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Executive Summary

The long-term safety of near-surface radioactive waste disposal facilities relies on the performance of engineered barrier systems, particularly multilayer cover systems and cementitious barriers. Water infiltration through the disposal facility is strongly controlled by the hydraulic and structural properties of these barriers and consequently governs the migration of mobile, long-lived radionuclides such as ^{36}Cl, ^{14}C, ^{99}Tc, and ^{129}I. While the chemical degradation of cementitious materials has been extensively studied, the impacts of crack formation and the accumulation of steel corrosion products on radionuclide transport remain insufficiently understood and require further consideration in safety assessments.

The EURAD2 Work Package 14 (SUDOKU) project aims to improve the understanding of the long-term behaviour and performance of multilayer covers and cementitious barriers in near-surface disposal facilities. Emphasis is placed on the coupled chemo-mechanical evolution of these barriers and its influence on the transport of mobile radionuclides.

Within SUDOKU, Task 5 investigates the effects of multilayer cover performance and cementitious barrier degradation on radionuclide migration in the repository near field with help of numerical models. Cover system performance is evaluated in terms of water flow through the cover, whereas cementitious barrier performance is assessed through radionuclide release and transport. In addition, the task examines the dependence of concrete degradation processes on water saturation conditions and water fluxes within the repository system.

This milestone report presents the generic repository concept selected as the common basis for the modelling activities of Task 5. The design is primarily derived from the IAEA reference concept (IAEA, 2004) and the SUDOKU State-of-the-Art report (Jacques et al., 2025). It describes the overall repository architecture, with particular focus on the multilayer cover and cement-based barrier system as the principal safety functions. To enable efficient numerical modelling, the repository design has been simplified to retain only the essential safety-relevant features while omitting non-critical engineering details. Whenever possible, the selected materials and barrier components are aligned with those investigated in SUDOKU experimental Tasks 3 and 4, thereby ensuring consistency between experimental characterisation and modelling activities, and facilitating the use of experimentally derived hydraulic, mechanical, transport, and chemical parameters.

Keywords

Surface disposal facilities, cementitious barriers, chemical degradation, corrosion, radionuclide mobility

Table of content

1 Scope

The safety of surface disposal facilities typically relies on the performance of the multilayer cover and the cementitious barrier system. The main contributors to the dose are long-lived mobile radionuclides, whose mobility through the disposal zone depends strongly on the properties of these engineered barriers.

The water flux passing through the disposal facility is closely linked to the durability of these barriers and directly influences the migration of mobile radionuclides (e.g. ^{36}Cl, ^{14}C, ^{99}Tc,^{129}I). The impacts of cracks and steel corrosion products on radionuclide transfer in cementitious barriers are still not well characterised and therefore need to be properly addressed in safety assessments.

The SUDOKU approach combines investigations of multilayer covers with studies on the durability of cementitious barriers to assess the transfer behaviour of mobile radionuclides in damaged systems. This assessment is carried out in the context of the chemo-mechanical evolution of the barriers. A better understanding of the coupled processes in such repositories will contribute to their optimisation.

Task 5 of SUDOKU focuses on assessing how multilayer cover performance and cementitious barrier degradation affect radionuclide migration in the repository near-field. The performance of the surface cover is evaluated in terms of water flow through the cover, whereas the performance of the cementitious barrier system is assessed in terms of radionuclide release. In addition, the task includes the investigation of concrete degradation as a function of water saturation and water fluxes within the repository.

This milestone report presents the generic repository design selected as the basis for all modelling activities in Task 5. It is largely based on an IAEA report (IAEA, 2004) and the SUDOKU SOTA report (Jacques et al., 2025). The description covers the overall repository concept, with particular emphasis on the multilayer cover and the cement-based barrier system as key components. For modelling purposes, the design is simplified to include only the essential safety-related functionalities, while less critical technical details are omitted. Wherever possible, the materials considered (clays, concrete, mortar, backfill) are aligned with those investigated in the experimental Tasks 3 (multilayer cover) and 4 (cement-based materials), for which physical (transport, mechanical) and chemical parameters are expected to be available or measured within SUDOKU.

To evaluate barrier performance with respect to radionuclide transport, simplified subsystems of the concrete barriers are modelled. The temporal evolution of the barrier system is taken into account only indirectly through the selection of material parameters. These models enable comparison of barrier performance under varying conditions and material states (e.g. saturation level, degree of concrete degradation, cover erosion). They also provide a framework for refining the initial parameter sets at a later stage of the project, once experimental results from Tasks 3 and 4 become available.

2 Generic surface disposal system

2.1 General system

The repository considered, shown in Figure 1, represents a typical near-surface disposal system for radioactive waste. It consists of a concrete vault structure located above the groundwater table and protected from above by a multilayer cover system. The primary objective of this engineered system is to minimise water ingress and to limit radionuclide transport over long time periods under passive conditions.

Within the vault, the waste is packaged in steel drums, which are placed in reinforced concrete containers and embedded in cementitious material. These containers are arranged within the vault structure, which comprises vertical walls as well as concrete top and base slabs, forming the main components of the near-field engineered barrier system.

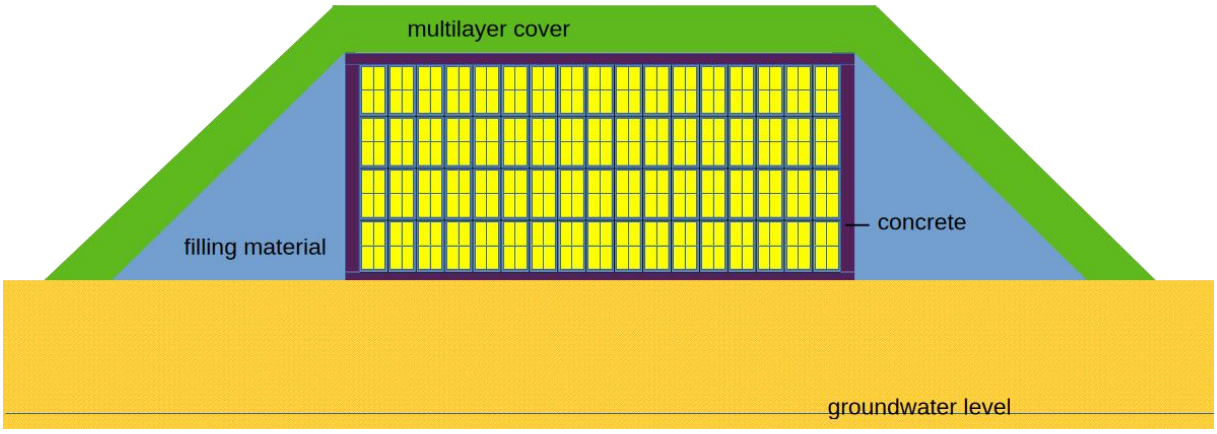

Figure 1: Generic near-surface disposal system. Details on multi-layer cover and concrete barriers are defined in this document.

