Deliverable 15.3: Strategic Guidelines for the Development of a Standardized Digital Twin Design in Radioactive Waste Management

Work Package DITOCO2030

DOI - 10.5281/zenodo.23038589

Co-funded by the European Union under Grant Agreement n°101166718, by The Research Council of Norway (Agreement No 355507) and Swiss State Secretariat for Education, Research and Innovation Contract

1.1.1.1 Document information

Project Acronym	**EURAD-2**
Project Title	**European Partnership on Radioactive Waste Management-2**
EC grant agreement No.	**101166718**
Work Package Title	**DITOCO2030**
Deliverable No.	**15.3**
Deliverable Title	**Strategic Guidelines for the Development of a Standardized Digital Twin Design in Radioactive Waste Management**
Lead Beneficiary	**INGECID**
Contractual Delivery Date	**30/04/2026**
Actual Delivery Date	**23/09/2026**
Dissemination Level	**High**
Authors	**Pablo Cayón (INGECID), Xavier Pintado (Clay Technology), Wendy Romero (INGECID), Alexandros Papafotiou (NAGRA), Réka Szőke (IFE); Attila Baksay (TS ENERCON)**
Contributors	**Arto Laikari (VTT), Diederik Jacques (SCKCEN), Gabriela Roman Ross (A21), Julien Cotton (ANDRA), Guillaume Pépin (ANDRA), Christophe Debayle (ASNR), Agnieszka Strusinska-Correia (BGE), Romain Chassagne (BRGM), Michaêl Chelle (BRGM), Francis Claret (BRGM), Veronique Remande (EGIS), Barbara Horvat (EIMV), Nadja Zeleznik (EIMV), Rita Plukiene (FTCM), Arturas Plukis (FTCM), Holger Seher (GRS), Vinzenz Brendler (HZDR), Abdenour Benkrid (IFE), Tiina Jalonen (NAGRA), Sergey Churakov (PSI), Dan Miron (PSI), Wilfried Pfingsten (PSI), Nikolaos Prasianakis (PSI), Federica Pancotti (SOGIN), Michela Raio (SOGIN), Stefania Uras (SOGIN), Mikláš Ondrej (SURAO), Arnaud Duchêne (TRACTEBEL), Attila Baksay (TS ENERCON), Jan Brezina (TUL), Ivan Ivanov (TUS), Rubén López-Vizcaíno López (UCLM), Vicente Navarro (UCLM), Olaf Kolditz (UFZ), Salvatore Cancemi (UNIPI), Rosa Lo Frano (UNIPI), Alan Tkaczyk (UTARTU), Zoltan Bothi (WSP), Tamas Olasz (WSP).**

To be cited as:
Cayón P., Pintado X., Papafotiu A., Romero W., Szőke R. & al. (2026): Strategic Guidelines for the Development of a Standardized Digital Twin Design in Radioactive Waste Management . Final version as of 15.07.2026 of deliverable D15.3 of the European Partnership EURAD-2. EC Grant agreement n°:101177718

Disclaimer
All information in this document is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose. The user, therefore, uses the information at its sole risk and liability. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Atomic Energy Community. Neither the European Union nor the granting authority or the individual Colleges of EURAD-2 can be held responsible for them.

1.1.1.2 Acknowledgement

This document is a deliverable of the European Partnership on Radioactive Waste Management 2 (EURAD-2). EURAD-2 is co-funded by the European Union under Grant Agreement N° 101166718, Co-funded by The Research Council of Norway under Grant Agreement n° 355507t, as part of the International Calls for International Collaborative Projects.

Status of deliverable		
	By	Date
Delivered (Lead Beneficiary)	Pablo Cayón De la Hoz (INGECID)	13/02/2026
Reviewed (Reviewers) Version1	Gyula Dankó (PURAM)	21/05/2026
Reviewed WP02 KM Version 1	Alexandru Tatomir (WP02-KM, BGE) Erika Holt (WP02 PMO representative, VTT)	17/03/2026
Verified (WP Leader)	Réka Szőke (IFE)	05/06/2026
Approved	Vaidas Matuzas (JRC)	23/09/2026
Submitted to EC (Coordinator)	ANDRA	02/10/2026

Executive Summary

This White Paper examines the potential role of Digital Twins in radioactive waste management, with particular attention to their possible future contribution to facility design, construction, operation, and long-term safety-related understanding. The document does not propose a fully developed solution. Instead, it takes an early-stage perspective and focuses on how the sector might begin to build the foundations needed for future progress based on initiatives implemented and deployed in other industries as well as in specific use cases completed within radioactive waste management.

