European Partnership
on Radioactive Waste Management

Perturbations

Domain Insight 4.2.1

EURAD Roadmap

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Authors: Erika Neeft

Reviewers: Tiziana Missana and Guido Deissmann

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The **EURAD Roadmap** is a representation of a generic radioactive waste management programme that shall enable users and programmes to access existing knowledge and active work or future plans in EURAD-2 and elsewhere. The content is focused on what knowledge, and competencies (including infrastructure) is considered most critical for implementation of RWM, aligned to the EURAD Vision.

All Roadmap documents can be accessed at the EURAD website: https://www.ejp-eurad.eu/roadmap.

The **Theme Overview Series** is part of the EURAD Roadmap, which is 7 high-level introductions to the EURAD Roadmap providing:

- **Guidance on typical goals and activities for RWM –** Activities (which may be of variable importance and scope depending on the nature of the disposal programme) provide generic guidance on how to achieve key programme goals and how priorities evolve throughout programme phases, from advanced programmes perspectives.
- **Competencies for RWM** – Needed competencies (and accessible infrastructure) for successfully managing a disposal program within the different phases of implementation.

The **Domain Insight Series** is part of the EURAD Roadmap, which in totality provides a high-level checklist of generic and typical activities needed for the full radioactive waste management lifecycle, leading to geological disposal including:

- **Functionality –** Contextual information about how activities and knowledge associated with a domain contribute towards achieving generic safety and implementation goals.
- **Maturity and State-of-Knowledge (SoK)** – Links to available SoK are included, providing an Experts' view of the most relevant knowledge and associated uncertainties (including areas of ongoing scientific and technological enquiry) in a specific domain applied in the context of a radioactive waste management programme.
- **Safety and Implementation Significance** – Contextual information about how activities and knowledge associated with a domain impact long-term safety or practical implementation.

The **Domain Insight Series** of EURAD comprises over 70 short documents, prepared by Europe's leading Subject Matter Experts across Radioactive Waste Management. The documents are aimed at early career professionals or new starters interested in best practice and key knowledge sources.

Overview

The host rock is the natural barrier that hosts the underground structure of the geological disposal facility (GDF). Host rocks can be crystalline rocks, argillaceous (clay) rocks or evaporites, such as rock salt. The host rock is a geological formation and has a crucial contribution in either the isolation of the waste (crystalline rock) or the containment of radionuclides in the waste (clay and salt rocks). The host rock can be perturbed by the chemical and physical interactions between barriers in the post-closure evolution of a disposal system with natural and engineered barriers, geomorphological processes induced by climate change and tectonic activity. Perturbations to the host rock are also made during construction, operation and closure of the GDF.

Climate change and tectonic activity induce hydrogeological and chemical perturbations in the host rock that need to be understood on the long-term. Large volumetric rates of melting water can be generated from a glacial climate towards an interglacial climate. The high strength of crystalline rocks ensures a negligible impact of the erosional power of melting water. The isolation of the waste can therefore solely be provided by the crystalline rock since the integrity of crystalline rock is negligibly changed in the post-closure safety phase. The lower strength of clay rocks and high solubility of rock salt makes these rocks vulnerable for the erosional power of melting water induced by this climate change. The isolation of the waste is achieved by the geological barriers that are covering these rocks. Tectonic activity can change the presence of already existing fractures in all geological barriers. Fractures are known to have a high impact on the water flow in a disposal system with natural and engineered barriers. The evolution of this water flow is more predictable in a low tectonic regime.

Construction-induced local fractures will be present in any host rock during the excavation of rock to generate void volumes to transport and emplace waste. The stress state of the rock has been changed with the presence of the void volumes. The convergence of the rock into the void volume depends on the lithostatic confining pressure, properties of the (locally damaged) host rock and its interaction with water. The chosen construction technique should minimize any connection between construction-induced fractures and already existing fractures. Only the engineered barriers contribute to the containment of radionuclides in a disposal system with crystalline rock. The maxima in water flow into the open void volume need to be assessed for a proper installation of a low permeable barrier, as well as to prevent (piping) erosion in the long-term. The high strength of crystalline rock ensures a negligible convergence in the operational phase of the GDF.

Clay and salt host rocks are the main barriers to contain radionuclides from the waste if radionuclides have been released from the engineered barrier system (EBS). The construction induced zones with a higher fracture density in the host rock in the vicinity of the EBS have a higher permeability than the virgin permeability of the rock as long as self-sealing of these fractures has not been completed. Self-sealing of fractures in the operational phase requires minimization in the convergence of the host rock and access to water. Gas generation processes in the EBS consume water such as anaerobic corrosion of metals in which a metal reacts with water to form metal-oxides and metal-hydroxides. Microbially induced corrosion rates are usually larger than solely chemical corrosion rates. A build-up of gas pressure can lead to gas perturbation in the host rock. The low water permeability in clay host rocks limits water flow towards the EBS by which only very small gas generation rates are possible. Gas perturbations in the salt host rock can be prevented with a well-designed sealing system in the EBS. A build-up of gas pressure in crystalline rock is not expected due to the high dissipation of gas through the existing fractures.

Clay and crystalline rocks have reducing conditions at disposal depth. Constructional and operational activities may cause a (temporary) exposure of the host rocks to the working air. The oxygen in this air reacts with iron-sulphide minerals that are present as traces in the clay rock or in the fractures of crystalline rock. This reaction may acidify the pore water in these rocks if insufficient calcareous minerals are present.

Keywords

natural barrier, geological barrier, host rock, crystalline, clay, salt

Key Acronyms

engineered barrier system (EBS), underground research facility (URF), underground research laboratory (URL), site descriptive model (SDM), high level waste (HLW), low and intermediate level waste (LILW), geological disposal facility (GDF).