For modelling purposes, the engineered barrier system includes both the multilayer cover and the concrete barrier system. In this work, the concrete barrier system comprises the structural concrete vault (walls, base slab, and top slab), the reinforced concrete containers, the internal cementitious backfill, the steel drums, and the waste matrix.

Together, these components form a multi-barrier system designed to delay saturation, reduce water fluxes, and attenuate radionuclide migration.

The key engineered barrier components are the multilayer cover system and the cementitious containment system. These two subsystems are therefore the primary focus of modelling and degradation studies within Task 5.

Wherever possible, material parameters for the different materials are taken from the Belgian disposal system described in Seetharam et al. (2018), ensuring consistency with established reference data.

2.2 Multilayer cover system

2.2.1 Introduction

Multilayer cover systems constitute a fundamental component of the engineered barrier system (EBS) in near-surface radioactive waste disposal facilities. Their primary function is to ensure long-term isolation of disposed waste by controlling water infiltration, limiting gas migration, providing mechanical protection against intrusion, and maintaining structural and hydraulic stability over extended post-closure timescales.

In the safety case framework for low-level radioactive waste (LLW) repositories, the final cover is not merely a surface treatment, but a performance-critical barrier intended to provide long-term protection to disposal cells by reducing infiltration and isolating the waste for extended timeframes, typically for at least 300 years during the institutional control phase. It contributes directly to key safety functions, including (i) minimisation of leachate generation, (ii) control of contaminant transport pathways, (iii) protection against inadvertent human intrusion and bio-intrusion, and (iv) long-term geomorphological stability. As such, its design is closely linked to performance assessment modelling, optimisation studies, and regulatory compliance requirements.

2.2.2 Functional objectives and design philosophy

Multilayer covers are designed to fulfil several interrelated objectives:

1. Infiltration control

   The principal hydraulic function is to minimise downward percolation of rainfall water into the waste. Reduced infiltration lowers leachate production and consequently decreases radionuclide mobilisation and transport via groundwater pathways.

2. Gas management

   Covers may incorporate controlled venting or diffusion-limiting layers to manage gas generation resulting from waste degradation processes, while preventing preferential pathways for contaminant release.

3. Mechanical protection and intrusion resistance

   Adequate thickness and inclusion of bio-intrusion barriers provide resistance against burrowing animals and deep-rooting vegetation.

4. Long-term stability and erosion resistance

   Surface layers are designed to resist erosion, differential settlement, and climatic variability, preserving the integrity of underlying hydraulic barriers.

The cover must maintain structural and hydraulic integrity for a defined period of time while satisfying the above-mentioned functional requirements and also assuring maintainability, constructability, and compatibility with monitoring systems. Material selection and vertical stratification are critical design parameters. The hydraulic properties, thickness and distribution of the different layers must be defined according to:

- Maximum allowable infiltration rate
- Durability requirements
- Geometrical constraints and slopes
- Climatic and meteorological conditions

- Site-specific hydrogeological characteristics

2.2.3 Cover design concepts

Most cover designs are based on one, or a combination, of the three following cover concepts, each defined by its dominant hydraulic mechanism:

a) Hydraulic Barrier Covers

Traditional designs rely on low-permeability layers (e.g., compacted clay, geomembranes, geosynthetic clay liners) to reduce infiltration by providing a resistive barrier. While such barriers effectively limit water movement, they may be susceptible to degradation through desiccation cracking, differential settlement, and bio-intrusion.

b) Water-Balance or Evapotranspirative (ET) Covers

ET covers operate on water storage principles, retaining infiltrated water during wet periods and releasing it via evapotranspiration during dry periods. Their performance depends strongly on thickness and vegetation cover. Although effective in arid and semi-arid climates, they may be less robust under variable climatic conditions.

c) Capillary Barrier Covers

Capillary barriers exploit contrasts in unsaturated hydraulic properties between a fine-grained upper layer and a coarse-grained lower layer. This configuration promotes lateral diversion of infiltrating water while keeping the lower layer unsaturated. The mechanism remains effective as long as the matric suction in the upper layer exceeds the entry pressure of the coarse layer. However, intense or prolonged precipitation can reduce its effectiveness, and bio-intrusion remains a concern.

2.2.4 Typical functional layers in multilayer cover systems

Although site-specific adaptations are required based on climatic, hydrogeological, and regulatory conditions, multilayer covers commonly include the following components:

- **Surface soil layer**: supports vegetation, promotes evapotranspiration and minimizes erosion
- **Filter and drainage layers**: prevent clogging and promote lateral water flow
- **Low-permeability barrier**: compacted clay, geosynthetic clay liners (GCLs), geomembranes, or composite systems that provide the primary hydraulic barrier to hinder vertical water flow
- **Bio-intrusion barrier**: coarse rock or combinations of layers with different grain size materials that prevent root penetration and burrowing

2.2.5 Integrated modelling, laboratory testing, and field validation framework for cover design

The design of a multilayer cover requires an integrated methodology in which numerical modelling, laboratory testing, and field-scale observations are mutually reinforcing components of a single iterative process. The cover design can be structured into three strongly interrelated blocks: (1) data analysis and process studies, (2) material characterisation, and (3) numerical simulation. Field-scale data obtained from the monitoring systems of the mock-up cover provide boundary conditions, performance indicators, and validation datasets for the numerical models. These observations also guide the formulation of targeted laboratory experiments. Laboratory-scale tests, in turn, generate quantitative information on hydraulic, mechanical, and retention properties of materials, supplying essential input parameters for simulations and clarifying the detailed physical processes that must be reproduced within the modelling framework. Numerical models integrate these datasets to simulate the cover system behaviour under site-specific and long-term scenarios, identify sensitivities, evaluate alternative configurations, and determine where additional instrumentation or refined testing may be required. Through this continuous feedback loop between field data, laboratory experiments, and modelling, the necessary level of process understanding and design confidence is achieved, enabling a technically justified and performance-optimised cover design.

Within this framework, two cover design cases will be assessed through numerical modelling: one based on the Spanish case and the other on the Lithuanian case. Both cases follow the premises described above and pursue the same overall performance objectives, but they are represented by different cover configurations, allowing the modelling work to compare how alternative designs respond to similar functional requirements. More details on these two designs can be found in the Appendix.

