Advancing Digital Twin Technology for Optimized Nuclear Waste Management: Bridging Disciplines and Enhancing Safety

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EURAD-2 DITOCO2030 project

Next-generation **DI**gital **T**wins to support **O**ptimisation, **C**onstruction and **O**peration of surface and subsurface radioactive waste management facilities

DITOCO

eurad 2

As per EURAD-2
WP description Template

Strategic study

2-years duration
work concentrated between M2 – M14
(=> R&D)

Total funding 500 k€ +

Total Person-Months 43.80 +

Links with EURAD SRA / Roadmap Themes (if multiple choices, indicate the primary link **in bold – maximum 3**)	☒ Programme Management (Theme 1) ☐ Pre-disposal (Theme 2) ☐ Engineered Barrier Systems (Theme 3) ☐ Geoscience (Theme 4) ☒ **Disposal facility design and optimisation (Theme 5)** ☐ Siting and Licensing (Theme 6) ☒ Safety Case (Theme 7)		
Links with EURAD SRA topics (if multiple choices, indicate the primary link **in bold – maximum 3**)	*Please indicate the corresponding Domains (number) and Description of R&D, StSt or KM needs (second column of SRA)* - 5.2.2 Optimisation (of the facility components and design) - 5.2.4 VR / Digital Twin - 7.3.1 Performance assessment and system models		
SRA drivers **(maximum 3)**	☒ Implementation Safety	☐ Tailored Solutions	☒ Scientific Insight
	☒ Innovation for Optimisation	☐ Societal Engagement	☐ Knowledge Management

OBJECTIVES

Lay-out the path on **how to close the R&D gap** between the currently fragmented digital twins (DT) of individual disciplines, common data environments and decision-making platforms **to better understand** the **opportunities & limitations** of DT in their **deployment** in **whole life cycle of waste management**.

DT is a relatively new technology & **could be considered disruptive** from a regulatory perspective.

Its novelty nature **challenges existing frameworks & standards**, which may not be fully equipped to address the unique aspects and implications of DT.

TASKS

Management /Coordination of the WP

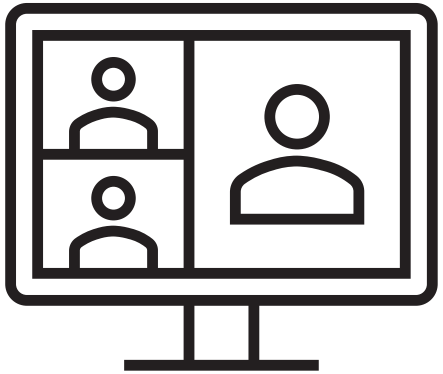
Knowledge Management

Green paper

- Current practices of digital twins (DT)
- Gap analyses

White paper

- Strategic recommendation of the common approaches and standards in the design of DT



Dissemination & Stakeholder engagement

What is the Digital Twin for Eurad-2?

A key challenge lies in aligning & integrating the diverse objectives of Digital Twin technologies (ranging from digital engineering to long-term safety) across multiple disciplines, including geology, performance assessment, systems optimization, realization, and infrastructure.

Achieving a coherent & functional integration across these areas remains to be significantly difficult.

DRIVERS FOR THE DIGITAL TWINS IN RADWASTE (AND NUCLEAR) SECTOR(S)

