Near-surface Disposal Facilities: Design, Safety, and Climate Resilience

Topical session 4: Near-surface disposal and climate change (WPs CLIMATE and SUDOKU)

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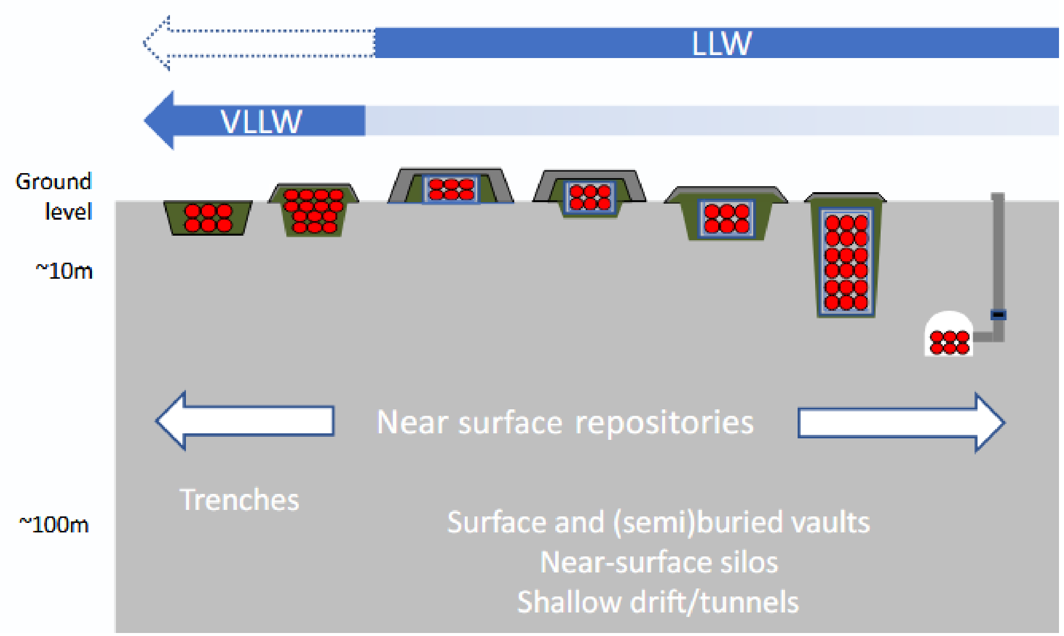
Co-funded by the European Union under Grant Agreement n° 101166718

OUTLINE

- **Designs of Near Surface Disposal Facilities**
  - Similarities & differences in designs of NSDF
  - Multi-barrier system of vault-type repository
- **Key climate parameters relevant for Safety Assessment**
  - Climate characteristics relevant for multilayer covers performance
  - Climate characteristics relevant for cementitious barrier systems performance
- **Examples on how climate aspects are included in SA**
- **Potential design optimizations to cope with climate change**

NEAR SURFACE DISPOSAL FACILITIES

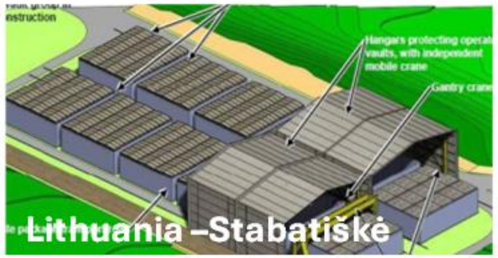
- **Near surface disposal facilities are designed for safe disposal of radioactive waste containing mainly short-lived radionuclides, that will decay to insignificant levels within a few hundred years, and only acceptably low concentrations of long-lived radionuclides**
- **The concept of near surface disposal covers a wide range of facilities, such as:**
  - disposal at the surface in highly engineered vaults or a more simple trench design
  - disposal at varying depths, from a few metres to a few tens of metres, in facilities (vaults, silo, rock cavity caverns) with various types of engineered barriers
- **Passive containment and isolation of the waste will rest on engineered barriers, natural barriers, when present, and favourable features of the natural environment of the disposal facility (e.g. its long term stability)**