The starting point is a shared problem across the sector: relevant information is often generated in separate systems, by different disciplines, and for different purposes. Engineering models, monitoring records, safety-related evidence, geoscientific data, and operational information may all exist, but they are not always connected in a way that supports continuity, traceability, or a clear understanding of the system as a whole. This fragmentation limits efficiency, weakens knowledge transfer, and makes it harder to communicate evidence in a transparent and accessible way.

In this context, Digital Twins are considered not as a single software product, but as a possible future framework for bringing together different types of data, models, and digital tools within a more coherent environment. At this stage, the value of the concept lies mainly in its potential to improve digital continuity across lifecycle phases, support better-informed decisions, and strengthen long-term knowledge management.

The White Paper builds on the gap analysis previously developed in the Green Paper and translates that initial diagnosis. The paper proposes a gradual way forward. In the near term, attention should focus on preparatory actions, beginning with the mobilisation and coordinated governance of the main stakeholder groups, in particular **Waste Management Organisations (WMOs), Technical Support Organisations (TSOs), and Research Entities (REs)**, so that shared needs can be identified and the most relevant use cases prioritised according to their expected positive impact. In parallel, efforts should be made to improve the conditions for data interoperability, develop shared concepts and terminology, and create small pilot environments that help test ideas and reveal practical constraints. These steps are intended to reduce uncertainty and create a common basis for future development.

In the longer term, these initial steps could support the development of more integrated digital environments capable of linking design, construction, operation, monitoring, and evidence generation more effectively. However, the paper emphasizes that such an outcome depends on progressive development, collaboration across organisations, and the careful consolidation of early lessons.

Overall, this White Paper presents Digital Twins as an area of strategic opportunity for radioactive waste management. Digital Twins should not yet be seen as a mature answer for the sector, but they do represent a promising direction for future research, experimentation, and coordination. The priority now is to move from fragmented digital practices towards a shared basis for learning, testing, and progressive consolidation.

Table of contents

Executive Summary 4

1.Introduction 6

2.Challenges 7

3. Proposed way forward 9

3.1Near-Term R&D Steps - Laying the Foundation 9

3.1.1 Develop an Integrated Data Governance Framework and Open-Source Semantic Data Model - Ontology 9

3.1.2 Create a Modular Reference Architecture for Nuclear DTs 10

3.1.3 Execute High-Value, Limited-Scope Pilot Projects 10

3.1.4 Digital Information Platform for Digital Model Validation 10

3.1.5 Lifecycle Integration Framework (Design–Construction–Operation–Maintenance) 11

3.2Long-Term R&D Horizon - Scaling and Integration 11

3.2.1 Implement a Full-Scale, "Living" Safety Case DT 11

3.2.2 Establish a Community-Wide Benchmark and Validation Programme 12

4. Call to Action 13

4.1. Recommended actions for the near term 13

4.2. High level Roadmap and suggested next steps 14

5. References 16

6. List of acronyms and abbreviations 17

.

1. Introduction

This White Paper also contributes to the strategic objectives outlined in the EURAD Roadmap. In particular, it relates to Theme 5, *Disposal Facility Design and Optimisation*, especially the need for improved approaches to design integration and optimisation, including SRA topics 5.2.2 and 5.2.4. It also connects with Theme 7, *Safety Case*, by considering how digital approaches could in time support the organisation, transparency and accessibility of evidence, and with Theme 1, *Programme Management*, through their potential contribution to knowledge preservation and decision support. It builds on the findings of the previous Green Paper and moves one step further by **asking a practical question: if Digital Twins are to become useful in radioactive waste management, what common foundations should be put in place now?**

Radioactive waste management is one of the most demanding long-term responsibilities faced by modern societies. It requires facilities and processes that must remain safe, understandable, and well-documented over very long periods of time. This creates a particular challenge: decisions made today must still be traceable and meaningful many years from now, even as technologies, organisations, and people change.

At the same time, the amount of information involved in radioactive waste management is constantly growing. Geological data, engineering designs, construction records, monitoring results, operational information, and safety assessments are often produced by different teams, using different tools, for different purposes. Although each of these sources may be useful on its own, they are not always well connected. This makes it difficult to obtain a clear and shared view of the system as a whole.

In recent years, the concept of the Digital Twin has gained attention in multiple sectors as a possible way to improve this situation. In simple terms, a Digital Twin can be understood as a digital representation of a real asset or process that brings together information from different sources in a structured and usable way. Rather than being just a 3D model or a database, it is a broader concept that can help link design information, monitoring data, operational knowledge, and analytical models within a common digital environment. Digital Twins can detect, incorporate, and interpret changes in the real-world system through feedback and the integration of data from sensors and existing data management systems. Within Radioactive Waste Management (RWM) this idea is still at an early stage of maturity. The aim is not to suggest that full Digital Twins are already available or ready for immediate large-scale deployment across the sector. Instead, the purpose is to explore how this concept could gradually evolve into a practical support tool for better understanding, better coordination, and better decision-making throughout the lifecycle of a facility A relevant recommendation is to on proven use cases from the nuclear sector (and other industries, this White Paper advocates for **a phased, modular approach** based on **common standards** and targeted high-value pilot projects to demonstrate tangible benefits, build stakeholder confidence, and establish a foundation for the progressive adoption of DTs in *Radioactive Waste Management*.