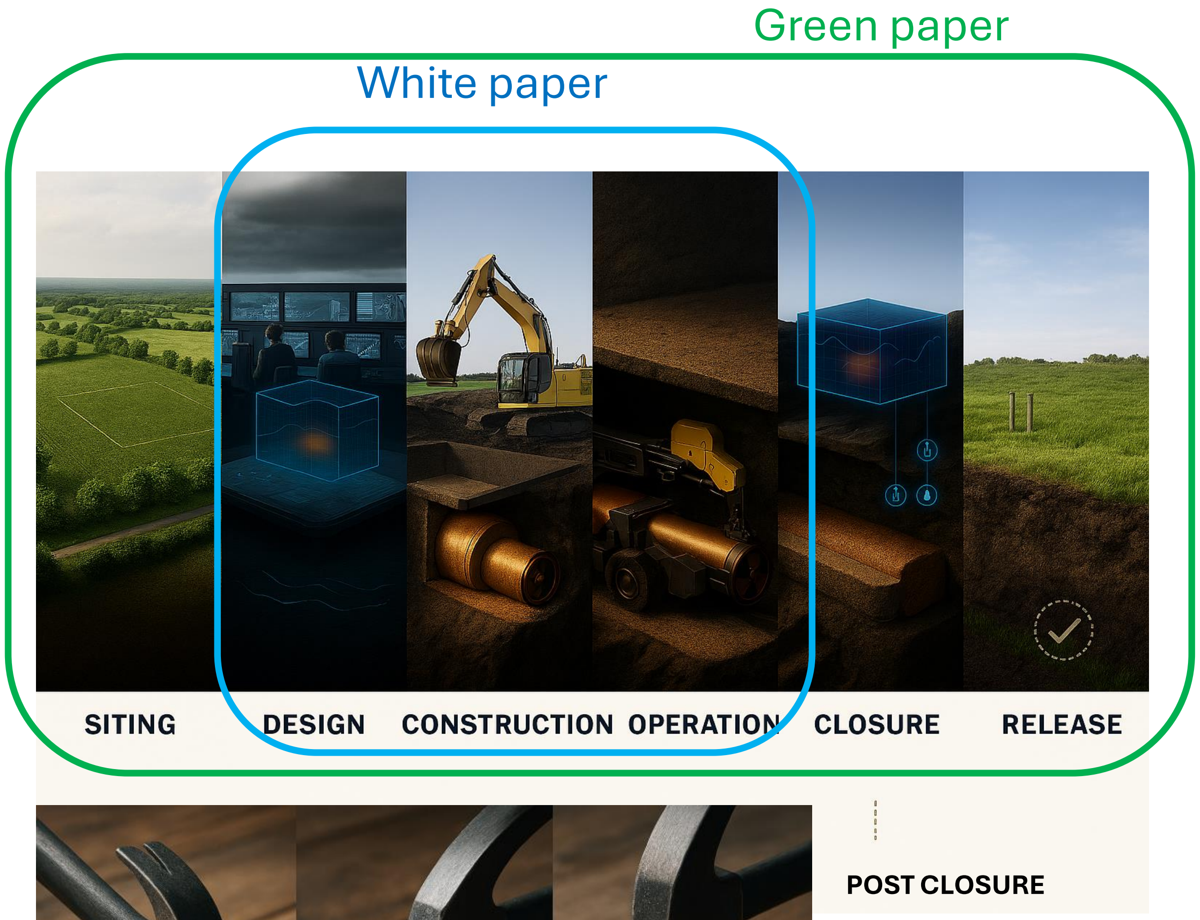
- **Economic Efficiency:**
  - Digital twin technology in the nuclear sector enhances economic efficiency by optimizing maintenance, minimizing downtime, and improving asset utilization.
- **Safety Protocol Improvements:**
  - Digital twins enhance safety protocols through real-time condition monitoring and emergency response optimization.
- **Compliance with Regulatory Requirements:**
  - Digital twins streamline regulatory analyses and verify conformity using high-fidelity models.
- **Long-Term Operation Program:**
  - Digital twins enable predictive maintenance and structural health analysis, extending the lifespan of aging nuclear reactors.
- **Technology Advancement:**
  - Advancements in high-performance computing and AI enhance the use of digital twins for decision support and operational effectiveness.

eurad 2

WHAT IS A DIGITAL TWIN?