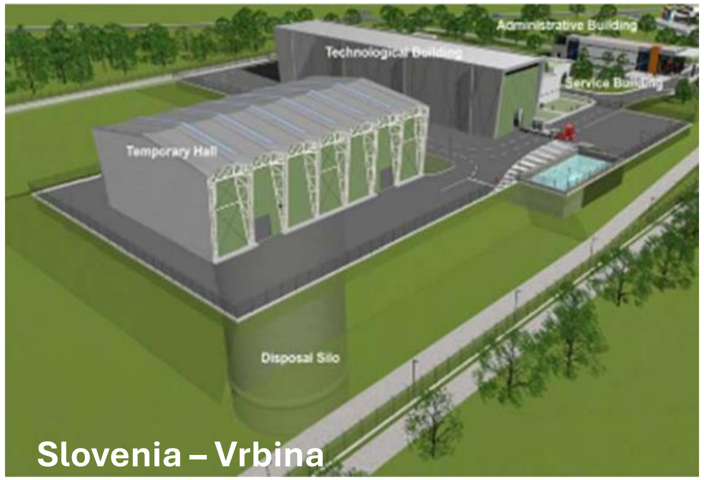
IAEA Nuclear Energy Series, No. NW-T-1.27

EXAMPLES OF SHALLOW FACILITIES IN EUROPE

- **above/below-ground vault-type concept**



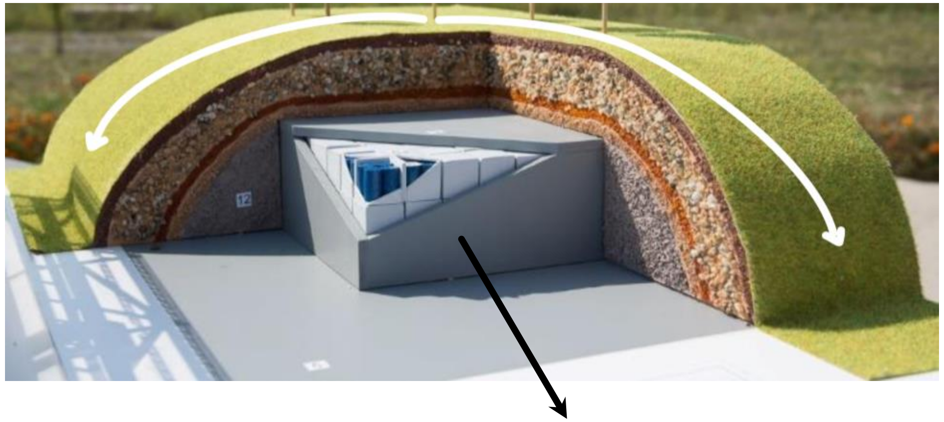
- **below-ground silo concept**



SIMILARITIES IN DESIGN OF VAULT-TYPE REPOSITORIES

- The primary similarity across all vault-type repository designs is the use of **multiple barriers**, generally engineered, but also in some cases natural (geology), to ensure containment of radioactive waste and to divert the meteoric water from infiltrating in the disposal area
  - **with the main aim of preventing the release of radionuclides into the environment** for period of time long enough to ensure their decay to insignificant levels (few hundred of years)
- All designs incorporate **long-term monitoring** to assess the repository performance and ensure there are no releases
- In the short term after closure (usually ~ 300 years), the safety of the NSDFs relies on **institutional controls** (active & passive controls) aiming **to keep the integrity of the engineered barriers**

Meteoric water diversion



Disposal vaults/modules with stabilized radioactive waste

DIFFERENCES IN DESIGN OF VAULT-TYPE REPOSITORIES

The main differences in the designs stem from geological context and operational approach:

- **Above-Ground vs. Below-Ground**:
  - The disposal units (vaults/modules/boxes) can be constructed **above ground** (i.e. Belgium, France, Czech Republic, Slovakia) or **semi-buried** (Spain, UK, Ukraine, Bulgaria, Romania), relying on engineered barriers to avoid water infiltration in the disposal area
  - A particular design of **below ground double-walled silo** was adopted by Slovenia, to ensure increased resistance to external hazards, such as seismic activity and flooding
- **Waste emplacement method:**
  - Some designs involve **direct placement of waste packages** in disposal units (vaults/boxex/silo) - France, Slovenia, Czech Republic
  - In some designs only **monolithic structures** obtained by grouting the waste (either as conditioned or bulk) inside reinforced concrete containers are accepted in the disposal units - Spain, Belgium, Bulgaria, Lithuania, Slovakia, Romania
- **Waste packages** – a large variety of waste packages are licensed for disposal for standard 220 l steel drums to large metallic or concrete packages (for example, in France 16 types of packages are accepted by Andra to be disposed of in CSA).