The paper therefore does not present a final solution or a fixed technical recipe. Its purpose is more fundamental. It aims to identify why Digital Twins may matter for the sector, what problems they could help address, and what first steps could support their future development in a realistic and coordinated way. In this sense, the document should be read as a strategic orientation paper for an emerging field rather than a detailed implementation manual.

A key idea running through this White Paper is that progress will depend not only on technology but also on organisation, governance, and shared understanding. Before advanced digital solutions can be trusted and adopted, the sector needs a clearer view of what information should be connected, which questions these systems are expected to answer, and how different actors can work with a common language and a common direction.

For that reason, the White Paper adopts a progressive and accessible perspective. It focuses on the early building blocks that could enable future Digital Twin development, while keeping in view the broader objective: supporting safer, more transparent, and better-connected radioactive waste management over the long term.

2 Challenges

The main challenge is not simply the lack of digital tools. The deeper issue is that radioactive waste management is a long-duration, knowledge-intensive activity in which large amounts of information must remain understandable, reliable, and connected over time. Today, that continuity is difficult to achieve.

Radioactive waste management facilities, and in particular deep geological repositories, bring together many different types of knowledge. They depend on an understanding of the site and the surrounding geology, the design of engineered structures, the behaviour of materials over time, the way facilities are built and operated, and the evidence needed to demonstrate safety. Each of these aspects may be studied in depth, but they are often handled through separate tools, separate datasets, and separate working practices.

This fragmentation creates a practical problem. Information may exist, but it is not always easy to combine, compare, or reuse. A design model may not be well connected to monitoring records. Construction information may not be carried forward in a structured way into operation. Important assumptions may become difficult to trace as projects evolve. Over time, this can make it harder to understand why decisions were taken, what evidence supports them, and how the real system compares with what was originally expected. This issue can be summarised simply: all the pieces of a wardrobe set are in the box but need to be assembled and coordinated in a precise manner to provide the expected functionalities of a wardrobe. This affects not only technical efficiency, but also communication, trust, and long-term knowledge preservation.

The challenge becomes even greater because radioactive waste management extends across very long timescales. Facilities are planned, developed, and assessed over decades, while the safety arguments behind them may look much further ahead. Over such long timescales, professional teams change, software evolves, institutions develop, and the legal and societal environment undergoes significant change. Data may become difficult to interpret unless it is managed in a robust and consistent way. What is needed is not only information storage, but **information continuity**. This concept should be understood as the ability to maintain the usability, meaning, and value of information across all stages of the asset lifecycle, despite changes in operational context, data formats, hardware, and technologies.

Another difficulty is that repository systems are complex by nature. Their behaviour depends on the interaction between the natural environment and the engineered components built by humans. Temperature changes, water movement, material degradation, and mechanical or chemical effects may all play a role over time. Even without going into technical detail, it is clear that these systems cannot be fully understood through isolated snapshots. They require approaches that help connect observations, models, and decisions in a more dynamic way.

Existing digital and data management practices across the Radioactive Waste Management (RWM) community are still limited in their ability to integrate real-time monitoring data, simulation outputs, and operational records into a **single coherent digital framework**. As a result:

- Design decisions are often based on **standalone models** without consistent feedback loops during construction or operation.
- Monitoring data from sensors are **poorly linked to predictive models**, reducing their usefulness for adaptive management.
- **Knowledge continuity** between design, construction, operation, and closure phases is not guaranteed.
- The lack of **standardized data formats and interoperability protocols** prevents efficient information exchange between organizations, software, and stakeholders.
- The inability to establish a “digital thread” from design to long-term safety assessment hinders traceability and the demonstration of operational and post-closure safety.

These limitations hinder the full realization of a **systems-level understanding** of DGR behaviour and restrict the ability to apply advanced analytics or AI for predictive maintenance and long-term safety assurance.

The *Green Paper* Digital Twins and their gaps in the Radioactive Waste Management domain (Laikari, Diederik, & Szöke, 2025) highlighted these challenges as shared gaps across European end-users: waste owners; waste generators; waste management organisations and regulators, reflecting a common need for digital continuity, traceability, and transparency in Radioactive Waste Management activities.