- **Lifecycle of the repository is very long**
  - Many repository phases are not yet existing
  - We won’t even see those phases (in DGRs)
    - Note, there exist also low-level waste repositories
  - Technologies evolve fast – or slow
- **Terminology is important, are we speaking the same language?**
- **Digital twin is a tool in this domain.**

1. **For what is the digital twin used for?**
2. **What size the digital twin is?**
3. **For whom is the digital twin made for?**
4. **Who is using the digital twin?**
5. **Who is making the digital twin?**



TERMINOLOGY EXAMPLE - BIM vs. DIGITAL TWIN
SOMEONE MIGHT CALL BIM MODEL AS A DIGITAL TWIN – BUT…

Feature	**BIM (Building Information Model)**	**Digital Twin**
Purpose	Design, construction planning, and documentation	Real-time monitoring, simulation, and predictive analytics
Data Source	Static design and construction data	Live operational data + historical data
Update Frequency	Updated during design and construction phases	Continuously updated throughout the asset lifecycle
Connectivity	Typically standalone or linked to project databases	Connected to IoT sensors, SCADA, and other real-time systems
Lifecycle Coverage	Primarily design and build phases	Full lifecycle: design → operation → maintenance → decommissioning
Simulation Capability	Limited to design scenarios	Advanced simulations (what-if, predictive maintenance, etc.)
Decision Support	Supports design and construction decisions	Supports operational, maintenance, and strategic decisions

WHAT A DIGITAL TWIN CAN BE?

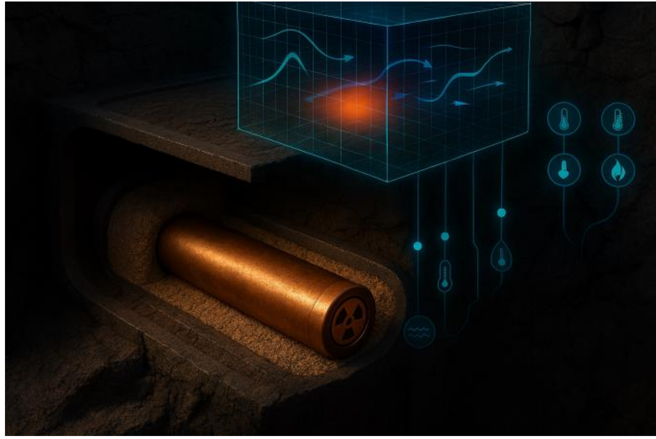
- **Predictive Model:** A digital twin predicts the state and evolution of a physical system by assimilating measured data into a numerical simulation model.
- **Unified Digital Environment:** It brings together computational and visualization methods to extract information from multisource and multiscale data.
- **Decision-Support Tool:** The ultimate goal is to synthesize all knowledge to support operational decision-making.
- **Real-Time Synchronization:** A digital twin continuously updates with real-time data from the physical system.
- **Virtual Representation:** It is a virtual representation of a physical system that enables predictive control and decision-making.
- **Simulation Model:** The digital model maps a current state vector to a future state vector, which can be based on physical laws, data-driven approaches, or hybrid combinations.
- **Control Process:** The control process includes both explicit human interventions and automatic optimization of model parameters.
- **Visualization and Communication:** Digital twins use virtual reality and other visualization tools to present complex model outputs.
- **Historical Context:** Is a virtual model that not only mirrors the current state of a system but also integrates its past data and evolution to enable analysis, prediction, and decision-making over time.
- **Repository Digital Twin:** In the context of waste management, it includes detailed descriptions of underground facilities and integrates models for design, construction, and operational phases.

EXAMPLES OF DESIRED FUNCTIONALITIES FOR WMOs

- Compatibility with industry standards and evolving project requirements
- Cutting-edge technologies (e.g., high-fidelity modelling, leveraging AI/ML and AR/VR, data quality management, digital thread integration, etc.)
- Flexible, scalable, maintainable, upgradable, interoperable tools
- Full connectivity, control and access within our organization's digital ecosystem
- Compliance with regulatory frameworks and requirements
- Compatibility with IT workflows and requirements, robust cybersecurity and access controls
- Intuitive user interfaces with role-based access, customizable workflows and knowledge transfer support

…And numerous specific functionalities (safety, cost/ROI tracking, resources tracking, …)

EXAMPLES OF DESIRED FUNCTIONALITIES FOR WMOs



- Collaborative working
- Single source of truth
- Linkage and traceability across deliverables, reports, input data and hypothesis during the whole lifecycle of the asset. - Bi-directional linkage across entities in the system.
- Process simulations, minimize dose rates in the performance of activities.
- Estimation of the amount of waste allocated to each waste route and simulation of the effects of different treatments in the overall cost and declassification of materials.
- Remote understanding and control of the process and activities occurring in the plant.
- Track record / traceability of components during the operating lifespan, removal, treatment, segmentation and packaging.
- Resource allocation. Multiproject planning connecter to workorders, project plan tasks, reports etc.
- Sensoring and real-time decision-making supported AI generated projections and simulations

