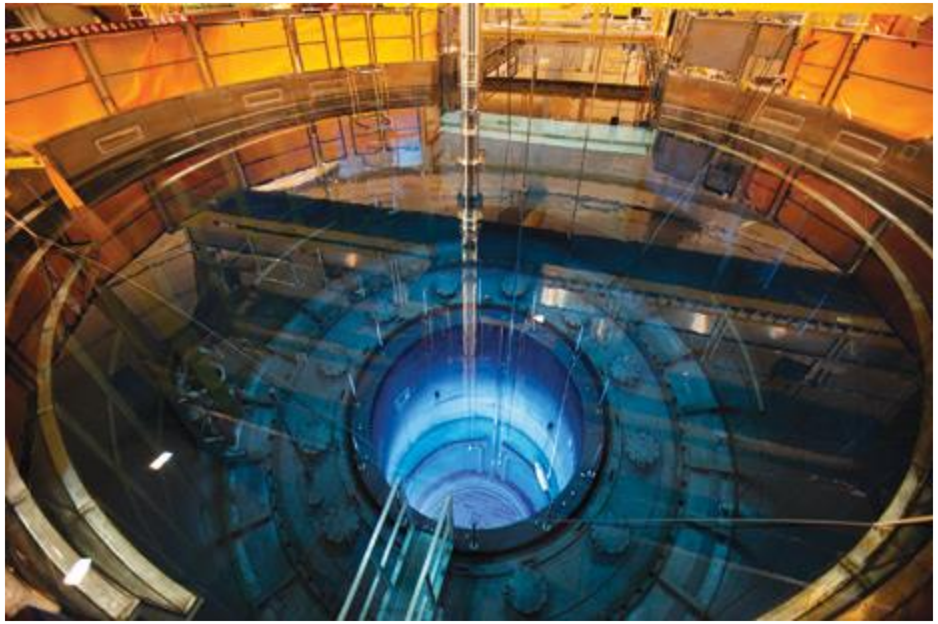
Lemmens, K., González-Robles, E., Kienzler, B., Curti, E., Serrano-Purroy, D., Sureda, R., ... & Hózer, Z. (2017). Instant release of fission products in leaching experiments with high burn-up nuclear fuels in the framework of the Euratom project FIRST-Nuclides. Journal of Nuclear Materials, 484, 307-323.

SAREC – IN A SAFE FINAL DISPOSAL PERSPECTIVE

- Radionuclide release can only happen in case of canister failure
  - canisters are designed to withstand the processes affecting them in the repository environment
- The fuel matrix, containing most of the radionuclides, can be considered a barrier in a multi-barrier design
- Analysis of the consequence of failing barriers requires a sound understanding of the waste form – here, spent nuclear fuel
- Radionuclide release from the fuel also affects criticality analyses – link WP8 & WP17
- More & better data & improved process understanding can
  - reduce uncertainty,
  - change how the process is handled
  - strengthen the safety case.

CRITICALITY SAFETY IN THE FINAL DISPOSAL OF RADIOACTIVE WASTE

- High-level radioactive waste (e.g. irradiated nuclear fuel) still contains certain amounts of fissile material.
- Under very specific circumstances, this could potentially lead to new fission chain reactions ocurring in the deep geological repository (DGR).
- **Criticality safety of the DGR is a safety requirement in all national programmes that have to dispose of high-level waste.**
- Criticality safety - typically to be ensured and demonstrated both in the operational and in the post-closure phase of the DGR.



CRITICALITY SAFETY IN THE FINAL DISPOSAL OF RADIOACTIVE WASTE - II

- **Criticality safety in the operational phase**:
  - Limited time frame → direct controls/actions;
  - Analogous to measures for criticality control implemented in nuclear facilities presently in operation.

- **Criticality safety in the post-closure phase**:
  - Long time frames: orders of magnitude larger than in any other areas of the fuel cycle;
  - Handling of uncertainties associated to the long-term evolution of the system.

- **The DGR post-closure phase requires a dedicated approach due to the long time frames.**

CRITICALITY SAFETY IN THE FINAL DISPOSAL OF RADIOACTIVE WASTE - III

- **The R&D work in WP-17 addresses the challenges of ensuring and demonstrating post-closure criticality safety for long time scales.**

- **Two key aspects of criticality safety for final disposal**:
  - Identifying, optimising and implementing **measures to ensure criticality safety** of DGR;
  - Developing methods to perform **criticality safety assessments**
    → basis for the criticality safety case for national final disposal concepts.

WP-17 «CSFD» - PARTICIPATING ORGANISATIONS

- **WP-17 comprises contributions from 22 partner organisations from 12 different countries:**

WMO

TSO

RE

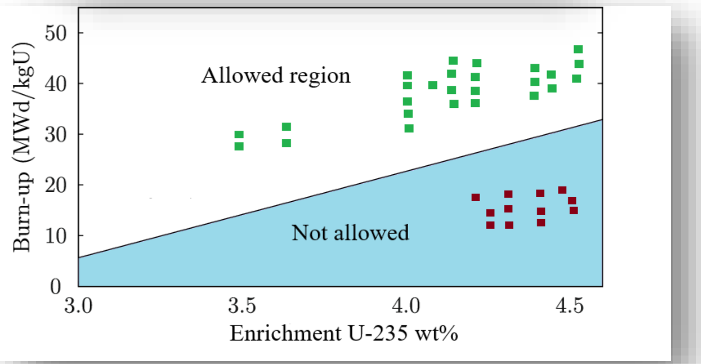
ANDRA
BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG
enresa
Nuclear Waste Services
nagra.
Posiva
PURAM
SKB
SÚRAO

amentum
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EIMV ELEKTROINŠTITUT MILAN VIDMAR
GRS
SSTC NRS STATE SCIENTIFIC AND TECHNICAL CENTER FOR NUCLEAR AND RADIATION SAFETY
TRACTEBEL ENGIE
VTT