Content

1. The overall goal in the domain of Perturbations

The overall goal of this Perturbations domain is to characterize the potential impact of disposal facility construction, operation and closure on the natural geological barrier as extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to phase of implementation, needed to achieve this characterization of perturbations. Activities are generic and are common to most geological disposal programmes. The host rock is the natural barrier that hosts the underground structure of the disposal facility. Host rocks can be crystalline rock, argillaceous (clay) rocks or evaporites, such as rock salt (see Theme 4 Geoscience).

Domain Goal	
4.2.1 Characterize or confirm the chemical, hydrogeological, geomechanical, thermal, geomicrobiological, gaseous and radiation-induced perturbations which may be caused by facility construction, operations or closure and their impacts on long-term disposal system evolution (Perturbations).	
Domain Activities	
Phase 1: Programme Initiation	In this phase, radioactive waste may already be processed into solidified waste products and conditioned to be disposed of. The engineered barrier system (EBS) comprises the materials in this packaged waste and materials to close the geological disposal facility (GDF) such as a backfill. In this phase, the potential perturbations in the long-term evolution of a disposal system with engineered and natural barriers needs to be known with the choices in materials to process and condition the (heat-producing) waste. Make a preliminary safety assessment with the expected perturbations in the host rock in the post-closure phase, EBS and radiological characteristics of the waste to be disposed of. Fractures will be generated in each type of host rock upon excavation of the rock. On the long-term, these fractures are present in the vicinity of components of the EBS. A rough estimate of the extent of damage in the host rock needs to be made. Optimise the construction costs, costs for the maintenance of waste emplacement rooms and tunnels and closure of the GDF in the disposal concept. In case of clay or salt as a host rock, assess the impact of the extent of the damaged zone on the containment of radionuclides and other contaminants in the evolution of the disposal system in the long-term. For the crystalline rock, assess the impact of the construction induced fractures on the installation of engineered materials that contribute to the containment of radionuclides and the behaviour of these fractures in the long-term.

Phase 2: DGR Site Identification	Evaluate the integrity of the host rock based on the geomorphological processes and tectonic activity in the past two million years. Evaluate the hydrogeological evolution of the disposal system with the already existing fractures in the natural barrier(s), fractures due to tectonics in the future and assess the homogeneity of the host rock. In case of clay or salt as a host rock, assess the contribution of isolation of the waste by the geological barriers surrounding the host rock. In case of crystalline rock or clay rock as a host rock, evaluate the prevailing chemical conditions such as redox potential and salinity of the pore water. Outline the impact of natural induced fractures and construction induced fractures on the hydrogeological and geomicrobiological evolution of the disposal system. Underground research facilities (URFs) may be needed in the process of identification of a site. Assess the requested mechanical support for the constructed waste emplacement rooms and tunnels if convergence of the (locally damaged) host rock needs to be minimized. Integrate all necessary (construction-changed) host rock properties in site descriptive models (SDMs) and use tools such as a (digital) twin of the GDFs or another documentation system. Assess the access of water for components of the EBS in the design of the GDF and determine the expected alteration rate of components in the EBS and derive their associated gas generation rates and other chemical interaction rates between components of the EBS and the host rock. Make a site-specific safety assessment with the expected perturbations in the host rock in the post-closure phase and EBS including the characteristics of the waste forms to be disposed of.
Phase 3: DGR Site Characterisation	Extend the URF of the chosen site and outline a system with which the inflow and outflow of (vaporised) water, radionuclides and gases such as oxygen and carbon dioxide can be monitored and registered. Obtain data from the natural barrier(s) to calculate the impact of natural fractures and construction induced fractures on the hydrogeological and geomicrobiological evolution of the disposal system and update the SDM. Verify the requested mechanical support if convergence of the host rock needs to be minimized. Update the site-specific safety assessment including the expected perturbations and characteristics of the waste to be disposed of.

Phase 4: DGR Construction	Excavate the host rock with the appropriate technique. If needed, install the requested mechanical support. Justify the changes in this support with adjusted information about the (locally) damaged host rock. Measure properties of the host rock and mechanical support with which the extent of the damaged zone in the host rock can be calculated and the self-sealing of fractures in the (locally damaged) host rock can be monitored. Start to monitor the inflow and outflow of (the chemical and radiological components of) air in the disposal facility. Update the SDM and site-specific safety assessment with the characteristics of the waste to be disposed of, additional engineered barriers and properties of the (locally damaged) host rock as measured during construction.
Phase 5: DGR Operation and Closure	Continue to monitor and register the inflow and outflow of (the chemical and radiological components of) air in the disposal facility in the operational phase of the disposal facility. Validate the understanding of the uptake or release of (vaporised) water by the host rock with the data provided by the system with which the inflow and outflow of (vaporised) water was monitored. Determine the potential generation rate of gas as a function of time in the evolution of a disposal system with installed EBS and the changing variation of the water content in all materials in the long-term. Update the SDM and site-specific safety assessment with the characteristics of the waste and the monitored properties of the host rock. Validate the understanding of the in and out of flux of the chemical and radiological composition in the air that flowed in the underground part of the GDF before closure of the GDF.

2. The impact of perturbations to long-term safety and implementation goals

This section describes how perturbations (and its associated information, data, and knowledge) can have an impact on the high level disposal system requirements as described in EURAD Roadmap Generic Safety and Implementation Goals (see Domain Insight 7.1.1 Safety Requirements). It further illustrates, in a generic way, how safety and implementation goals are impacted by perturbations. It is recognised that the various national disposal programmes adopt different approaches to how disposal system requirements are specified and organised. Each programme must develop its own requirements, to suit national boundary conditions (national regulations, different spent fuel types, different packaging concept options, different host rock environment, etc.). The generic safety and implementation goals developed by EURAD and used below are therefore a guide to programmes on the broad types of requirements that are considered, and are not specific or derived from one programme, or for one specific disposal concept.