GAPS

SOME IDENTIFIED GAPS
THERE IS NO COMMON DEFINITION OF A DT AVAILABLE

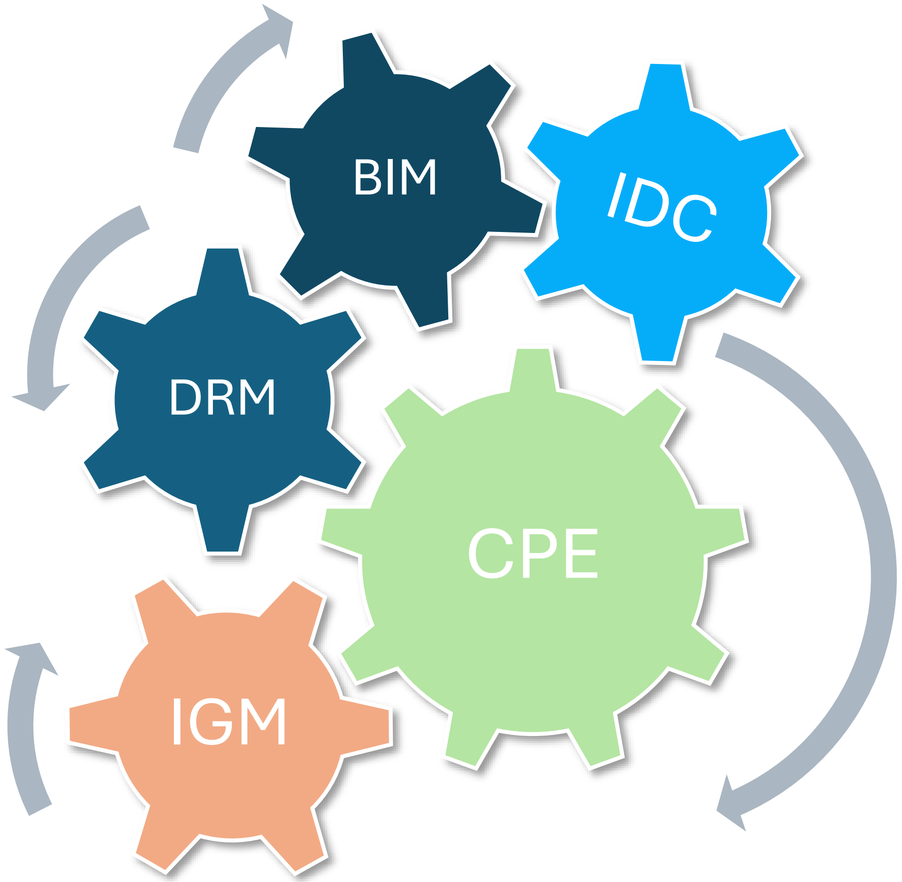
- **Limited Nuclear-Specific Case Studies:** There is a lack of nuclear-specific case studies and developments, which limits the ability to apply lessons learned.
- **Data Quality, Latency, and Cyber-Security:** There are gaps in data quality, latency, and cyber-security for real-time nuclear applications. This includes the need to integrate available standards into digital twin safety models.
- **Regulatory Acceptance Framework:** There is no universal regulatory acceptance framework for digital twin data or technology in the nuclear sector. This gap affects operational transparency and real-time insights.
- **Asset History Records and Lifecycle Management:** There is a need for asset history records and lifecycle management tools to ensure data retention and readability across multiple decades.
- **Computational Power and Accessibility:** Computational power is limited, and accessibility to high-performance supercomputers and cloud computing comes with high costs. This limitation means that simulations are often conducted in simplified 1D/2D domains.
- **Validated Simulation Models:** There is a lack of validated simulation models covering radwaste evolution and system scenarios. This gap affects the ability to perform sensitivity analysis and uncertainty quantification.
- **High-Fidelity Models and Sensitivity Analysis:** Full 3D THMC (thermal-hydraulic-mechanical-chemical) repository evolution simulations cannot currently be performed. This limitation affects the ability to demonstrate safety and performance through high-fidelity models and sensitivity analysis.
- **HPC Architecture Development and Codes:** The rapid evolution of high-performance computing (HPC) architectures creates challenges for code development, especially for complex numerical problems. Changes in HPC architecture open up opportunities for model realism but also present challenges in porting existing models.