TYPICAL MULTI-BARRIER SYSTEM OF VAULT-TYPE DESIGN

- **Engineered Barriers:**
  - **Waste Form**: the radioactive waste is treated and solidified into a stable waste form to minimize the radionuclide mobility. The currently used conditioning matrix for LILW is based on cement or bitumen
  - **Waste packages**: the solidified waste is placed inside robust containers (e.g., concrete boxes or metallic drums)
  - **Disposal units (vaults/modules/boxes)**: the waste packages are placed either directly, or overpacked in monolithic structures in the disposal units made of reinforced concrete, providing a durable physical barrier. After filling, the disposal units are sealed with a concrete slab
  - **Backfilling**: the spaces between waste packages/monoliths are filled with gravel or mortar
  - **Drainage system**: located beneath the disposal units to collect any potential water seepage
  - **Multi-layered cover**: After filling and approval for closure, a final engineered cover (often including layers of clay, geomembranes, and vegetative ground) is installed, which is intended to divert water away from the waste and to act as a barrier to seepage, greatly reducing the potential for percolating water to reach the waste
- **Geological Barrier:** some concepts are relying also on the host geology for retarding the radionuclide transfer to biosphere

CLIMATE CHARACTERISTICS RELEVANT FOR MULTILAYER COVERS PERFORMANCE (1/2)

- **Precipitation (Rainfall and Snowfall):**
  - **Intensity and Frequency:** directly affecting the **erosion** (which could reduce the cover thickness and compromise its protective function), **surface runoff**, and **infiltration rates**
  - **Total annual/seasonal precipitation:** directly impacts the water balance within the cover, influencing **moisture content**, **hydraulic conductivity**, and **the potential for water ingress into the waste**
  - **Extreme precipitation events:** can overwhelm drainage systems, lead to significant erosion or even failure of cover components
- **Temperature:**
  - **Daily and seasonal fluctuations:** Large temperature swings can induce thermal stresses, leading to cracking in soil layers or damage to geomembranes (e.g., freeze-thaw cycles)
  - **Mean annual temperature:** Influences evapotranspiration rates (also influenced by wind, sunshine radiation, and precipitation) and biological activity within the cover
  - **Extreme temperatures (heatwaves, freezing events):** Prolonged heat can lead to desiccation cracking in clay layers, increasing permeability. Extreme cold and freeze-thaw cycles can cause frost heave and structural damage

CLIMATE CHARACTERISTICS RELEVANT FOR MULTILAYER COVERS PERFORMANCE (2/2)

- **Evapotranspiration:**
  - **Rates:** Higher evapotranspiration rate can promote desiccation of cover materials (especially clay), potentially leading to cracking and increased permeability. Lower evapotranspiration rate can lead to higher moisture content within the cover
  - **Seasonal variation:** The balance between precipitation, evapotranspiration, surface runoff and canopy interception affect the flux of water infiltrating through the multi-layer cover
- **Wind:**
  - **Speed and direction:** Can cause erosion of surface layers (e.g., topsoil, vegetation), especially during dry periods, potentially exposing underlying barrier components
- **Vegetation growth:**
  - **Type and density:** Influenced by climate. A healthy, well-established vegetative cover can reduce erosion, promote evapotranspiration, and stabilize the soil. Changes in climate could impact suitable vegetation types or lead to die-off

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CLIMATE CHARACTERISTICS RELEVANT FOR CEMENTITIOUS BARRIER SYSTEMS PERFORMANCE (1/2)

- **Water flux/humidity:**
  - **Sustained water contact:** Continuous exposure to water can accelerate various degradation mechanisms in cementitious materials, such as leaching of calcium hydroxide, sulfate attack, alkali-aggregate reaction, and carbonation
  - **Fluctuations in water content (wet-dry cycles):** Can lead to cycles of expansion and contraction, promoting cracking and increasing permeability
- **Temperature:**
  - **Fluctuations:** Thermal cycling can induce stresses and microcracking, particularly if there's a significant thermal gradient across the barrier
  - **Elevated temperatures:** Can accelerate chemical reactions, potentially leading to faster degradation of the cementitious matrix (e.g., increased dissolution rates, faster alkali-silica reaction)

CLIMATE CHARACTERISTICS RELEVANT FOR CEMENTITIOUS BARRIER SYSTEMS PERFORMANCE (2/2)

- **Sulfate and Chloride concentrations in water:**
  - **Environmental sources**: Changes in climate (e.g., increased evaporation in coastal areas) could lead to higher concentrations of aggressive ions in groundwater, accelerating chemical attack on cementitious material
- **Freeze-thaw cycles:**
  - **Fluctuations:** Thermal cycling can induce stresses and microcracking, particularly if there's a significant thermal gradient across the barrier
  - **Frequency and Severity**: Water within pores of the cementitious material can freeze and expand, causing internal stresses and progressive deterioration (spalling, cracking), leading to increased porosity and permeability