2.1 Characteristics of perturbations that can have an impact on the post-closure safety of the disposal system

The following five high-level long-term safety goals have been defined in EURAD (see Domain Insight 7.1.1 Safety Requirements) and EURAD Roadmap Generic Safety and Implementation Goals:

- Ensure **isolation** of waste from people and the accessible environment;
- Provide **containment** of contaminants;
- Contain contaminants within the whole disposal system by **retention or retardation**;
- Ensure long-term **stability** with respect to **external** events and environmental evolution;
- Ensure long-term **stability** with respect to **internal** evolution.

This section describes the potential perturbations in the host rock that affect these five safety goals in the evolution of the disposal system. In the post-closure phase, host rocks can be geomechanically, chemically and geohydrologically perturbed by geomorphological processes and human intrusion. The construction induced local fractures have generated geohydrological, geomicrobial and geomechanical perturbations in the host rock. Lack in water initially in the EBS and in the excavated damaged zone of clay and salt rocks limits release of contaminants. Gas formation reactions with engineered barriers consume water; gas perturbations therefore require sufficient access to water. Thermal decomposition of traces of organic matter present in all host rocks is a thermal perturbation that may increase the solubility of contaminants. The content of radionuclides in the host rocks is too small to induce radiation-induced perturbations that have an impact on the post-closure safety of the disposal system.

2.1.1 Isolation

Geomorphological processes such as glaciation and glacial erosion are external events that can perturb two types of host rocks: clay and salt rock. The presence of ice caps and glaciers in mountains in the past millions of years has been site-specific. Parts of lower strength sedimentary rocks can be eroded due to the high run off of melting water during the reduction in ice coverage (van Dijke and Veldkamp, 1996). The depth of the top of the clay or salt formation should therefore be sufficiently high in order to provide sufficient isolation by the geological barriers on top of these two types of host rocks (Breuer et al., 2023). The high strength of crystalline rock and low solubility of crystalline rock in water cause the crystalline rock to be negligibly affected by glacial erosion.

Isolation of waste requires prevention of human intrusion (see Domain Insight 1.2.6 and 4.3.3). A large disposal depth minimizes human intrusion but the excavated tunnels in crystalline rock are preferential pathways for human intrusion if these tunnels are not backfilled with a material that is difficult to excavate. Concrete material is used as plugs to prevent human intrusion for these GDFs. Salt, crystalline and clay rock are currently also resources. Crystalline and clay rock are abundantly available at the Earth's surface which makes deep underground mining for these resources highly unlikely in the future. These rocks are mined in pits at the surface. The high solubility of rock salt is used for dissolution mining to extract salt from the underground. Salt mining only takes place in the underground.

2.1.2 Containment

During construction of waste emplacement rooms and tunnels, additional local fractures are generated in each type of host rock (see Theme 5 Disposal facility design and optimisation). Containment is provided by the low permeable components in the EBS within higher strength crystalline rock. Whether construction induced fractures in crystalline host rock act as water-conducting features that complicate the installation of the low permeable components of the EBS depends on the construction technique, local density of already existing fractures and excavated diameter of waste emplacement vertical holes. Acceptable water inflows for installation of components of the EBS need to be defined e.g. Baxter et al. (2018).

The natural heterogeneity of clay and salt host rocks determines the potential presence of water conducting features. Non-destructive spatial characterisation and careful excavation of these host rocks can prevent the connection between these conducting features and construction-induced fractures. This connection changes the hydrogeological flow in the disposal system and can generate a preferential geosphere pathway for radionuclides. Without or too limited mechanical support, these lower strength rocks will convergence into the excavated emplacement rooms and tunnels. A mechanical support therefore minimizes further growth of fractures in the host rock during the operational phase of the GDF. Another measure to minimize the extent in detrimental convergence is to limit the period in time of the emplacement tunnel or room by immediate emplacement of waste packages and backfilling just after rock excavation (see Domain Insight 3.4.1 EBS).

The self-sealing of construction induced fractures requires compressive load, limited convergence and access to water (Alcolea et al., 2014). This self-sealing process reduces the higher permeability zone in the host rock generated during construction. During the operational phase of the GDF, this access of water is determined by the relative humidity of the air as well as the water permeabilities of the host rock and the mechanical support. In the post-closure phase, the width of the fractures and the fracture density in the vicinity of the EBS can control the transport of water in the disposal system. This fractured zone in the host rock can become a preferential geosphere pathway for radioactive contaminants if these contaminants are released from the EBS. Any radionuclide release requires alteration of components in the EBS such as anaerobic corrosion of metal (steel or cupper) canisters containing waste or zeolitisation of vitrified waste. These alteration processes consume water. Release of radioactive contaminants is therefore usually controlled by the potential fluxes of water in the EBS and the (locally damaged) host rock. Another consideration is that the amount of solutes (iron in case of steel or silicon in case of glass) in equilibrium with the alteration products must be reduced in order to proceed the alteration process. This reduction can be controlled by a low hydraulic conductivity (Chapman et al., 1981). These potential fluxes between barriers depend on the connectivity between void volumes such as pores and fractures within a barrier. The connectivity between capillary pores decreases with lower saturation degrees (Blanc et al., 2024).