GAP - REGULATORY ASPECTS - ACCEPTANCE

- **General acceptance**
  - Twin technology can represent a huge shift in the operational practices
  - Acceptance of new technologies for their application to safety-related issues by stakeholders
    - Limited Nuclear-Specific Case Studies – Lessons learns needed
  - Risks related to the cybersecurity of systems employing DT technology
    - DT deemed disruptive tech; there is no clear regulatory guidance on mitigating these risks
- **Regulatory framework**
  - Regulatory Acceptance Framework: There is no universal regulatory acceptance framework for digital twin data or technology in RWM.
    - Gaps include areas related to data integrity, model certification, integration with legacy systems, and cybersecurity, all of which are critical for safe and effective implementation.
    - This gap affects operational transparency and real-time insights

SOME EXISTING DEEP GEOLOGICAL REPOSITORY DIGITAL TWIN EXAMPLES

NAGRA'S INTEGRATED DIGITAL ENVIRONMENT



- **Integrated Geo-Model (IGM)**

→ *Subsurface representation and evolution*

- **Building Information Modelling (BIM)**

→ *Engineering design and construction information*

- **Dynamic Repository Modelling (DRM)**

→ *Safety and Performance Assessment*

Main modelling components

- **Common Project Environment (CPE)**

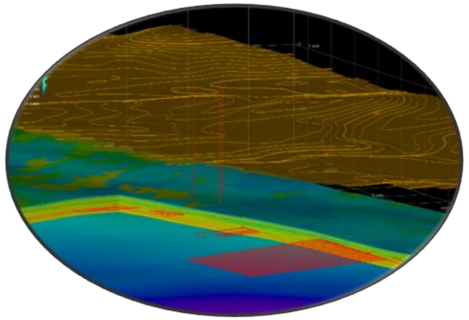
→ *Reference configuration, requirements and change*

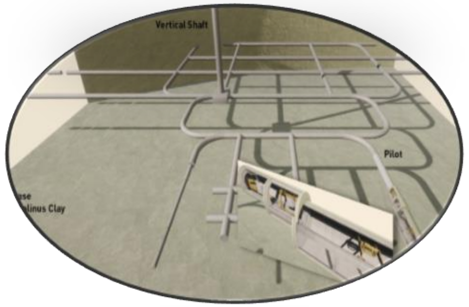
- **Information & Data Centre (IDC)**

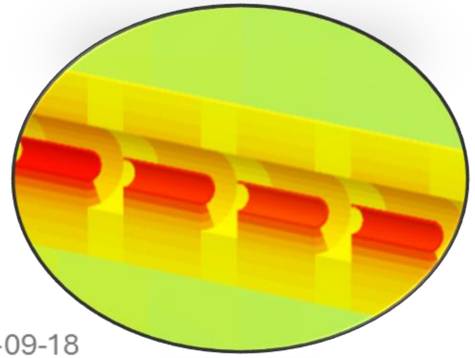
→ *Storage, archiving, provenance*

"Anchors"