2.2.6 Key processes to be represented in the cover numerical model

The numerical model should represent the main coupled processes that control the water balance and the movement of moisture and energy through the cover. In particular, it should account for the transition between saturated and unsaturated conditions, as well as the movement of liquid water and heat within the soil profile. Depending on the cover configuration, climatic conditions and objectives of the simulation, water vapour transport may also need to be included, especially where evaporation–condensation processes, temperature gradients or very dry soil conditions are expected to play a significant role.

The water balance should include five main terms. First, precipitation must be introduced as a time-dependent atmospheric boundary condition derived from meteorological data. Second, evaporation should be calculated as a function of humidity gradients and vapour pressure, considering both external atmospheric conditions and model variables. Third, surface runoff should be represented as a model variable activated when the soil is unable to absorb the effective precipitation. Fourth, transpiration should be included as a sink term distributed through the vegetated layers, decreasing exponentially with depth in the topsoil and soil layers, and limited by the evapotranspiration demand and plant wilting conditions. Finally, drainage flow at the base of the cover should be represented to quantify the amount of water reaching the drainage layer or leaving the system.

Overall, the numerical model should include, as a minimum, coupled liquid water flow under saturated and unsaturated conditions and heat transport. Water vapour transport can be incorporated as an additional process when required to better reproduce evaporation, condensation and vapour migration within the cover (see Figure 2). This flexible modelling approach allows the level of process complexity to be adapted to the specific objectives of the study, while still supporting the assessment of infiltration, runoff, transpiration, drainage and the long-term hydraulic performance of the cover system.

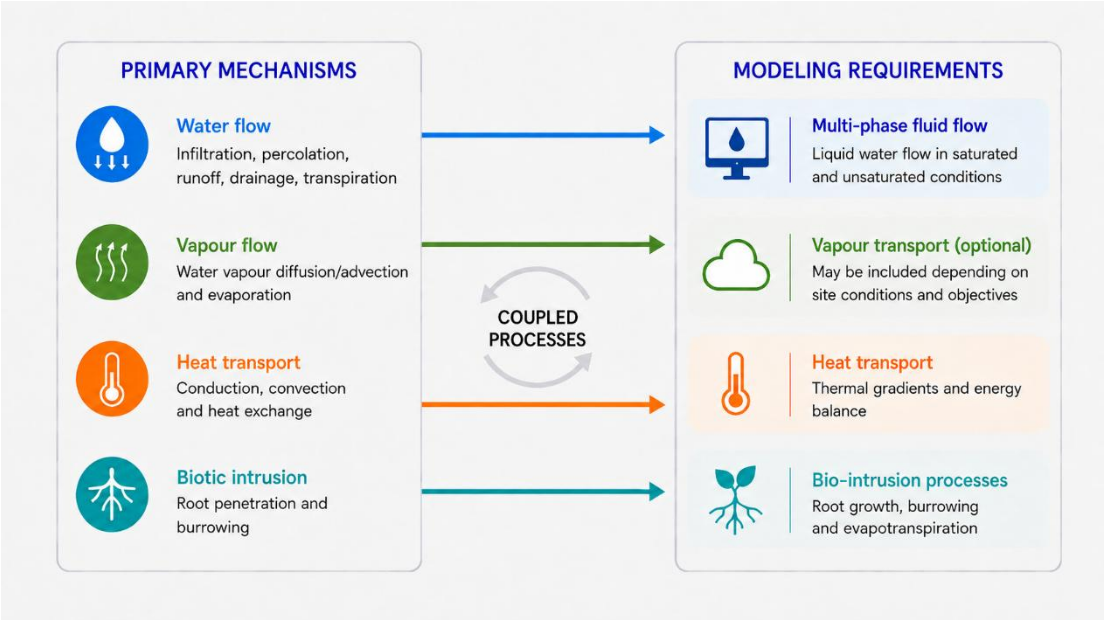

Figure 2: summary of the main coupled processes that control the system and that need to be considered for the numerical modelling.

2.3 Concrete barrier system

2.3.1 Functional objectives

The concrete barrier system is a key component of the engineered barrier system. In this work, it comprises the structural concrete vault (walls, base slab, and top slab), the reinforced concrete containers, the internal cementitious backfill, the steel drums, and the waste matrix.

The concrete barrier system shall provide

- **Favourable chemical environment**: High pH levels within the cement-based materials control chemical reactions such as metal corrosion and microbiologically driven degradation of organic matter. They also retard the transport of most radioactive elements due to enhanced sorption.
- **Water Diversion**: The encapsulation of waste and the use of dense, low-permeability concrete for the containers and vault walls divert water flow around the repository and waste containers, thereby significantly delaying water ingress into the waste and preventing rapid flooding. If the barrier components, specifically the waste matrix remains partially unsaturated and radionuclide transport is governed primarily by diffusion in the aqueous phase, radionuclide release is substantially reduced.
- **Structural Stability**: The extensive reinforcement ensures the mechanical integrity of the barrier components, prevents the formation of highly permeable pathways for water and radionuclide transport, and therefore contributes to maintaining a stable chemical environment.

Like the multilayer cover system, the concrete barrier system must maintain its safety functions for a defined period, which depends on the waste inventory, the local conditions and the expected evolution of the overall repository. Material selection and barrier design need to consider, among other things:

- Geometrical constraints and surface cover design

- Climatic and meteorological conditions
- Site-specific hydrogeological characteristics
- Expected water infiltration through the multilayer cover system
- Potential degradation of concrete, e.g. by carbonation, aggregate-cement reactions,leaching caused by water flow
- Material compatibility with other barrier materials or the surrounding geological environment

2.3.2 Reference design

The setup and geometry of the concrete barrier system follow closely the "vault test case" described in IAEA (2004). The cemented waste is stored in 200 L steel drums with a diameter of approximately 0.5 m, and a height of 1 m. Eight waste drums are packed into a container with dimensions of 1.2 m x 1.2 m x 2.25 m (width × length × height).

A cross-section of a typical long vault is approximately 9 m high and 20.5 m wide and contains 4 layers of 17 containers each (Figure 1). In the vault test case, an 83 m long vault consists of 69 rows of such container assemblies (4 × 17 containers per row), resulting in a total of 4,692 containers and 37,536 drums. In this conceptual design, a full repository is assumed to composed of several such vaults.

In this generic concept, we assume that the void space in the containers and the space between containers is backfilled with a dense backfill mortar.

In our test cases, the length of the vault is not fixed and may be freely extended according to the requirements of the modelling scenario.