Initially in the post-closure phase, water fluxes towards the waste forms for LILW are very small as the engineered barriers and the host rock in the vicinity of the EBS are desaturated. Desaturated areas of the disposal system minimize build-up of internal gas pressures due to passage of gas through unsaturated pores (Harris et al., 1993). Moreover, the corrosion rates of metals in desaturated porous media are smaller due to capillary condensation (Stefanoni et al., 2018). Eventually, the pores in all barriers can be filled with water. The waste form for HLW is contained in a metallic canister. Contact between the HLW waste form and water only takes place when the reduction in thickness of this metallic barrier after thousands of years or more has either been completely corroded or can no longer sustain the lithostatic load. This load can increase after hundreds of thousands of years by the weight of ice during glaciation events.

Anaerobic metal corrosion rates can be orders of magnitude smaller than aerobic corrosion rates (Crossland, 2005) but gas is only produced during anaerobic corrosion. Oxygenated water becomes present in crystalline rocks at larger depths during the retreat of glaciers. The occurrence of the presence of oxygenated water in clay host rock is determined by its geological setting and expected hydrogeological evolution.

2.1.3 Retention and retardation

The potential water fluxes in the entire disposal system with engineered and natural (geological) barriers usually control the radionuclide release from the waste form (see section 2.1.2). Big changes in the shoreline over hundreds of thousands of years can change the salinity and redox potential of pore water in crystalline rocks. The low permeable engineered barriers in the EBS control the access of these chemical changes in the host rock to metallic barriers in the EBS.

Retention of contaminants by co-precipitation or other solid precipitates depends in all barriers on the content of dissolved species in pore water (bicarbonate, sulphate) and on the redox potential. Low permeable engineered barriers and clay host rocks are ion exchangers. The permeability is so small that the dominant transport of dissolved species is diffusion. Clay minerals in these barriers usually have a high affinity of cationic dissolved species and complexes. The affinity of dissolved ionic species and complexes can be ranked e.g. for cations: caesium has a higher affinity than sodium (Stumm, 1992, Helfferich, 1962). Radionuclides such as caesium are exchanged by non-radioactive sodium that are originally present in a clay barrier by which the amount of radionuclides that leave the clay barrier is smaller than without this ion exchange process. Concrete can also be a low permeable barrier that can contain anionic dissolved radionuclides at basic (high pH) conditions (Pointeau et al., 2008). The pH in concrete pore water can be reduced by leaching of concrete and ingress of species dissolved in groundwater (Atkinson et al., 1985) by which the anionic exchange capacity of concrete reduces.

Frequently concrete is used in disposal systems in any host rock. The chemical perturbation in rocks can be limited with the application of hardened concrete interfacing rocks instead of applying cementitious fluid to the constructed surfaces of rocks. The cementitious fluid chemically interacts with the rock upon hardening of concrete. Salt is locally dissolved and a transformed zone with secondary minerals between hardened concrete and salt rock will be formed. Clay and crystalline rocks are both alumina silicate bearing rocks and secondary minerals are formed by interaction with alkaline leachates. These secondary minerals are calcium silicate hydrates and zeolites that also have beneficial features to contain radionuclides. The low permeability of clays ensures that the mineral alteration takes place for hundreds of thousands to millions years (Deissmann et al., 2025). This alteration can only locally change the properties of any host rock due to the low volume of concrete compared to the host rock in any disposal system.

Leaching of alkali leachates is minimized by the low permeability of hardened concrete. The reduction in pH in concrete pore water in low-permeable concrete is rather caused by ingress of dissolved species present in clay and crystalline rock pore water such as bicarbonate and magnesium. The dissolution of cementitious minerals in concrete increases the size of the connecting pore throat in concrete. This increase in pore throat can increase the likelihood for microbial activity (see 2.1.5). This increase in this throat can be minimized by matching the calcium concentration in these rock pore waters with the choice in type of cement to manufacture the concrete.

2.1.4 External stability

The understanding of the hydrogeological setting of any host rock with already existing fractures ensures that the facility is sited in a stable tectonic regime and that the isolation potential of the depth of the underground structure of emplacement tunnels and rooms in the host rock is sufficient for the post-closure safety. The residence time of pore water in geological formations that surround the clay and salt host rocks should indicate whether the hydrogeological setting of these rocks is favourable for geological disposal of radioactive waste.

Crystalline and clay rocks are naturally enriched in radionuclides uranium, thorium and radioactive potassium. There can be parts in rock salt with enriched radioactive potassium. Micron-sized fission tracks are generated upon decay of these naturally present radionuclides. The natural content of radionuclides is too small to reduce the strength of any rock. Radiation-induced formation of gas by ionisation of pore water also takes place. The dissipation rate of these gases are too large to induce gas perturbation in the host rock.

2.1.5 Internal stability

Water is consumed in almost any gas generation process either due to chemical reactions with materials in the EBS or ionisation of pore water. The exception is gas generated by decay of radionuclides but its contribution to build-up of gas pressure is negligible. The minimization of fluxes of water in the disposal system by low permeable barriers therefore enhances the internal stability (see section 2.1.2). The radiation-induced formation of gas is negligible compared to gas generated by chemical corrosion of metals such as steel (Levasseur et al., 2021). Microbial degradation of organic waste forms and microbial induced anaerobic corrosion of metals can generate higher gas generation rates than pure chemical processes. The water activity can be too low for microbial activity (Stroes-Gascoyne and West, 1997, Swanson et al., 2018) or the size of the connecting pore throat can be too small for microbes to be active (Wouters et al., 2016). Detrimental microbial induced processes such as microbially enhanced corrosion of steel or enhanced chemical decomposition of organic waste and beneficial microbial induced processes such as consumption of hydrogen can be accounted for by design and understanding of the evolution of the (construction-induced) fractures. Carbon steel is a metal frequently used in the EBS. The dose rates for steel interfacing pore water are too low for radiation-enhanced corrosion after the envisaged cooling periods for HLW and proposed thicknesses of carbon steel (Neeft et al., 2025).