HOW IS THIS UTILISED IN THE SWISS PROGRAMME



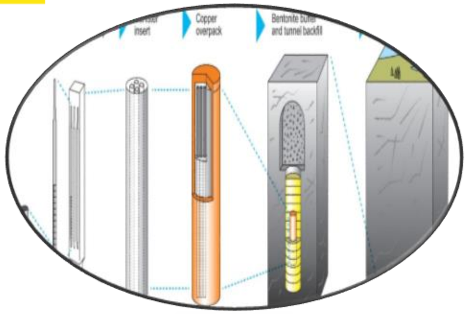


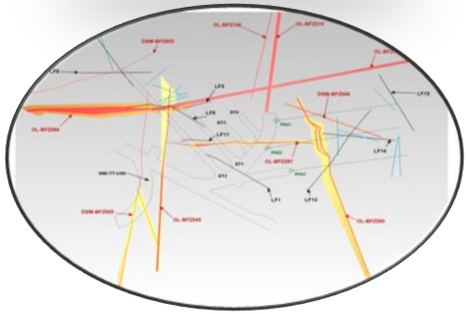


- Streamlining of data, resources & analyses
- Access to entire organization via “single-source-of-truth”
- Implementation digital engineering
- Implementation digital safety case
- End-to-end integration
- Change & configuration management

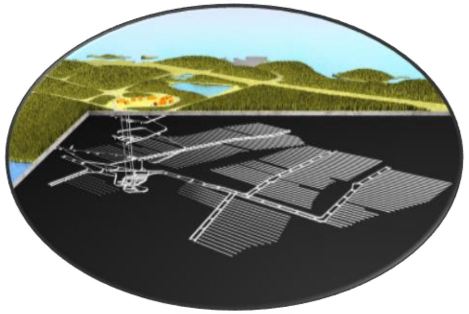
- Project development towards construction
- Repository optimization
- RD&D needs