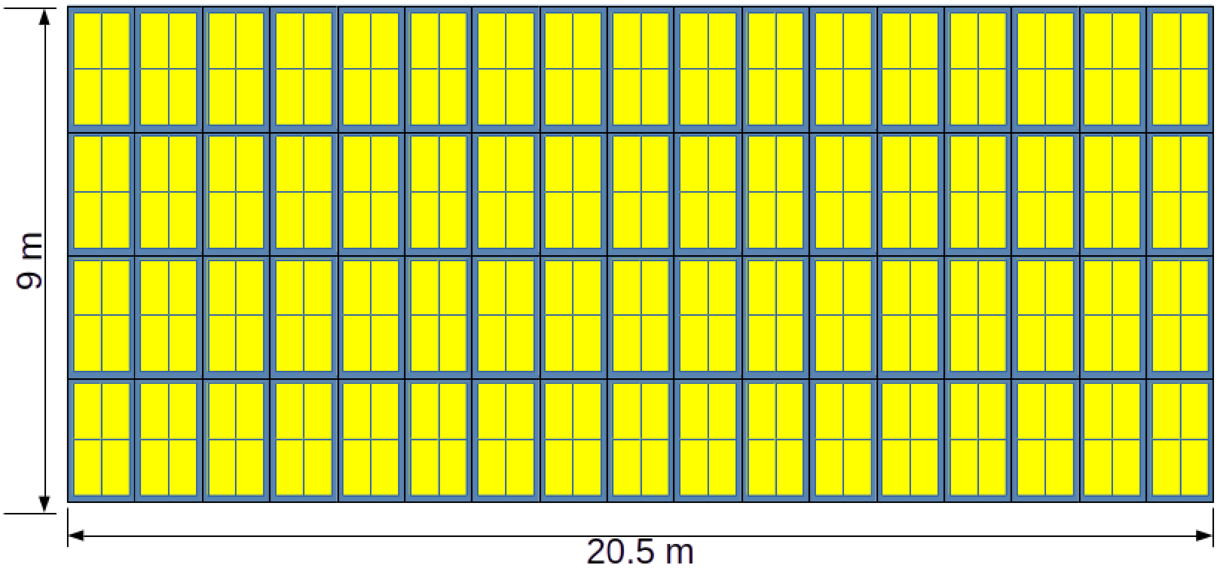

Figure 3: Dimension of the vault test case. 4 x 17 containers, with 8 200 l waste drums per container, are stapled in one row. Vault walls, top and base slabs are not shown.

2.3.2.1 Vault walls, top and base slab

The thickness of the vault walls, as well as of the top and base slabs, is assumed to be 0.3 m (for the walls and top slab) and 0.5 m (for the base slab).

2.3.2.2 Drum

The dimensions of the waste drums follow the size given in the Vault Test Case of IAEA ((2004).

For simplicity, it is assumed that radionuclides are homogeneously distributed throughout the waste drum and that the radionuclide transport properties of the waste matrix are similar to those of other concrete barrier elements. Aqueous radionuclides are only released after corrosion of the steel walls, and provided that transport pathways exist and water saturation is sufficiently high to allow aqueous radionuclide transport (see e.g. section 2.2.2 of Perko et al. (2018)).

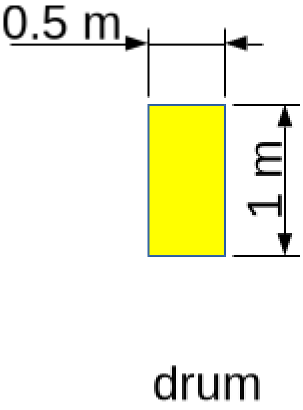

Figure 4: Dimensions of waste drums following IAEA (2004).

Table 1: Description of waste drums

Item	*Value*	*Remarks / Rationale / Justification*
shape	Cylindrical drum	Standard package used across EU near-surface designs and IAEA ISAM test cases
Container		
Material	Carbon steel	Typical for LILW drums; consistent with design baseline
Dimensions (outer)	Diameter ~0.5 m; Height ~1.0 m	Representative 200-L drum geometry used for modelling and packing layout
Wall thickness	1.2–1.5 mm	Preliminary range: to be aligned with Task 4 material set and literature values
Volume	200 L	Standard capacity for reference packing (8 drums per concrete container)

2.3.2.3 Container

The definition of the containers also follows the Vault Test Case in IAEA (2004).

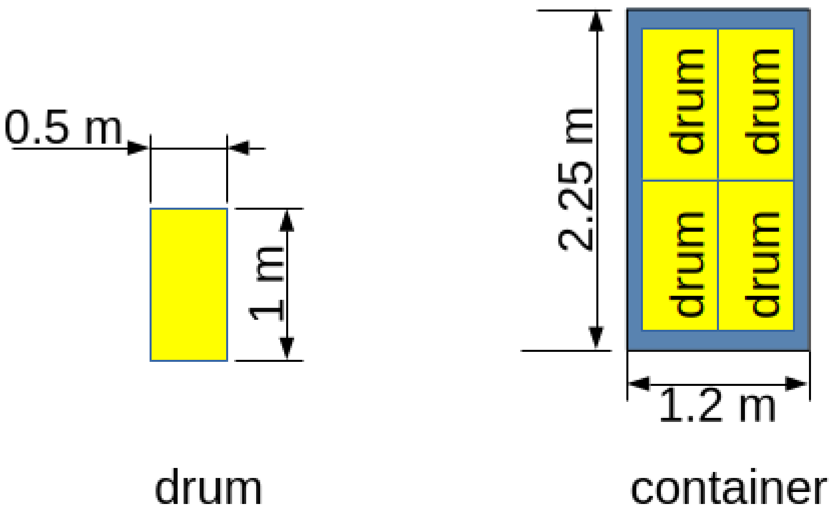

Figure 5: Drum and container dimensions as defined in IAEA (2004). One container contains 8 drums in 2 layers with 4 drums.

Table 2: Description of waste containers

Item	*Value*	*Remarks / Rationale / Justification*
Shape	Rectangular box (monolith type)	As used in Belgian and other EU near-surface designs for LILW designs
Container		
Material	Reinforced concrete - (CEM I) to be confirmed by Task 4	Consistency with Task 4 material characterisation and Belgian Dessel case
Dimension (outer) (WxDxH)	Approx. 1.20 m × 1.20 m × 2.25 m	IAEA (2004)
Thickness (bottom, walls, top)	10 cm	
Internal volume (for drums)	Space for 8 - 200-L steel drums	

2.3.3 Preliminary concrete properties for concrete barrier materials

For the present modelling study, identical water and radionuclide transport properties are assumed for the containers, backfill mortars, vault walls, waste matrix and other concrete barrier elements considered in the model setup (Section 2). These properties will be updated as experimental results from Task 4 become available. Should the experimental data indicate significant differences between barrier components, component-specific transport properties will be implemented in the model.