The absence of an integrated digital environment has **multi-dimensional impacts** across the lifecycle of radioactive waste management treatment facilities and repositories:

Impact Dimension	Description
Cost	Fragmented data and inefficient coordination lead to duplicated efforts during design and construction. The lack of predictive tools increases maintenance costs and delays during operation.
Safety	Incomplete data integration reduces the capacity to detect anomalies early. Limited predictive modelling may lead to underestimation of potential failures or safety-critical interactions. Furthermore, the lack of a unified digital thread and a governed data backbone, complicates the comprehensive traceability of waste packages and the accurate prediction of their long-term behaviour and interaction with the engineered and geological barriers.
Time	Redundant validation and manual data transfer processes prolong project timelines, especially during design review and licensing.
Knowledge Management	Discontinuities between project phases and institutions cause loss of critical know-how and contextual data essential for long-term safety assessments.
Public and Regulatory Confidence	The inability to provide transparent, traceable, and visual evidence of repository behaviour weakens stakeholder engagement and regulatory trust.

The challenge identified in this White Paper is therefore both technical and organisational. It is technical because existing systems and data sources are not sufficiently connected. It is organisational because the sector still needs common ways of structuring information, defining interfaces, and agreeing how digital practices should evolve. Without these shared foundations, even good digital tools may remain isolated and underused.

This is where the interest in Digital Twins begins. At this stage, the value of the concept lies less in any single software solution than in the possibility of creating a more connected framework for information, evidence, and decision support. The challenge is not to build a perfect digital replica from the outset, but to understand how the sector can progressively move from fragmented digital practices toward more integrated and more useful digital environments.

The opportunity is clear. If the sector can establish **common foundations** for **data**, **models**, and **workflows**, Digital Twins could eventually help improve traceability, support better coordination between lifecycle phases, strengthen knowledge management, and provide a clearer basis for communication and safety-related reasoning. But before that can happen, the first problem to solve is the current lack of continuity and integration across the information landscape.

3 Proposed way forward

3.1 Near-Term R&D Steps - Laying the Foundation

The objective is not to define a fully mature Digital Twin solution for RWM, disposal and repository facilities, nor to prescribe a single technical pathway for all organisations. The priority is more fundamental: to identify the first practical steps that can help the sector move from fragmented digital practices towards a more coherent and better connected digital approach.

The way forward should therefore be understood as a gradual development process. Before advanced functionalities can be deployed at scale, several enabling conditions need to be clarified and progressively established. These include a shared understanding of the most relevant use cases, a common approach to data and information management, and a clearer view of how different digital tools, models, and actors could work together over time.

Therefore, the recommendations set out in this section are structured as a progressive pathway rather than as a fixed implementation plan. The near-term focus is on building the basic foundations that would make future Digital Twins credible, useful, and scalable. This includes creating common reference points, testing ideas in limited and meaningful contexts, and reducing uncertainty before larger commitments are made.

The longer-term perspective is to enable a more integrated digital environment capable of supporting repository development across multiple lifecycle stages. However, such an ambition can only be approached realistically if the early groundwork is addressed first. In other words, progress depends less on starting with highly sophisticated solutions and more on establishing the conditions that allow those solutions to emerge in a controlled and purposeful way.

The following proposed steps should therefore be seen as building blocks for a shared European direction: not as final answers, but as a structured basis for experimentation, learning, and progressive consolidation.

3.1.1 Develop an Integrated Data Governance Framework and Open-Source Semantic Data Model - Ontology

A key near-term priority is the production of a robust, FAIR (Findable, Accessible, Interoperable, Reusable)-compliant data governance framework. to support the progressive development of Digital Twins in radioactive waste management. This should not be understood as a single centralised database, as a governed interoperability framework comprising rules, metadata conventions, and *Application Programming Interface* API-based integration mechanisms that enable existing siloed digital models and shadows, monitoring databases, and simulation environments—to exchange and use information in a consistent and controlled manner. In parallel, an open-source semantic data model, or **ontology**, should be developed for the nuclear waste domain in order to define standardized terminology and explicit relationships between the principal entities involved, including waste packages, geological features, sensor data, and engineered barrier components.

This action must be led by WMOs, as they will be the end-users of the DTs and therefore and must define the rules, standards and exchange information required to answer the expected functionalities that Digital Twins must fulfil. Our recommendation is to work in close collaboration with research institutions and standardization institutions, for instance Building Smart (BuildingSMART International) or the Open Geospatial Consortium (Open Geospatial Consortium).

The development of a high-level framework that could be detailed over time is addressing the issue posed by disconnected data silos, enabling seamless data exchange, ensuring long-term interpretability, and providing the "glue" for integrated and scalable DTs.

3.1.2 Create a Modular Reference Architecture for Nuclear DTs

A further priority is the definition of a high-level, technology-agnostic **architecture** for DTs in the nuclear sector focussed on waste management purposes which specified how the core components of a Digital Twin (Data Backbone, BIM/GIS and simulation digital models, Integration Layer, AI Model Manager, Visualization & Interaction Interface) connect and communicate. This architecture must mandate open standards (e.g., OPC UA for sensor data, IFC/BIM-ISO for engineering models, OGC standards for geospatial data).