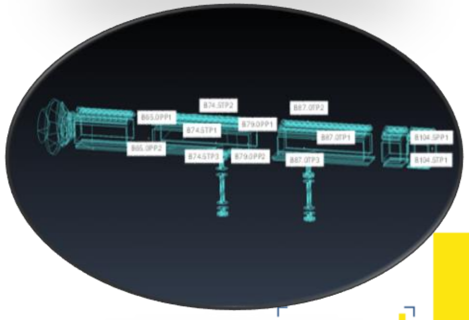
MITTA'S DIGITAL TWIN APPLICATION IN DGR



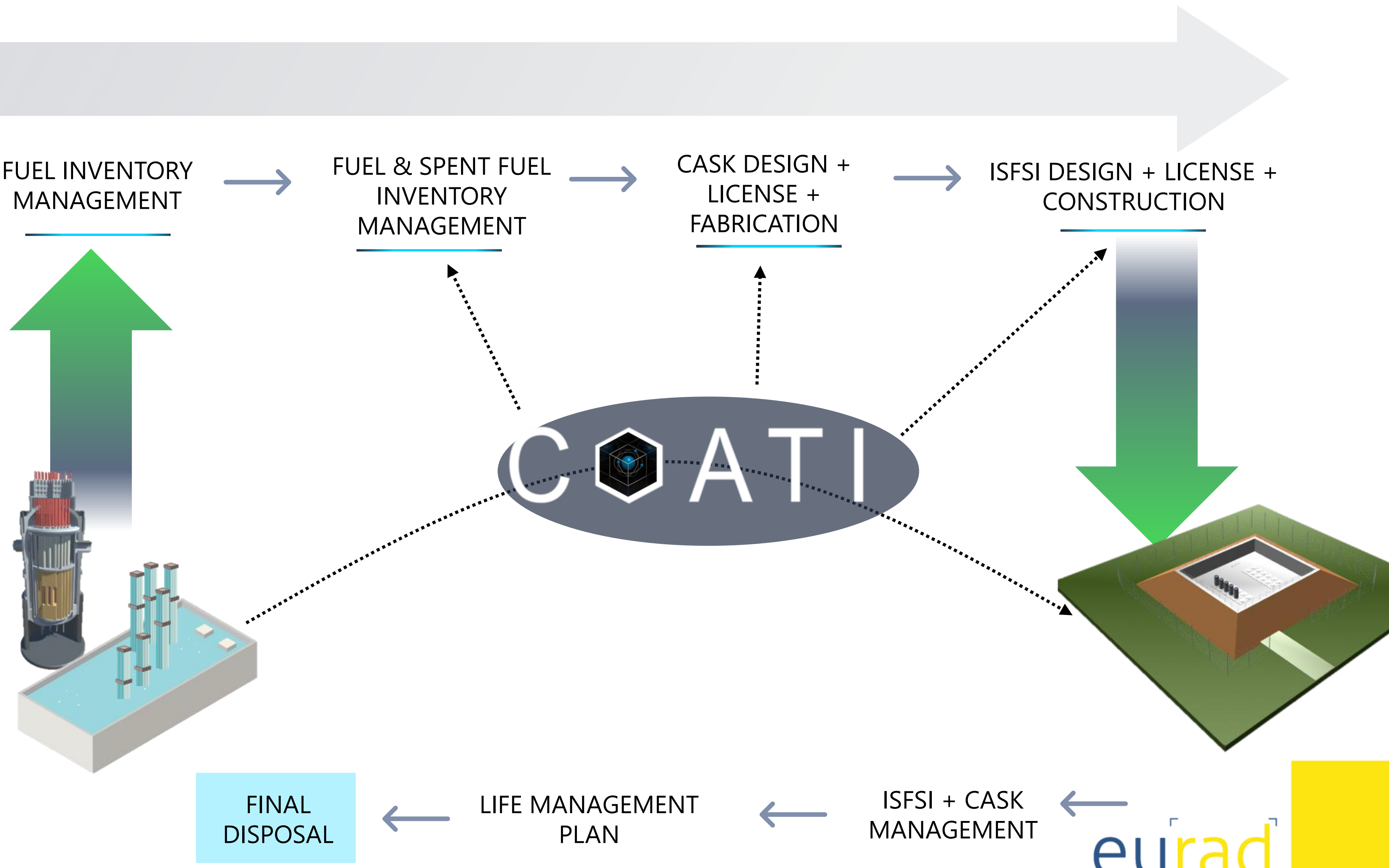


- Thermo-hydro-mechanical simulations - 5 degrees of freedom
- Simulation – CODE_BRIGHT
- Geometry definition for each canister dimension
  - Simulation on real geometry based on CAD files
  - CAD postprocessing required. Coordinate transformation
  - Mesh Generator GiD / FLAC / PLAXIS CONSIDERED
- Transformation process. CAD (dxf/dgn) → RHINO→ IGES → GiD
- Include fractures with the right positioning and orientation.
- Fracture simulation
  - Sensors identified with elements of the mesh. Compare sensor and simulation data.
  - Scalar, vectorial and tensorial measurements





COATI, by its Spanish acronym: ***C**arga **O**ptimizada de un **ATI**,* is an informatic system that Supports the management of spent fuel stored in nuclear power plant pools, helping to optimize ISFSI loading and minimize operational costs after final shutdown. Software supported by **VIRCORE** environment.



HOW TO KEEP STAKEHOLDERS ENGAGED AND AWARE?

STAKEHOLDER ENGAGEMENT IN DITOCO

- **Comprehensive strategy ensures engagement of the key stakeholders and dissemination of the outcomes to advance the implementation of digital twins in the nuclear industry.**
- **Stakeholder engagement emphasizes collaboration, knowledge transfer, and dialogue on digital twin technologies to promote informed decision-making and foster sustainable impact.**
- **It aims to involve diverse stakeholder groups, including academia, industry, regulatory bodies, and the public, ensuring their perspectives are integrated into the project's development and outcomes.**
- **Objectives:**
    - Leverage cross-sector expertise to apply digital technologies in nuclear waste management.
    - Facilitate knowledge transfer from other sectors to improve technical and economic outcomes.
    - Promote collaboration by engaging experts from various industries.
    - Disseminate findings to keep stakeholders informed about project advancements.
    - Incorporate feedback to refine strategies and address concerns.

DITOCO OUTPUT

- **Green paper**
  - Outlines the landscape
  - Presents gaps
  - Gives some answers, maybe also leaves some questions to be answered
- **White paper**
  - Continues to provide next steps and strategic recommendation of the common approaches and standards in the design of digital twins.

- **Shared vision**
  - How DTs can be used across the full lifecycle of radioactive waste management—from design to operation and long-term safety.
- **Stakeholder Engagement**
  - Structured approach to involve stakeholders through mapping, co-creation, and feedback mechanisms.


Danke schön