Table 3: Hydraulic and transport properties for the generic concrete. For the degradation stages and mechanisms see Jaques et al. (2025), Perko et al. (2017) and section 2.4 in this report.

Item	*Values (undegraded)*	*Values (chemically and/or physically degraded/cracked)*
porosity	Θ_s: 0.109*	See Section 5.2.4 in Perko et al. (2017)
hydraulic conductivity (fully saturated)	K_s: 2.06×10^{-13} m/s*	See Section 5.2.4 in Perko et al. (2017)
Van Genuchten parameters for flow/infiltration in partially saturated concrete	Θ_r: 0.0* Θ_s: 0.109* α: 0.000765 1/m* n: 1.307* l: 35.2*	Same values as undegraded

* from Section 5.2.2 in Perko et al. (2017)

Table 4: Radionuclide transport parameters ^{36}Cl, ^{14}C, ^{99}Tc, and ^{129}I from Perko et al. (2018).

Radionuclide	*Half-life (y)*	*Value (undegraded Stage I)*	*Value (degraded stage II)*	*Value (degraded IV)*
^{36}Cl	*3.01E5*	K_D: 0.02 m^3/kg	K_D: 0.05 m^3/kg	K_D: 0.0 m^3/kg
^{14}C	*5.70E3*	K_D: 2 m^3/kg	K_D: 5 m^3/kg	K_D: 1 m^3/kg
^{99}Tc	*2.111E5*	K_D: 0.001 m^3/kg	K_D: 0.001 m^3/kg	K_D: 0.001 m^3/kg
^{129}I	*1.57E7*	K_D: 0.001 m^3/kg	K_D: 0.01 m^3/kg	K_D: 4e-4 m^3/kg
^{93}Mo	*4.0E3*	K_D: 0.003 m^3/kg	K_D: 0.003 m^3/kg	K_D: 1e-4 m^3/kg
all		D_p: 4.0 ×10^{-11} m²/s	D_p: 6.0 ×10^{-11} m²/s	D_p: 7.0 ×10^{-11} m²/s

More sorption parameters (Kd values) for a generic concrete and different degradation stages for other radionuclides can be found in Table 7 of Perko et al. (2018). Decay data is obtained from ICRP (2008). Possible solubility limitations for radionuclides are currently not considered in the calculations. For the pore diffusion coefficient (D_P) the simplified approach of using a non-radionuclide dependent value is adopted from Tables 4 and 5 of Perko et al. (2018), where also data on bulk density can be found. For radionuclide specific data and more detailed considerations refer to Seetharam et al. (2018).

2.4 Evolution of disposal system

In describing the evolution of the disposal system, it is recognised that the relevant timeframes, processes, and available data vary between cases and have not yet been fully defined for the reference design considered in this study. The present analysis is therefore based on a set of agreed assumptions and parameters, using the Belgian case as a source of material property data and the IAEA benchmark vault layout as the basis for representing system evolution. This approach enables the key aspects of long-term barrier degradation and repository evolution to be assessed while retaining sufficient flexibility to incorporate new information and refine the conceptual model as it becomes available.

2.4.1 Reference scenario

To ensure consistency across modelling activities and to provide a transparent basis for safety-oriented evaluations, a reference evolution is defined. This scenario is not intended to represent the full range of possible evolutions, but rather to capture typical and representative system behaviour.

2.4.1.1 Assumed evolution

This scenario represents the nominal evolution of the disposal system. Water ingress increases gradually as cover performance declines over time, leading to progressive wetting of engineered barriers, a delayed onset of significant degradation, and the development of connected aqueous transport pathways. The onset of relevant degradation and transport conditions is assumed to occur after approximately 1,000 years. Thereafter, degradation progresses gradually through successive stages of chemical evolution, without assuming an instantaneous collapse of the concrete system.

2.4.1.2 Saturation and drainage

In the reference scenario, the repository is assumed to be located well above the groundwater table and to have no contact with an underlying aquifer. Water migration occurs only through the cover and is directed around the vault. Specifically, water passing through the cover flows first along the vault roof and then downward along the vault walls. Moisture can enter the vault via capillary suction, gradually saturating first the vault walls, then the containers, and eventually the waste packages.

Water movement is very slow as long as the concrete materials remain intact and exhibit very low permeability. Degradation of the concrete, particularly cracking, can significantly accelerate water ingress. Whether and when full saturation is reached depends on the magnitude and variability of water fluxes through the cover.

For the initial saturation state of the repository, the assumptions discussed in Section 2.2.3 of Perko et al. (2018) are adopted. The initial saturation of concrete materials, expressed in terms of relative humidity, is assumed to be approximately 80%.

The considered vault system is designed such that the walls, base slab, and top slab act as hydraulic barriers. A specific scenario may therefore be considered in which the vault cover (top slab) is damaged while the other structural elements remain intact. In such a case, water may enter the vault, potentially leading to flooding and full saturation.

Although upward flow and capillary saturation from below are not included in the reference case, such effects may be considered in dedicated sensitivity analyses.

2.4.2 Near-field materials

Key assumption: The same type of concrete, with harmonised properties, is used for containers, backfill mortar, and vault walls and slabs. This simplifies the modelling and ensures a consistent representation of degradation processes, which are assumed to proceed in a similar manner across all system components.

2.4.2.1 Drums

The steel drum walls, as well as the potentially complex internal structure of the waste and its temporal evolution, are not explicitly considered. For example, the onset and duration of drum corrosion are not fixed to a specific time period, as they depend on saturation evolution, concrete degradation, and redox conditions within the repository.

In the reference scenario, the drums are represented as concrete blocks with material properties identical to those of the reference concrete. The radionuclide inventory is assumed to be homogeneously distributed within the waste package. The effective material properties of the waste packages may be adjusted at a later stage if more detailed information becomes available.

2.4.2.2 Containers

Containers made of reinforced concrete are assumed to act as an intermediate barrier but will gradually lose their integrity as cracking develops. It is important to use parameters corresponding to the specific concretes and materials investigated in Tasks 3 and 4 to avoid inconsistencies between experimental results and modelling. In the absence of such data, reference parameters will be used initially, but these should be updated as more information becomes available.