This task should be led by consortium of engineering partners and research entities with demonstrated experience in both nuclear projects and digital platform design.

The expected benefit of this sector-controlled development is the prevention of vendor lock-in, ensures that tools and modules developed by different teams can interoperate within a common framework while providing a clear basis for incremental development. It transforms the DT concept from a monolithic, high-risk project into a manageable-progressively deployable, modular system.

3.1.3 Execute High-Value, Limited-Scope Pilot Projects

To continue with the implementation roadmap a limited number of pilot project must be promoted and completed to validate the proposed framework and demonstrate its practical value in RWM and repository contexts. One of the objectives of Digital Twins is to add value during the whole lifecycle of the facility. Considering that existing use cases cover the pre-construction stages and lessons learnt can already be extracted from those, our recommendation is to emphasize the potential functionalities connected to construction and operation phases.

The **construction-oriented** DT must be used to test functionalities such as a 4D and 5D BIM uses[1] for a defined repository tunnel section, where the 3D engineering model are linked to construction planning and cost information and is continuously updated through real world data capture by laser scanning and site progress records.

Additionally, an **operation-oriented** DT shall address predictive maintenance for a critical handling asset, such as a waste emplacement machine, by integrating IoT sensor streams with a digital model to anticipate failures and optimize maintenance interventions, environment monitoring indicators etc.

These pilots should be led by the WMOs as asset owners and ultimate end-users, working in partnership with technology providers and research organizations responsible for methodology development and independent validation. The completion of these pilot projects will be a proof of concept or *Minimum Viable Product* (MVP), which will serve to prioritize and emphasize the functionalities with a higher added value while increasing stakeholder confidence before a wider-scale deployment. Such pilots must be monitored and evaluated to demonstrate that the implementation of DTs provide a tangible return on investment through reduced downtime, improved construction project control, more informed operational decision-making, and information persistency among others.

3.1.4 Digital Information Platform for Digital Model Validation

Building on the methodological principles demonstrated in FISST test (Posiva Oy) and NAGRA's integrated repository Digital Twin (Cayon De la Hoz, et al., 2026), a real-scale information hub should be established to federate **data, geometry and multiple simulation models** within a controlled, traceable environment. This information hub must be understood as a software ecosystem which connects solutions answering to a certain functionality (geometrical features, operation and

[1] **4D BIM – Time simulation:** 4D BIM links model elements to the project schedule to visualize construction, operation, or dismantling sequences over time.
5D BIM – Cost management: 5D BIM links model elements to quantities and cost data to support cost estimation, budget control, and change assessment.
For further information, see buildingSMART International, "A New Way of Working", and NBS, "BIM dimensions: 3D, 4D, 5D, 6D BIM explained (BuildingSMART International, 2026)

maintenance, thermal simulations) enabling a seamless data flow from the models and deliverables created by the multiple teams included in the project delivery and later phases of the asset's lifecycle. This platform will serve as the starting point for developing a **Digital Twin validator** to support the proposed pilot projects, enabling systematic testing of DT functionalities and providing evidence-based feedback on performance and gaps.

The recommended way forward is to leverage existing repository digital environments and model-integration use cases already developed by organizations contributing to this work package (e.g., initiatives led by Clay Technology, NAGRA, and relevant NND or SGDEs use cases) (Cayon De la Hoz, et al., 2026). This approach accelerates validation activities by taking advantage on the substantial progress already achieved, focusing effort on those aspects that require further attention rather than rebuilding baseline capabilities from scratch. The selected baseline it system will be used to configure a validation dataset catalogue (metadata, quality assurance flags and access rules). It shall provide digital model registry functionalities (versions, parameter sets, assumptions and validity domains), and automated calibration and cross-validation pipelines with benchmark scenarios and acceptance criteria, generating auditable scorecards and reproducible validation reports. Once the solution(s) have been deployed and tested, the WMOs shall define the functional and technical requirements for their future standardized solution. Even when those requirements might be covered by certain commercial solutions, it is important that WMOs retain control over the system architecture and ownership of the resulting platform to avoid vendor lock-in problems and drive the platform development and growth through the path they consider more adequate.

This approach enables a controlled cost access to already available platforms which enables benchmarking and identification of MoSCoW (MoSCoW Prioritisation. DSDM Project Framework) requirements for the future Radioactive Waste Management DT platform.