Any host rock can be heated by heat-producing waste in the vicinity of the EBS. The potential thermal perturbation in any rock is decomposition of traces of organic matter from past marine life in salt and clay host rock and organic matter becoming present in the fractures of crystalline rock. Consequences of this thermal perturbation are the formation of gas (methane) but also organic complexes that increase the solubility of radionuclides are generated during decomposition of organic matter. Swelling clay minerals can be altered into non-swelling clay minerals and this heat induced alteration can lead to smaller self-sealing rates of fractures. Fluid inclusions in rock salt will move toward the heat source. The migration rate, size and density of these inclusions controls the access of water (as a brine) for anaerobic corrosion of metals in the EBS (Redder and Belkin, 1980).

2.2 Characteristics of implementation goals that can cause perturbations in the host rock

Many features that are related to the implementation to construct, operate and close the disposal facility are related to the design of the EBS. The host rock and its geological setting cannot be designed but only selected. A balance needs to be made between limiting damage to the host rock, operational safety, environmental impact and optimisation. Critical information for the evolution of the disposal system can be provided by monitoring properties of the (locally damaged) host rock (see Theme 5 Disposal facility design and optimisation).

2.2.1 Operational safety

The convergence rate depends on the properties of the (damaged) host rock, the interaction between the (damaged) host rock and the relative humidity of air in the operational phase as well as the strength and permeability of the applied support. Too much convergence of the host rock results into growth of construction induced fractures by which pieces of rock can fall. Maintenance of the waste emplacement tunnel or room is needed such as removal of rock debris. Rock fall is a non-radiological risk for workers that is minimized by mechanical support. A rockslide in clay host rock in the URL in Bure (France) in 2016 killed a worker. The Waste Isolation Pilot Plant (WIPP) facility in Carlsbad (New Mexico, USA) was temporarily closed to improve the safety culture after two incidents in 2014. Maintenance of the void volumes in rock salt did not take place for a couple of years. Precautionary evacuation was needed in 2016 due to rock fall risks. The WIPP facility has been re-opened in 2017. A mechanical support in excavated waste emplacement of tunnels and rooms minimizes the convergence of lower strength host rock. Steel nets are even applied for higher strength crystalline rocks to mitigate the consequence of loose rocks from the construction induced zone. The understanding of the convergence of any host rock provides input for the evolution of the locally damaged host rock in the vicinity of the EBS for the post-closure phase.

Radioactive radon is generated by the decay of uranium and thorium present in crystalline rock and clay. The release rate of radioactive radon into the waste emplacement tunnels depends on the saturation degree of clay and fracture density in crystalline rock. Concrete is usually used as a mechanical support for clay host rocks and concrete is frequently present in processed waste forms and waste packages. The cement used to manufacture concrete is also enriched in radionuclides uranium, thorium and radioactive potassium. The radiological risk for workers can be minimized by sufficient ventilation. Understanding the release of radioactive radon can provide input of the saturation degree of concrete and clay.

The ventilation rate can control the saturation degree of the clay and salt host rock in the vicinity of the EBS at the start of the post-closure phase. Understanding the uptake or release of water from ventilation of air by these rocks can provide input for saturation degree of the locally damaged host rock in the vicinity of the EBS. Sandy formations and limestone might be passed in the shafts in the geological formations on top of the clay and salt rock. These parts of the shafts interfacing these high-water permeability formations should be properly sealed to keep the underground part of the GDF dry.

A higher strength of concrete is usually associated with a lower water permeability. The ventilation rate may have a negligible influence on the saturation degree of the host rock if that support is thick enough. The saturation degree of the (locally damaged) clay host rock in the vicinity of the EBS is then controlled by its permeability.

The ventilation does not only control the uptake and release of water from the host rock but can also have an impact on the redox potential of the pore water in clay and crystalline rock. The initial reducing conditions can be perturbed by ingress of oxygen present in the ventilation air. Iron-sulphide is a microbially formed mineral millions of years ago just after sedimentation of the clay or formed in a fracture in crystalline rock filled with seawater. The reaction of iron-sulphide with oxygen leads to the formation of acid. This acid formation is buffered by calcareous minerals. The ingress rate of oxygen depends on the saturation degree of the clay host rock and the saturation degree of construction induced fractures in crystalline rock depends on their connectivity with existing fractures.

2.2.2 Environmental impact

The recycling of excavated rock material in the closure process of the disposal facility reduces the environmental impact and increases the chemical compatibility of the disposal system in the post-closure phase. The potential perturbation of the treated excavated material in the post-closure phase depends on its function. The washed crushed crystalline rock backfill ensures that intruding groundwater water preferentially flows away from the caissons with disposed of waste (Vahlund and Andersson, 2015). The function of crushed rock salt backfill is different and requires convergence of the salt rock wall and compaction of crushed salt rock to achieve low porosities and low (brine-saturated) permeabilities (Svensson et al., 2025).

The high water permeability of emplaced excavated sand and crushed limestone on top of the clay host rock can also contribute to a favourable hydrogeological evolution of the disposal system with clay host rock as flowing water is carried away from the clay host rock with the disposed of waste. The use of excavated clay host rock as an impermeable backfill may require an evaluation of potential admixtures to minimize its acidified extent by its reactions between iron-sulphide in order to minimize perturbation of engineered barriers. The requested permeability and swelling pressure for the disposal system can be tailored with the compaction pressure and additional admixtures.