2.4.2.3 Container and gap backfill

The cementitious backfill within the containers is also expected to degrade over time, resulting in a loss of its initially low permeability. The presence of cracks is taken into account, as these features may influence local water pathways and radionuclide transport.

3 Definition of scenarios for evaluation of barrier performance

Because water saturation, concrete degradation, and the transport of radionuclides (RNs) are highly dependent on assumptions regarding repository evolution, the performance of cover and cement-based barriers is evaluated independently of repository evolution. Such an approach, in which barrier performance is evaluated independently of each other and overall system evolution, allows the use of simple analytical and numerical models that do not explicitly include all relevant processes influencing water and radionuclide transport.

3.1 Cover models and water infiltration

The main performance indicator for cover models is the water flux ($m^3\ m^{-2}\ s^{-1}$), i.e., the infiltration of water through the cover towards the underlying cementitious barriers.

For the investigation of cover performance, several scenarios are considered:

- **Reference Scenario (Cover-A):** The multilayer cover functions as designed for 1,000 years. Cover performance is evaluated assuming constant material properties over a period of 1,000 years following repository closure. This case is consistent with the cover evolution scenario presented by Perko et al. (2018).
- **Optional Scenario (Cover-B):** An alternative case in which cover materials maintain constant properties for the first 100 years (representing the active institutional control period), after which the confining clay barrier degrades.
- **Optional Scenario (Cover-C):** A sensitivity analyses in which cover performance is evaluated by varying the thicknesses and hydraulic properties of the cover materials.

3.2 Cement based barriers and radionuclide transport

The main performance indicator for the concrete barrier system is the release of radionuclides from the engineered barriers. This is quantified as the radionuclide flux ($mol\ m^{-2}\ s^{-1}$) across the interface between the barrier system and the surrounding materials (backfill or soil).

Figure 6 shows a possible conceptualisation of the model used to estimate the performance of a system consisting of waste packages, a concrete container, and vault structures (walls and slabs). Edge waste packages are selected because they possess the largest outward transport boundary area, allowing the investigation of how variations in wall and slab thickness influence transport.

- **Reference Scenario (RN-A):** Maximum expected radionuclide release (flux) from the engineered barriers under fully saturated conditions, assuming diffusion-controlled transport.
- **Optional Scenario (RN-B):** Same geometry as Scenario RN-A, but with material parameters corresponding to partially saturated conditions.
- **Optional Scenario (RN-C):** Maximum expected radionuclide release (flux) from engineered barriers along a discrete transport pathway (fracture) intersecting a waste package.

Initially, radionuclides are assumed to be homogeneously distributed within the waste drums. All steel drum walls are assumed to have failed due to corrosion at time t = 0 s and are therefore not explicitly represented in the model.

For Scenarios RN-A and RN- B, transport is assumed to occur exclusively by diffusion.

For radionuclide transport, boundaries A and B are assumed to be perfect sink boundaries (C = 0 mol m^{-3}) in all scenarios. All other boundaries are treated as reflecting (no-flux) boundaries. The performance of the concrete barriers is evaluated in terms of the integrated radionuclide flux across boundaries A and B.

For Scenarios RN-A and RN-C, fully saturated conditions are assumed. For Scenario RN-B (partially saturated conditions), the lower boundary is assumed to have a degree of saturation of 0.8. The equilibrium saturation profile in the vertical direction is calculated using the saturation-pressure relationship and the van Genuchten parameters given in Table 3

For Scenario RN-C, a fracture is assumed to cross a waste package diagonally, extending through the concrete container and vault wall. Water flows through the fracture at a constant flux. Radionuclide transport within the fracture occurs via advection and diffusion/dispersion, whereas in the surrounding matrix pore water is assumed to be stagnant, with transport occurring solely by diffusion.

The fracture aperture is assumed to be 1 mm. Hydraulic properties will be estimated using the cubic law, which is based on the idealized assumption of laminar flow between smooth, parallel fracture walls with a constant aperture. Furthermore, 2% of the water flux passing through the cover towards Boundary A (area = 1.2 m × 1.2 m) is assumed to enters the fracture, while the remaining water bypasses the vault and flows through the surrounding materials along the vault walls.

Possible sub-scenarios may address:

- different sorption properties,
- the influence of radionuclide solubility limits,
- variations in fracture flow rates in Scenario RN-C,
- the influence of concrete degradation state, including:
    - Stage II (OPC, pH ≈ 12.5),
- Stage III (low-pH material), Stage IV (carbonated material).

3.3 Saturation and degradation of cement-based barriers

In support of the radionuclide transport scenarios, repository resaturation is investigated with respect to the following two questions:

1. How long does it take for all materials within the repository to equilibrate with an atmosphere at 100% relative humidity? In this case, resaturation is driven by moisture transport in the gas phase.
2. How long does it take for the repository to become fully saturated if the top cover is damaged and water enters the vault from above? What are the resulting water fluxes within the vault walls and the base slab?

The calculated saturation times can subsequently be integrated into simplified concrete degradation models to refine radionuclide transport scenarios.