3.1.5 Lifecycle Integration Framework (Design–Construction–Operation–Maintenance)

The nuclear community, with the leadership and contribution of multiple stakeholders such as permanent organizations (PECD/NEA; IAEA), WMOs and TSOs should promote an approach which pursues digital continuity across the entire repository lifecycle from conceptual design and construction to operation and maintenance. Therefore, a lifecycle Integration Framework (LIF) must be defined, enabling seamless information flow between engineering design models, as-built records, and operational monitoring data.

This action is based in the output extracted from the previous subchapter 3.1.4 Digital Information Platform for Digital Model Validation while complemented with specific functionalities for Design, Construction and O&M phases. Functionalities such as 4D; 5D BIM environments, asset management, predictive maintenance, warehouse management functionalities to determine the capacity and retrieve data an information from the waste packages allocated to a certain cell and evolve into operational twins, integrating real-time feedback from monitoring to inform future design modifications, maintenance and development strategies.

For WMOs, the principal benefit lies in establishing a complete digital thread across repository development, enabling end-to-end traceability from initial design assumptions through field execution to operational performance. Such integration helps reduce lifecycle costs, improves the reliability and consistency of data, and provides regulators with transparent, auditable evidence across project phases to support the long-term safety case.

3.2 Long-Term R&D Horizon - Scaling and Integration

With the foundations in place, the focus shifts to integrating advanced capabilities and scaling the DT to encompass the entire repository system and its long-term evolution.

3.2.1 Implement a Full-Scale, "Living" Safety Case DT

A key long-term objective is the implementation of a full-scale, “living” Safety Case Digital Twin. This requires the integration of the principal components described under section 3.1 Near-Term R&D Steps

- Laying the Foundation into a single platform capable of continuously assimilating monitoring data and using it to inform and update long-term safety assessments. This proposed an evolution of the safety from a static body of evidence into a dynamic and continuously enriched framework, in which performance assessment models can be progressively calibrated against observed repository behaviour.

This activity should be led by a WMO as a strategic programme, bringing together the outputs of the preceding R&D steps within a dedicated cross-disciplinary structure involving safety case specialists, data scientists, and software engineers. Its enables dynamic, evidence-based safety case that can strengthen regulatory confidence and public trust whine providing a transparent, auditable and continuously improving understanding of repository performance, transforming the safety case from a static document into an active decision-support environment.

3.2.2 Establish a Community-Wide Benchmark and Validation Programme

A community-wide benchmark and validation programme should be established in order to provide a common basis for assessing the robustness and reliability of Digital Twin tools and methodologies. This would involve the creation and maintenance of a set of standardized benchmark cases, ranging from component-level representations to full-repository scenarios, against which DT models, workflows and tools can be tested.

Such benchmark exercises could also include mock-up digital challenges based on recognised experimental or repository-related environments, such as Mont Terri or ONKALO®, as well as partial benchmark representations covering selected stages or functions of a radioactive waste disposal programme.

Such an initiative should be undertaken by an international consortium operating under the umbrella of organisations such as the IAEA or the OECD/NEA, with technical contributions from major WMOs, research institutions and regulators. The expected benefit is that it would help ensure quality, build confidence in DT outputs, and enable objective comparison between alternative methodologies. At the same time, it would accelerate the adoption of DT solutions by providing a common technical focus for the wider community and would constitute an essential step towards regulatory acceptance of emerging digital approaches in radioactive waste management.

4 Call to Action

We recommend moving from theory to action articulating and effort to demonstrate how AI/LLM-powered (**A**rtificial **I**ntelligence / **L**arge **L**anguage **M**odels), ontology-based Digital Twins can transform **DGR design**, **implementation**, **operation** and long-term safety assessment, while delivering common standards, architectures and methodologies for interoperable deployment.

In order to advance the implementation of digital twins in radioactive waste management, it is essential to promote a coordinated program led by end users. This program should focus on defining common requirements, testing priority use cases with representative data, and consolidating standards and qualification pathways that can be confidently adopted by WMOs and TSOs. Furthermore, it is necessary to address the conservative and demanding regulatory environment of the nuclear sector, thereby facilitating the adoption of digital practices and maximizing their benefits. If action is not taken now, efforts in digital twins will remain fragmented, costly to integrate, and difficult to qualify for nuclear applications.

It is recommended that the broader radwaste community undertakes future activities focused on developing and implementing integrated digital-twin concepts, as outlined in this White Paper. It should be focussed on moving from theory to action articulating and effort to demonstrate how AI/LLM-powered, ontology-based Digital Twins can transform **DGR design**, **implementation**, **operation** and long-term safety assessment, while delivering common standards, architectures and methodologies for interoperable deployment.

4.1 Recommended actions for the near term

To advance the implementation of standardized Digital Twins in Radioactive Waste Management, the following actions have been prioritized as the most relevant near-term measures for establishing common foundations, demonstrating practical value, and enabling coordinated, interoperable deployment across the sector.