2.2.3 Optimisation

The use of explosives to excavate rock can be fast and cheap but is only used to construct void volumes in crystalline rock in areas where large water flows in the far future are of less concern such as the access tunnels. Scraping of crystalline rock with cutters in tunnel boring machines (TBMs) minimizes construction induced damage. Waste emplacement holes for HLW are more carefully excavated through drilling.

For clay and salt rock, too much construction-induced damage by explosives is generated in any area of the host rock. Slower excavation methodologies, such as the use of road headers are used to excavate these rocks more carefully. Minimization of convergence of the host rock by installation of a mechanical support (rigid liner or the density of applied rock bolts sometimes with shotcrete) is balanced with maintenance to remove fallen rock and keeping the void volume open. The costs for maintenance can exceed the costs for the installation of a more expensive mechanical support such as a rigid liner. ANDRA for Bure in France and BGE for Konrad in Salzgitter (Germany) have both decided to use reinforced concrete support to minimize the maintenance costs during emplacement of (L)ILW.

Many countries require retrievability of waste. The requirements for retrievability are country specific. The growth of construction-induced fractures can be minimized with the application of a mechanical support but also by minimization of the period that the waste emplacement tunnel or room can be entered. Immediate backfilling after waste emplacement to minimize further growth of constructed induced fractures makes the retrieval of waste more costly.

3. International examples of characterizing key perturbations

3.1 Crystalline rock

Disposal facilities to dispose of HLW are being constructed in Finland (Onkalo, www.posiva.fi) and Sweden (Forsmark, www.skb.se). Engineered barriers in close proximity to the waste form are made of bentonite. The installed bentonite is dry and the pore water will become similar to the crystalline rock pore water. The swelling pressure of bentonite should be low enough to prevent mechanical disturbance of the crystalline rock and high enough to prevent microbial induced corrosion of engineered materials. Underground research laboratories (URLs) in crystalline rock have been constructed in Switzerland (Grimsel, www.grismel.com) and Sweden (Aspö, www.skb.se). These underground laboratories have been constructed for research and demonstration purposes. Radioactive waste will not be disposed of in these laboratories. URF is being constructed in China to assess the suitability of the site (Beishan, Gansu). Construction-induced perturbations have a negligible impact on the long-term safety due to the use of well-designed engineered barriers and appropriate installation measures to install these barriers.

Disposal facilities to dispose of LILW have been constructed in crystalline granitic rock in Finland, Sweden and Hungary (www.mecseker.hu) many decades ago. Frequently, also engineered barriers close to the LILW waste form are made with concrete.

3.2 Clay rock

URLs have been constructed in Belgium (Mol, www.euridice.be), France (Bure, internationaladra.fr and Tournemire, en.irsn.fr) and Switzerland (St Ursanne, www.montterri.ch). Their operational periods for several decades have provided sufficient knowledge to characterize construction induced fractures, understanding of the hydrogeological evolution of locally damaged host rock on the long-term and measures to minimize the growth of fractures in the operational phase of the disposal facility.

Chemical perturbations by concrete interfacing clay host rock have been characterised and understood to take place at such a small rate that the contributing role of the host rock to contain the radionuclides is not jeopardised by the use of cementitious materials.

3.3 Salt rock

The Waste Isolation Pilot Plant (WIPP) is a disposal facility in the United States (wipp.energy.gov) that is constructed in rock salt to dispose of long-lived transuranic LILW. The WIPP uses MgO as backfill material to remove the potential of microbially formed CO_2 when waste comes into contact with brine. Gas induced perturbations in the host rock are minimized on the long-term by the use of MgO in the EBS (EPA, 2021).

The Morsleben and Asse facilities are former salt mines in Germany (www.bge.de). Morsleben had been used to dispose of LILW. Magnesia concrete (Sorel concrete) is used in both former salt mines to obtain a favourable hydrochemistry on the long-term (see Domain Insight 3.4.1).

4. Critical background information

This section highlights specific key information, processes, data or challenges that have a high impact or are considered most critical for implementing geological disposal, with respect to the domain of perturbations in the host rocks.

4.1 Integrated information, data or knowledge (from other domains) that impacts understanding of perturbation

The other domains that key interfaces the EURAD Goal Breakdown Structure are the other Domain Insights in Theme 4:

4.1.1 Site Descriptive Model;

4.1.2 Aqueous transport and retention;

4.3.1 Geological and tectonic evolution

4.3.2 Climate change;

4.3.3 Human actions;

4.4.1 Conceptual models, stability, layout and construction.

Only Domain Insight 4.3.3 is currently available at time of writing Domain Insight 4.2.1 Perturbations. Domain Insight 3.4.1 explains that any EBS design is host rock specific. The overview of Theme 5 Disposal facility design and optimisation highlights the importance of understanding construction induced damage and monitoring.

5. Maturity of knowledge and technology

This section provides an indication of the relative maturity of information, data and knowledge with respect to perturbations in host rocks. It includes the latest developments for the most promising advances, including innovations at lower levels of technical maturity where ongoing RD&D and industrialization activities continue.

5.1 Advancement of safety case

Understanding the behaviour of the host rock in the past and the future in its geological setting is crucial for the safety case. Natural induced perturbations to the host rock can be minimized by a proper site selection with high qualitative SDMs. All URLs have contributed to how perturbations to the host rock during construction and operation of the disposal facility can be characterised and confirmed i.e. how the locally damaged and altered host rock can be measured and which properties need to be monitored. These human induced perturbations can be minimized. Perturbations induced by (microbially-enhanced) chemical reactions can be minimized by making choices in the design based on the understanding of the evolution of the multibarrier system.