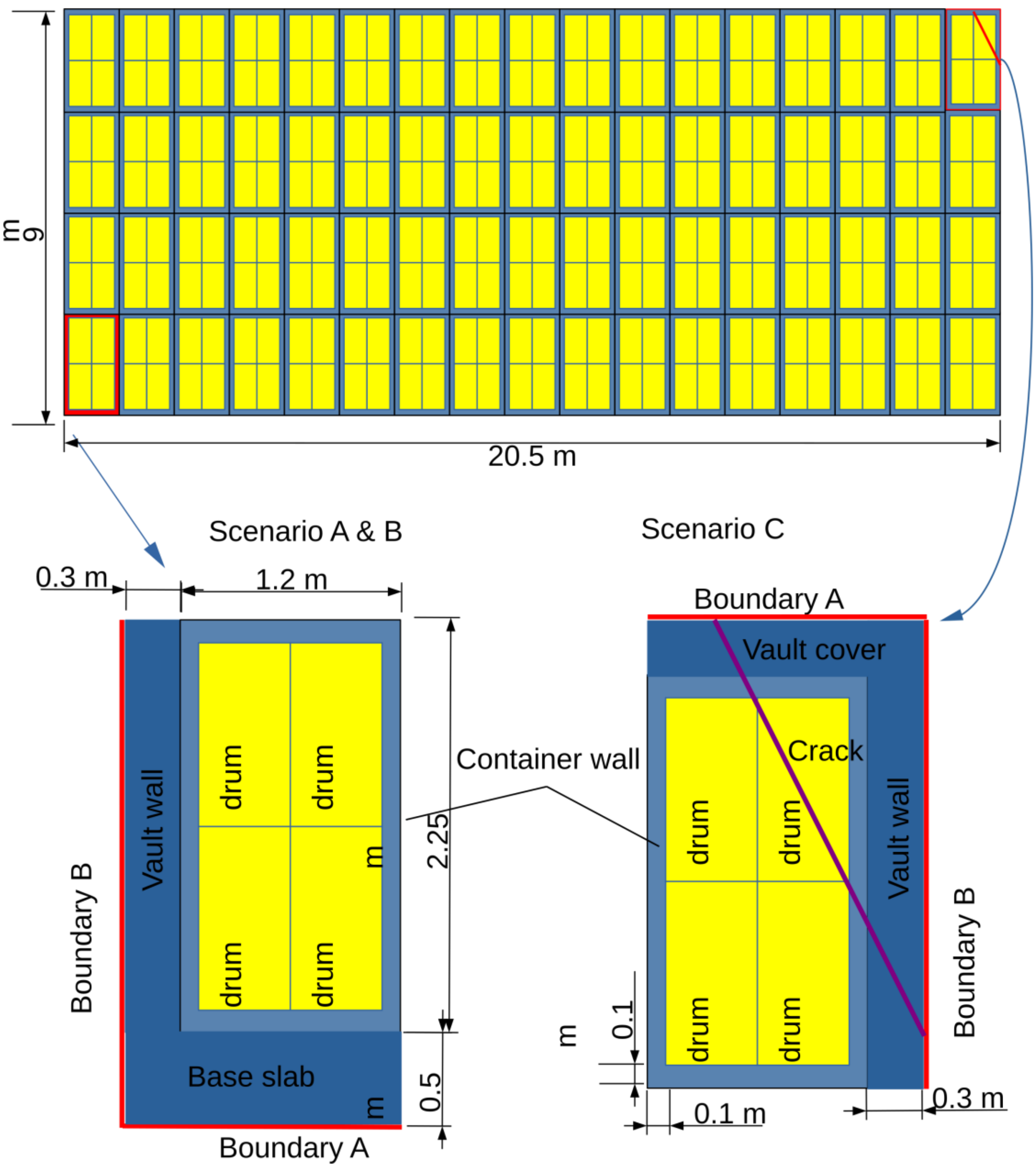

Figure 6: Sketch for conceptual 2D models for radionuclide transport scenarios.

4 Input from Kick-off meeting, system definition workshop and other discussions

4.1 Data exchange between tasks

It was proposed to use the materials investigated in Tasks 3 and 4 (multilayer cover materials, concretes, and backfill materials), as most material properties required for modelling in the undegraded state are already available. These include porosity, permeability, two-phase flow properties, sorption coefficients (K_d), and mechanical properties.

The milestone report currently relies on generic material parameters adopted from Belgian reports, as project-specific material parameters were not yet available. These parameters will be incorporated once the experimental results are collected and made available (MS109/MS111).

5 References

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A. Appendix

A.1 Spanish case

The Spanish facility for the disposal of low- and intermediate-level radioactive waste is located at El Cabril (Córdoba, southern Spain). The regional climate is semiarid, with mean annual precipitation of around 600 mm. Most of the rain falls during the winter, and the rest is distributed mainly between autumn and spring, when evapotranspiration rates are low. To overcome the excess of infiltration over evapotranspiration, a cover comprising topsoil water-balance layers overlying a capillary barrier protected by a bio-intrusion barrier was designed. Two covers, Test I and Test II, were set up to test different layer combinations. The surface area of each cover is approximately 245 m^2 (22 m long by 11 m wide). The geometry of the covers is imposed by the need to cover the concrete cells that contain the radioactive waste, together with geographic restrictions. The result is two contrasting slopes: 2% in the upper zone and 40% in the lower zone. The two multilayer systems are separated by a concrete gallery where the data acquisition system is located (see Figure A.1).

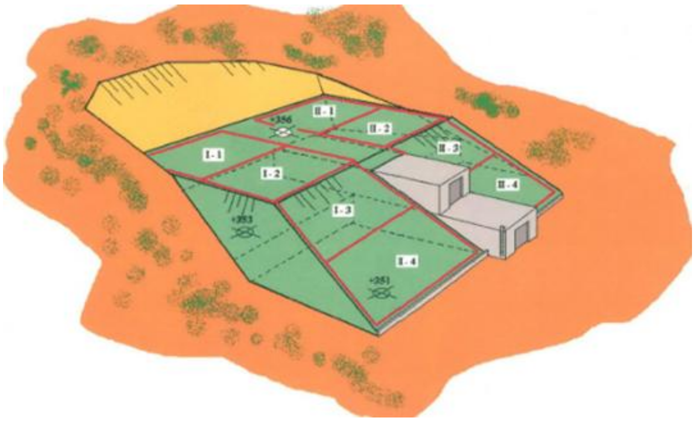

Figure A.1: *General layout of two multilayer systems (Test I and Test II) of the El Cabril mock-up cover.*

The basic criteria and requirements that the cover must satisfy are:

- Durability: the cover should last for 300 years before degradation
- Infiltration through the cover 1.5 l/m2/year
- Erosion due to wind and runoff below 0.5 kg/m2/year
- Rapid rainwater evacuation
- Bio-intrusion protection to prevent intrusion by small animals and deep-rooted vegetation
- Low water permeability
- Drainage of infiltrated water

Test I and test II differ in their layer configurations (see Figure A.2). The design for Test II features a thick layer of clay over a layer of sand, all beneath two filter layers (sand and gravel). For Test I, however, a double capillary barrier design is used (i.e. two superimposed sequences of clay over sand layers). Regarding the bio-intrusion barrier, the filter layers are relocated on top of the gravel layer, while an additional layer of sand is added between the gravel and clay layers.