- **WMO-driven use case selection and requirements.**

Start from a small, prioritised set of DT use cases that represent real decision points and deliver added value. Typical candidates are: (a) construction progress and quality control for an underground structure using 4D/5D BIM updated by site records and reality capture; (b) operational optimisation and predictive maintenance for a critical handling system integrating sensor streams and maintenance logs; and (c) monitoring-to-model feedback for selected indicators relevant to THMC (Thermal-Hydraulic-Mechanical-Chemical) evolution and operational constraints. For each use case, define scope boundaries, required datasets, interfaces, and SMART objectives with KPIs. This is of key importance to bound the scope and focus on achievable realistic proposals for the implementation of functionalities, while prioritizing those which deliver the best cost-benefit ratio.

- **Common semantic backbone and federated data governance.**

Interoperability cannot be achieved through file formats alone. The proposed work scope should deliver an open, FAIR-aligned (Findable, Accessible, Interoperable and Reusable) semantic data model (ontology) defining and relating core entities (waste packages, barriers, geologies, sensors, events, requirements, evidence and model versions). In parallel, define governance rules, metadata patterns and API conventions so existing systems can interoperate without forcing a single database. Where possible, align with existing EURAD KM assets and initiatives (e.g. Model-Hub) and with relevant external standards.

- **Geometrical and data model MVP as the DT anchor.**

The proposed work scope should implement a minimum viable geometric and parametric model, preferably by adapting existing WMO assets, and otherwise by developing a representative test model. This MVP must link geometry to requirements, documentation and datasets, and act as the integration testbed for connecting BIM/GIS, monitoring data and specialised simulation tools. It should be designed to interface with EURAD KM assets (including Model-Hub outputs) and to host structured links to datasets and surrogate models.
Data should be reported considering that is going to be used by other entities in further steps for

different purposes. Examples can be to use design drawings for the generation of finite elements meshes or to use drawings for the calculation of surfaces and volumes for managing the excavation costs and filling components consumption.

- **DT platform benchmarking, selection and configuration.**

A structured benchmarking must evaluate candidate DT platform approaches against the agreed requirements, focusing on integration capability, workflow automation, cybersecurity constraints and maintainability. The outcome should be both (i) a selected approach for the MVP and (ii) a reusable evaluation framework to support WMO decision making and minimise vendor lock-in.

- **AI/LLM-enabled workflows with provenance.**

The proposed work scope should demonstrate concrete, auditable value from AI/LLM functions under controlled governance: e.g. assisted interrogation ("what changed and why"), automated evidence retrieval with source references, anomaly triage from monitoring signals, or AI-supported optioneering for engineering alternatives. The emphasis must be on traceability, reproducibility and human-in-the-loop controls.

Massive data might make datasets and drawings unmanageable. The information might be reduced as function of the needs through AI/LLM. Examples might be "in situ" datasets and GIS (excavation profiles) which could be used in simulations.

- **Validation and qualification pathway.**

DT adoption depends on trust. In safety-critical domains, a DT must be demonstrably accurate, traceable, and reproducible, with clear version control, quality assurance, and auditability. The proposed work scope should define and test a validation framework combining benchmark cases, model versioning and provenance, procedures for anonymised/synthetic/mock datasets when access is constrained, and explicit treatment of uncertainty propagation. This should be shaped with early input from TSOs and regulators to ensure that DT outputs can support safety case evidence chains.

WMOs should take the responsibility under the supervision of the regulators to assure that it is robust and FAIR-aligned.

4.2 High level Roadmap and suggested next steps

The next step is to mobilize the right consortium and put governance in place from day one. This means confirming the core preparation team across WMOs, TSOs and Research Entities, agreeing who owns which deliverables, and setting up lean but effective steering and technical/KM structures. In parallel, the consortium needs to define baseline rules for data access and handling-including confidentiality, cybersecurity constraints, and pragmatic approaches for working with restricted datasets (e.g., anonymization, synthetic or representative datasets) so that technical work can progress without being blocked by access limitations.

With governance established, the program should converge quickly on a small number of decision-critical use cases and translate them into a consolidated requirements set. This requires structured workshops to prioritize scenarios with clear operational and safety-case relevance, and then define what "success" looks like: objectives, measurable outcomes, required datasets, interoperability needs, and acceptance criteria. The output should be a requirements package that is implementation-ready and anchored in the agreed semantic approach (i.e., consistent concepts, metadata and traceability rules).

On that basis, the consortium should produce a technology-agnostic reference architecture and integration blueprint. The goal is to define a modular target architecture for a federated Digital Twin ecosystem-covering the semantic/data backbone, integration layers for BIM/GIS/monitoring, model management and versioning, and the interfaces needed for analytics and visualization. Critically, this blueprint must include reusable API patterns, provenance requirements and traceability specifications, so that interoperability can be replicated across organizations and tools without bespoke one-off integration.