5.2 Optimisation challenges and innovations

Innovations to construct, operate and close a GDF will appear in the future. The challenge is to incorporate innovations that cause less human-induced perturbations to the host rock but are more costly. Even if innovations reduce the costs to construct, operate and close the disposal facility, another challenge can be that a change in safety culture is requested to implement these innovations in the worker's activities.

5.3 Past and ongoing (RD&D) projects

Past (RD&D) Projects in URLs have been frequently financed by the European Commission. Geological settings and evolutions of crystalline, clay and salt rocks have been studied in the framework programmes 1 and 2. The URL in Belgium has also been constructed in these two programmes. Framework programme 3 had CLUSTER (CLub of Underground Storage TEsting and Research) facilities in:

- crystalline rock in Sweden, Finland, Switzerland and associated country Canada;
- clay rock in Belgium, France and Switzerland
- salt in Germany and associated country United States of America

An EU bookshop has been launched in 2005 to stimulate public access to the reports. The Natural Analogue Working Group (NAWG) studied perturbations in the long-term in Framework programmes 3, 4 and 5 and results are published at https://www.natural-analogues.com/.

Framework programmes 4, 5, 6 and 7 studied the human induced perturbations such as construction induced zone of fractures in crystalline and salt rocks, indurated and plastic clay and chemical interactions between the host rocks and engineered barriers on the long-term. Also in Horizon 2020, gas and thermal induced perturbations in clay host rock as well as its interaction with cementitious material have been investigated. The IGD-TP (igdtp.eu) has published results from European projects from 2012 onwards.

Ongoing (RD&D) Projects:

Every European Member State should have a national programme for disposal of radioactive waste that is updated every decade (EC, 2011). This programme is usually published by the government with a description of the ongoing (RD&D) activities. Nations with chosen sites for GDFs have extensive SDMs with a description of natural induced perturbations on the considered host rocks.

In EURAD-2, RAMPEC studies the impact of chemical induced perturbations on radionuclide retention and CLIMATE addresses geomorphological processes.

CatchNet https://skb.se/catchnet/ also addresses geomorphological processes.

DEvelopment of COupled models and their VALidation against Experiments (DECOVALEX) has been initiated in 1992 to model thermal-hydraulic-chemical and microbially induced processes in crystalline, clay and salt rocks.

5.4 Lessons learnt

Perturbations in the crystalline, clay and salt rocks have sufficiently been characterised and understood. A URL to study these perturbations is no longer necessary. URFs are becoming part of a site selection process to characterize and confirm human induced perturbations to construct, operate and close disposal facilities.

6. Uncertainties

The processes that induce perturbations in host rocks are qualitatively well described and understood. However, a detailed quantitative verification of these processes on the long-term is frequently not possible. Bounding of the extent of perturbations in the host rock is usually included in the design of the EBS in order to understand the potential risks. This bounding requires understanding of the potential hydrogeological evolution of the disposal system, assessment whether chemical interactions between barriers can be microbially or radiation enhanced and a well characterization of the natural barriers and engineered barriers. The uncertainties in the potential releases of radionuclides from the system of these barriers are too high without understanding this hydrogeological evolution, without assessing enhancement of chemical perturbations and lack in characterisation of all barriers.

7. Guidance, Training, Communities of Practice and Capabilities

This section provides links to resources, organisations and networks that can help connect people with people, focussed on the domain of Perturbations.

Guidance
The International Atomic Energy (IAEA) has published several safety guides about monitoring SSG-31), design principles (NW-T-1.27) and requirements-driven management of site investigations (NW-T-1.40) implementation of a geological disposal programme (NW-T-1.43) and reports about site descriptive models can be found in their database as well.
Training
Organisations linked to URLs in Switzerland, Belgium and Sweden offer training: Crystalline rock www.grimsel.com (Switzerland) www.skbinternational.se (Sweden) Poorly indurated clay www.sckcen.be (Belgium) and indurated clay https://international.andra.fr/international-consultancy/andra-services (France)
Active communities of practice and networks
The Nuclear Energy Agency (NEA) has dedicated expert groups for GDFs in crystalline, clay and salt rock: Crystalline Club, Clay Club and Salt Club.
Capabilities (Competences and infrastructure)
The IAEA has an Underground Research Facilities Network to assess and share best practices in developing, evaluating and implementing geological disposal solutions https://nucleus.iaea.org/sites/connect/urfpublic/SitePages/Home.aspx

8. External Links and references

8.1 External Links

Perturbations in host rocks by engineered materials on the long-term have been documented by the Natural Analogue Working Group (NAWG) https://www.natural-analogues.com/

The current status activities about GDFs in Germany is available at http://bge.de/en/, in Finland at https://www.posiva.fi/en/, in Sweden at https://skb.com/,

European Nuclear Safety Regulators Group (ENSREG) has been created in 2007 following a decision by the European Commission (www.ensreg.eu). Western European Nuclear Regulators Association (WENRA) has a working group on waste and decommissioning and has developed Safety Reference Levels for disposal of waste https://www.wenra.eu/wgwd

8.2 References

ALCOLEA, A., KUHLMANN, U., LANYON, G. W. & MARSCHALL, P. 2014. Hydraulic conductance of the EDZ around underground structures of a geological repository for radioactive waste – A sensitivity study for the candidate host rocks in the proposed siting regions in Northern Switzerland. NAGRA Arbeitsbericht NAB 13-94 www.nagra.ch.

ATKINSON, A., GOULT, D. J. & HEARNE, J. A. 1985. An assessment of the long-term durability of concrete in radioactive waste repositories. *Mat. Res. Soc. Symp. Proc. Materials Research Society,* 50**,** 239-246.