CLIMATE ASPECTS IN SAFETY ASSESSMENT

- For near-surface disposal facilities, **the assessment period is a few hundred to a few thousand years**, but still sufficiently long for significant climate changes to occur
- Climate aspects are generally included in developing the **reference and alternative evolution scenarios**
- A "base case" or "**reference scenario**" representing **current or smoothly evolving climate** is usually established, along with alternative "extreme" or "conservative" scenarios (e.g., prolonged dry periods, intense rainfall, permafrost development in colder climates)
- **Climate data** (precipitation, evapotranspiration) are used as **inputs for hydrological models** that simulate water flow through the multilayer cover and into the cementitious barriers. This directly influences the water flux, a key driver of barrier degradation and radionuclide migration

EXAMPLES OF CONSIDERING CLIMATE ASPECTS IN THE SA

El Cabril, Spain:

- As a result of **potential fluctuations in climatic parameters**, primarily precipitation (increase or decrease) in the site area, two initiating events are presented as triggers for two alternative scenarios to the reference scenario: a change in the infiltration rate (EC1) and a change in the water table elevation (EC2)
  - **Scenario EC1** postulates **a change in average annual precipitation**, leading to **a change in the potential infiltration flux through the barriers**, affecting the processes of contaminant release and transport within the disposal facility and in the geosphere, the characteristics of the biosphere, agriculture/livestock, and human behavior. Depending on the change in average annual precipitation (increase or decrease), the reference scenario will be **quantitatively affected, not only in the maximum dose to the critical individual**, but also **likely in the time in which it occurs**.
  - **Scenario EC2**, **variation in the water table elevation**, a penalizing situation is considered according to the characteristics of the disposal site as a whole, and to pessimistic assumptions based on the analysis of the evolution of precipitation at the site, which would lead to **the elevation of the water table above the elevation of the disposal cells**, during the period of free disposal when cover and engineering barriers are assumed to be degraded. Thus, the scenario is characterized by a rise in the water table such that groundwater comes into contact with the waste, causing the source term to alter with respect to that estimated in the reference scenario

HOW THE CLIMATE ASPECTS ARE INCLUDED IN THE SAFETY ASSESSMENTS

Disposal facility on Dessel site, Belgium:

- climate (change) is taken into account in the **design of some barriers/components** as well as in the **SA (scenarios, near-field, hydrogeological and biosphere models)**.

NDF on Radiana site, Bulgaria:

- two alternative scenarios: **dry climate** and **wet climate** assuming respective changes in the current climate parameters
  - **Dry climate**
    - ✓ precipitation reduced to 66%
    - ✓ environmental infiltration reduced to 66%
    - ✓ flow rates of aquifers reduced to 66%
    - ✓ Irrigation of farm products increased to 150%
  - **Wet climate**
    - ✓ precipitation increased to 150%
    - ✓ environmental infiltration increased to 150%
    - ✓ flow rates of aquifers increased to 150%
    - ✓ Irrigation of farm products decreased to 10%

HOW THE CLIMATE ASPECTS ARE INCLUDED IN THE SAFETY ASSESSMENTS

NSR on Stabatiškė site, Lithuania:

- Climate aspects were included in the safety assessments by generation a set of scenarios. Besides the Reference scenario, additionally, scenarios with **more rapid engineered barriers degradation**, **increased precipitation**, **alternative groundwater discharge point** were analysed

CSA, France:

- Climate change is mainly considered in terms of **Biosphere**, and more precisely in terms of **eating habits**
- Climate change effect on erosion is considered in the SA - the designed properties of the cover would be considered over 300 years only, after that it is assumed totally degraded.
- Current studies on the **impact of climate change on the cover erosion** - not yet taken into account in safety assessments.
- On-going studies on the **impact of climate change on hydrogeology**

POTENTIAL DESIGN OPTIMIZATIONS TO COPE WITH CLIMATE CHANGE

1. **Multi-layer cover** - it is the primary engineered barrier against water infiltration and it is **most vulnerable to climate-related stresses**. Its design can be enhanced by:
    - **improving drainage and water diversion**
    - **reinforcing the water-resistant layer (Geomembrane)**
    - **strengthening the erosion control layer (Topsoil and Vegetation)**
2. Adaptation of **waste forms** and **disposal units**
    - **improved concrete formulations**
    - **modular and compartmentalized design**
3. Integrated long-term monitoring and maintenance
    - the facility could be equipped with a comprehensive network of **advanced sensors**