In parallel, the program should deliver a MVP for the Digital Twin anchor and use it to benchmark and validate the approach. This includes developing a representative geometric and information model,

connecting priority datasets, and implementing the core integration workflows that the use cases depend on. Where AI/LLM components are included, they should be introduced strictly as governed, auditable workflow enablers (e.g., evidence retrieval with sources, change interrogation, anomaly triage), with explicit provenance and human-in-the-loop controls. Platform benchmarking should be treated as a structured decision support exercise, producing both a recommended implementation route for the MVP and a reusable evaluation framework for WMOs.

Once the MVP is operational, the consortium should run pilots focused on proving end-to-end value and qualification readiness. This is where workflows are executed, outcomes are captured, and the validation/qualification framework is tested against benchmark scenarios and acceptance criteria. The emphasis should be on documenting what works and what does not: integration patterns, mappings, scripts, quality checks, governance controls, and repeatable validation steps that can be reused beyond the pilots.

Finally, the program should consolidate the results into a scalable adoption package: an impact narrative grounded in evidence, a high-level business case, and a roadmap for scaling from pilot contexts to full facilities. This roadmap should identify the main cost drivers, capability gaps, required organizational changes, and the sequence of adoption steps-positioning the outcome as a coherent bridge into longer-term European deployment and follow-on R&D beyond EURAD-2.

5 References

BuildingSMART International. (s.f.). Retrieved February 12 2026, from https://www.buildingsmart.org/standards/

BuildingSMART International. (27 de 05 de 2026). *A new way of working*. Retrieved from BuildingSMART Professional Certification: https://education.buildingsmart.org/a-new-way-of-working/

Cayon De la Hoz, P., Pintado, X., Romero, W., Papafotiou, A., Baksay, A., & Szöke, R. (June 30 2026). *Digital Twin Case Studies and their application to waste management treatment and repository facilities.* doi:10.5281/zenodo.20797560

Laikari, A., Diederik, J., & Szöke, R. (2025). Digital Twin and their gaps in the Radioactive Waste Management domain. Final version as of 31.10.2025 of deliverable D15.5 of the European Partnership EURAD-2. EC Grant agreement n°:101177718.

Open Geospatial Consortium. (s.f.). *Open Gesopatial Consortium.* Retrieved February 12 2026, de Standards: https://www.ogc.org/standards/

6 List of acronyms and abbreviations

- AI: Artificial Intelligence
- Andra (or ANDRA): Agence nationale pour la gestion des déchets radioactifs (National Agency for Radioactive Waste Management)
- API: Application Programming Interface
- BIM: Building Information Modelling
- CAD: Computer-Aided Design
- CDE: Common Data Environment
- CODE_BRIGHT: COupled DEformation BRIne Gas, Heat and Transport
- DITOCO2030: Digital Twins to support Optimization (including communication of safety), Construction and Operation of radioactive waste management facilities 2030
- DGR: Deep Geological Repository
- DRM: Dynamic Repository Model
- dSC: digital Safety Case
- DT: Digital Twin
- EBS: Engineered Barrier System
- FAIR: Findable, Accessible, Interoperable and Reusable
- FEFLOW (Finite Element subsurface FLOW)
- FISST: Full-Scale in Situ System Test
- GIS: Geographic Information System
- HGM – Hydro-geological model
- IAEA: International Atomic Energy Agency
- IGM: Integrated Geo-Model
- INGECID: Ingeniería, Consultoría, Investigación y Desarrollo (Engineering, Consulting and Research&Development)
- ISFSI - Independent Spent Fuel Storage Installation
- IT: Information Technology
- KBS-3V: Kärnbränslesäkerhet-3 Vertikal, nuclear fuel safety-3 vertical
- LIF: Lifecycle Integration Framework
- LLM: Large Language Model
- MVP: Minimum Viable Product
- NAGRA (or NAGRA): Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (National Cooperative for the Disposal of Radioactive Waste)
- NEA: Nuclear Energy Agency
- NHKV - Nemzeti Hulladékgazdálkodási Koordináló és Vagyonkezelő
- NND – Norsk nukleær dekommisjonering
- NRWR: Nemzeti Radioaktívhulladék-tároló (Hungarian National Radioactive Waste Repository). It is also known as NRTH
- OECD: Organisation for Economic Co-operation and Development
- PSI: Paul Scherrer Institute
- R&D: Research and Development
- RD&D: Research Development and Demonstration
- TH: Thermo-Hydraulic
- THMC: Thermo-Hydro-Mechanical and Chemical
- TSO: Technical Support Organization
- URL: Underground Research Laboratory
- VTT: Valtion Teknillinenn Tutkimuskeskus (State Technical Research Centre)
- WMO: Waste Management Organization