ČVUT ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
EPFL
Galson SCIENCES LTD egis
Institut "Jožef Stefan"
PSI
LITHUANIAN ENERGY INSTITUTE

WP-17 «CSFD» - OBJECTIVES

- **Support national programmes in ensuring criticality safety for their DGR concepts and inventories;**
- **Consolidate the technical basis of the criticality safety argumentation for final disposal of fissile wastes:**
  - Explore the optimisation potential of **measures for ensuring criticality** safety in final disposal – focus on post-closure phase:
    - Technical measures: e.g. optimising the design of final disposal containers for high-level waste;
    - Administrative measures: e.g. deriving fissile material limits per waste package (loading curves);
    - etc.
  - Further develop & improve understanding of **methodology to assess their effectiveness**
    - Validation and experimental verification of criticality safety assessments.



WP-17 – R&D ACTIONS' LANDSCAPE

Research measures to ensure criticality safety	Develop methodology for post-closure criticality safety case
Administrative measures: • **Task 5**: Development of methodology for deriving fissile mass limits for spent fuel & ILW packages. • **Task 2**: Fissile waste records for criticality safety assessments. **Technical measures:** • **Task 5**: Investigate factors that influence the derivation of fissile material limits with a view to optimise waste package & barrier design.	**Evaluate performance of crit.-safety measures:** • **Task 3**: Validation of long-term evolution scenarios for post-closure criticality safety (PCCS) assessments • **Task 4**: Verification of model implementation for PCCS assessments • **Task 6**: Experimental basis for validation of depletion and criticality codes for PCCS **Criticality consequence assessments** • **Task 7**: Develop and consolidate methodology for assessing criticality in the DGR post-closure phase.
Communication to stakeholders • **Task 2**: Develop an effective communication strategy to all relevant stakeholders (general public, national regulator, etc).	

OVERVIEW: CRITICALITY SAFETY IN FINAL DISPOSAL

- Criticality safety of a DGR is a requirement in all national programmes that must dispose of high-level waste such as spent nuclear fuel.
- **WP-17 “CSFD” supports national final disposal programmes in ensuring criticality safety for their DGR concepts and inventories**:
  - Identifying, further developing and optimising measures for ensuring criticality safety in final disposal – focus on the DGR post-closure phase;
  - Further development & understanding of methodologies to assess the effectiveness of these methods.
- **WP-17 “CSFD” contributes by consolidating the technical basis of the criticality safety argumentation for final disposal of fissile wastes**.
- The planned R&D programme will be carried out in collaboration between 22 partner organisations from 12 different countries (10 Member-States and 2 Associated Partners).

LINKS/SYNERGIES BETWEEN OUR WPS

- Source term! "Inverse" relationship: WP-8 is concerned with the amount of radionuclides released, while WP-17 is concerned with what remains…
- **For crit. safety rather detailed computational models (implies scenarios) are required**
  - Canister degradation scenarios
  - Fuel degradation scenarios (fissile material accumulation either inside or outside of the canister)
  - Burn-up credit: which radionuclides can we take credit for?
- **Perspective from WP-8:**
  - Canister evolution after failure – only some effects of corrosion products are taken into account, but understandning the process is important for potential additional scenarios (e.g. sorption, co-precipitation)
  - Full radionuclide inventory of fuel is important to know to estimate fraction released.

SUMMARY

- **How do our WPs contribute to ensuring safe final disposal?**
- **WP8: Understanding fuel dissolution processes, and what fuel parameters are important, ensures that**
  - Only fuel with acceptable characteristics are allowed in the repository (WAC)
  - Definitions of fuel related Safety functions are scientifically sound
  - Releases in case of barrier failures can be quantified
  - An adequately quantified source term is important when optimizing the barrier system
- **Criticality safety is a requirement (both to ensure and to demonstrate it) in all national programmes that have to dispose of high level waste such as spent nuclear fuel.**
  - WP-17 is carrying out an RD&D programme that aims to consolidate the safety assessment argumentation:
    - By exploring methods to ensure crticality safety in the repository post-closure phase
    - By developing approaches to carrying out the post-closure criticality safety assessment in the DGR long-term evolution.

THANK YOU

Thank you for your attention!

Next up: Thierry, then Anna

PANEL DISCUSSION

How do we ensure safe final disposal?
Panel and audience welcome to discuss

Our Panel

- **Mats Jonsson (RE: KTH, SE)**
- **Crina Bucur (RE: Raten, RO)**
- **Florian Voigts (WMO: BGE, DE)**
- **Marjan Kromar (TSO: IJS, SI)**
- **Maarten van Geet (WMO: Ondraf Niras, BE)**
- **Adrien Feuerle (WMO: ANDRA, FR)**

Pre-considered, preliminary questions

- Ensuring a safe radwaste management : similarities and differences in different countries. Could you give a brief description of your country's approach/philosophy to final disposal?
- Comparing national requirements regarding the safety assessment of radwaste disposal, such as e.g. assessment timeframe, etc.
- Roles of the waste form in the disposal design
  and barrier functionality.
- Importance of process understanding for
  1) repository requirements and design.
  2) radionuclide migration and consequence calculations.
- Radiation effects on repository materials, including the waste form
- Approach to long-term safety assessments: what features, events or processes in the long-term evolution would be relevant

SUMMARY REPORT FROM RAPPORTEUR

- **Virginie Solans (WMO: Nagra, CH)**