BAXTER, S., APPLEYARD, P., HARTLEY, L., HOEK, J. & WILLIAMS, T. 2018. Exploring conditioned simulations of discrete fracture networks in support of hydraulic acceptance of deposition holes. Posiva SKB report 07.

BLANC, P., GOAVERTS, J., GU, Y., JACQUES, D., KOSAKOWSKI, G., LEIVO, M., MARTY, N., NEEFT, E., SHAO, H. & VEHLING, F. 2024. Description of ILW modelling results and recommendations for future experiments and numerical work: Deliverable 2.15 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

BREUER, S., BEBIOLKA, A., NOACK, V. & LANG, V. 2023. The past is the key to the future – considering Pleistocene subglacial erosion for the minimum depth of a radioactive waste repository. *E&G Quaternary Science Journal,* 72**,** 113-125.

CHAPMAN, N. A., MCKINLEY, I. G. & SAVAGE, D. 1981. The effect of groundwater availability on the release source term in a low hydraulic conductivity environment. *Workshop on Radionuclide Release Scenarios for Geologic Repositories* Paris: OECD/NEA

CROSSLAND, I. 2005. Long-term corrosion of iron and copper - The 10th International Conference on Environmental Remediation and Radioactive Waste Management, ICEM05-1272. *The 10th International Conference on Environmental Remediation and Radioactive Waste Management.* Glasgow (Scotland): ASME.

DEISSMANN, G., NEEFT, E. & JACQUES, D. 2025. EURAD State-of-the-Art Report: Assessment of the chemical evolution at the disposal cell scale – part II – gaining insights into the geochemical evolution. *Frontiers in Nuclear Engineering,* 3.

EC 2011. Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. *Official Journal of the European Union L199/48-56 02.08.2011*.

EPA 2021. The geochemistry of the Waste Isolation Pilot Plant. *EPA-402/R-21/002.* https://www.epa.gov/radiation/epas-role-waste-isolation-pilot-plant-wipp.

HARRIS, A. W., ATKINSON, A. & CLAISSE, P. A. 1993. Transport of gases through concrete barriers. *Task 3 Characterization of radioactive waste forms - A series of final reports.* Luxembourg, Commission of the European Communities, EUR14194, No 33.

HELFFERICH, F. 1962. *Ion exchange,* United States of America, McGrawhill-Hill Book company.

LEVASSEUR, S., COLLIN, F., DANIELS, K., DYMITROWSKA, M., HARRINGTON, J., JACOPS, E., KOLDITZ, O., MARSCHALL, P., NORRIS, S., SILLEN, X., TALANDIER, J., TRUCHE, L. & WENDLING, J. 2021. Initial State of the Art on Gas Transport in Clayey Materials. Deliverable D6.1 of the HORIZON 2020 project EURAD, Work Package Gas. EC Grant agreement no: 847593. www.ejp-eurad.eu.

NEEFT, E., DEISSMANN, G. & JACQUES, D. 2025. EURAD State-of-the-Art Report: ACED assessment of the chemical evolution at the disposal cell scale—part I—processes at interfaces and evolution at disposal cell scale. *Frontiers in Nuclear Engineering,* 3**,** 1-50.

POINTEAU, I., COREAU, N. & REILLER, P. E. 2008. Uptake of anionic radionuclides onto degraded cement pastes and competing effect of organic ligands. *Radiochimica Acta,* 96**,** 367-374.

REDDER, E. & BELKIN, H. E. 1980. Thermal gradient migration of fluid inclusions in single crystals of salt from the Waste Isolation Pilot Plant (WIPP). *Scientific basis for nuclear waste management,* 2**,** 453-464.

STEFANONI, M., ANGST, U. M. & ELSENER, B. 2018. Electrochemistry and capillary condensation theory reveal the mechanism of corrosion in dense porous media. *Nature Scientific Reports,* 8**,** 1-10.

STROES-GASCOYNE, S. & WEST, J. M. 1997. Microbial studies in the Canadian nuclear fuel waste management program. *Federation of European Microbiological Societies. (FEMS) Microbiology reviews,* 20**,** 573-590.

STUMM, W. 1992. *Chemistry of the solid-water interface. Processes at the mineral-water and particle water interface in natural systems,* Canada.

SVENSSON, K., VAN OOSTERHOUT, B., HESSER, J., SPIERS, C. J. & LAURICH, B. 2025. Microstructural evolution of compacted granular salt: insights from 40-year-old backfill at a former potash mine (Sigmundshall, northern Germany). *Journal of Structural Geology,* 197.

SWANSON, J. S., CHERKOUK, A., ARNOLD, T., MELESHYN, A. & REED, D. T. 2018. Microbial Influence on the Performance of Subsurface, Salt-Based Radioactive Waste Repositories. An Evaluation Based on Microbial Ecology, Bioenergetics and Projected Repository Conditions. NEA No. 7387.

VAHLUND, F. & ANDERSSON, E. 2015. Safety analysis for SFR Long-term safety Main report for the safety assessment SR-PSU. SKB TR-14-01 available at www.skb.se.

VAN DIJKE, J. J. & VELDKAMP, A. 1996. Climate-controlled glacial erosion in the unconsolidated sediments on northwestern Europe, based on a genetic model for the tunnel valley formation. *Earth surface processes and landforms,* 21**,** 327-340.

WOUTERS, K., JANSSEN, P., MOORS, H. & LEYS, N. 2016. Geochemical Performance of the EBS: Translation and Orientation of existing Knowledge towards the Boom Clay in the Netherlands (GePeTO). OPERA-PU-SCK515, www.covra.nl.