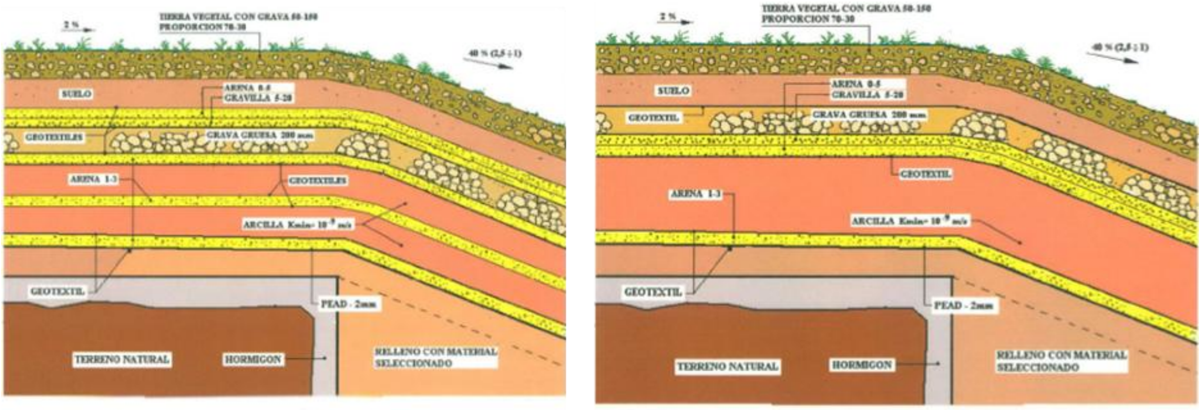

Figure A.2: *Detailed layer disposition of the two multilayer systems (test I on the left and Test II on the right) of the El Cabril mock-up cover.*

The total thickness of the mock-up cover is 3.15 m for Test I and 2.95 m for Test II. Every layer or set of layers has a specific purpose. From the surface to the bottom, the layers and their roles are:

- **Topsoil with gravel:** to reduce erosion from wind and runoff and to store water to facilitate the growth of vegetation promoting evapotranspiration and increasing slope stability.
- **Soil:** to retain enough water to allow the establishment of vegetation, promoting evapotranspiration, and enhancing the growth of shallow-root plants.
- **Sand (only present in Test I):** to act as filter, preventing fine soil from mixing with and contaminating the underlying coarse materials.
- **Gravel and Cobble:** to form a bio-intrusion barrier. In Test I, the gravel layer below the cobble has been replaced by a sand layer. In Test II, the gravel layer above the cobble has been removed. Animal access is avoided by combining different grain sizes and using materials with rounded corners. The largest grain sizes cannot be supported by small species and at the same time, their rounded corners show poor stability, collapsing when larger species excavate. Ants and small mammals cannot dig preferential pathways. The cobble layer, as a non-retentive material, prevents water storage and root growth through it (as roots prefer to grow laterally in the upper layers where water content may be higher).
- **Sand:** to provide a lateral drain for water that infiltrates through the soil and bio-intrusion layers.
- **Clay:** to act as a low-permeability infiltration barrier and as a capillary barrier (together with the underlying sand layer). Moreover, due to its high-water retention capacity, the clay is saturated which prevents gas diffusion. The effect of the clay layer thickness is also tested comparing the performance of using a thinner clay layer over a sand layer repeated twice (Test I) with a single thicker clay layer over a sand layer (Test II).
- **Sand:** as the lowest layer of the capillary barrier, acting as drainage layer below the low-permeability clay layer. In the case of water breakthrough, its high permeability promotes drainage of infiltrating water, facilitating reactivation of the barrier.

A HDPE (high density polyethylene) geomembrane underlays both covers to divert water to a collection system. Perimeter drains were installed around the cover surface to prevent the ingress of external water into the system and to collect runoff.

A.2 Lithuanian case

This section presents a preliminary multilayer cover concept that will be considered by the Lithuanian Energy Institute (LEI) in the frame of SUDOKU for investigations of cover performance.

The multilayer cover concept that will be considered in the LEI assessment is based on the cover foreseen for the planned near-surface repository for low- and intermediate-level short-lived radioactive waste in Lithuania. The repository will be constructed in the eastern part of Lithuania, close to the Ignalina nuclear power plant, where long-term average annual precipitation is about 690 mm and evaporation is approximately 480 mm.

The proposed repository cover includes draining and confining layers, with a soil layer and vegetation on top. The main functions of the cover are to minimize water infiltration into the radioactive waste area, to serve as a barrier against human intrusion, and to limit direct irradiation. The slope of the cover is 3% (3:100) at the top and becomes 33.3% (1:3) at the lower zone. The cover materials and their safety functions are presented in Table A.1.

Table A.1: *Multilayer cover materials and their safety functions*

Barrier	Material	Assignment
Vegetation	Soil, plants	Protect against negative climatic impact (freezing, thawing, erosion), protect against water infiltration
Draining layers	Pebbles	Drain water, evacuate gas, protect against human/animal intrusion, protect against direct irradiation
	Gravel	
	Silty sand	
Protective layer	Moraine clay	Protect against external conditions, protect against human intrusion, direct irradiation
Draining layer	Gravely sand	Drain water
Confining layer	Clay	Protect against water infiltration, protect against human intrusion, direct irradiation
Draining layer	Fine sand	Evacuate gas

The main function of the topsoil layer with vegetation is to protect deeper layers of the cover from adverse climatic conditions (e.g. freeze–thaw effects), to minimize erosion of the cap, and to reduce water infiltration.

The upper draining layer is composed of silty sand, gravel and pebbles. The main purpose of this layer is to drain infiltrated water and to act as a barrier against animal intrusion. In addition, it reduces direct irradiation from the waste.

The moraine clay in the cover separates the two drainage layers and serves a protective function. It protects deeper layers of the cover from the adverse external conditions, acts as an additional barrier against human intrusion and reduces direct irradiation from the waste.

Below the protective clay layer, there is a draining layer of gravelly sand. It provides lateral drainage of infiltrating water.

The confining clay layer has low permeability and serves as the main barrier to water infiltration deeper into the repository. It also helps to reduce direct irradiation from the waste and is considered a barrier to human intrusion.

At the bottom of the multilayer cover, there is a sand layer. Its main function is the redistribution and evacuation of gas that may be generated in the waste.

The conceptual model of the cap and the thickness of each layer are presented in Figure A.3. The material properties assumed for modeling are presented in Table A.2. Considering the objective of Task 5, the assessment will focus on water flow through the cover.

Layer	Thickness, m
Vegetation	0.2
Draining layer	2.0
Protective layer	0.7
Draining layer	0.3
Confining layer	1.9
Draining layer	0.2

Figure A.3: *Conceptual model of the multilayer cover*

Table A.2: *Properties of the cover materials*

Layer	Material	Hydraulic conductivity (m/s)	Bulk density, (kg/m^3)	Effective porosity (-)
Soil with vegetation	Soil	4.63E-05	1680	0.2
Draining layers	Gravely sand	5.00E-05	2000	0.55
Protective layer	Moraine clay	1.00E-06	2250	0.35
Draining layer	Gravely sand	1.74E-04	2000	0.55
Confining layer	Clay	1.00E-09	2000	0.42
Draining layer	Fine sand	1.20E-04	1800	0.6