European Partnership
on Radioactive Waste Management

4.3.1 Geological and tectonic evolution

EURAD Roadmap

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Version: 1.0, 24/10/2025

DOI: 10.5281/zenodo.17453718

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

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

In radioactive waste management, understanding the geological context, tectonic evolution, and climate change is essential for selecting and evaluating safe disposal sites. This knowledge is critical for assessing the effectiveness of the natural barrier system that isolates radioactive waste from the biosphere.

Many geological settings can be suitable for constructing deep geological disposal facilities. In all nuclear waste management programs, the term host rock refers to the specific near-field rock unit where the repository's disposal facilities are located. The surrounding geological environment, including the host rock, functions as a natural barrier, helping to contain and slow down the movement of radioactive materials. The effectiveness of this barrier varies depending on the geological setting.

Over thousands to millions of years, natural processes such as earthquakes, volcanic activity, erosion, and glaciation can affect the long-term stability of a repository. Therefore, the goal is to select a site with a stable geological history and a low risk of future disruption. To achieve this, experts assess a region's geodynamic and seismotectonic setting, faults and shear zones, seismic activity and historical seismicity to predict how the area might evolve. They also study past geological events to forecast future ones via modelling. Seismic hazard is assessed using deterministic, probabilistic and empirical approaches (IAEA, 2022a). This evaluation is crucial for determining whether the selected natural rock formations can safely isolate radioactive waste. If natural events were to damage the host rock (and EBS), alter groundwater flow, or change its chemistry, radioactive materials could potentially escape from the repository.

These assessments are a vital part of the safety case for any disposal facility. They guide the selection of suitable sites and the design of the repository layout and engineered barriers, ensuring that the waste remains securely contained for thousands to millions of years.

Keywords

geological processes, tectonic evolution, stability, groundwater, seismicity, volcanism, erosion, glaciation

Key Acronyms

deep geological repository (DGR), engineered barrier systems (EBS), underground rock laboratory (URL), waste management organization (WMO)

1. Typical overall goals and activities in the domain of geological and tectonic evolution

This section provides the overall goal for this domain, extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to phase of implementation, needed to achieve the domain goal. Activities are generic and are common to most geological disposal programmes.

Domain Goal	
4.3.1 Assess the expected geological and tectonic evolution and the potential for natural disruptive events and their impacts on the stability of the natural barrier (Geological and tectonic evolution)	
Domain Activities	
Phase 1: Programme Initiation	**Description of the local/regional/country-wide geological and tectonic setting.** An overview of the regional geological setting and tectonic history, including rock types, volcanic activity, deformation events, structural features, hydrogeology, hydrogeochemistry, and tectonic evolution, is essential for understanding the long-term stability of potential disposal sites. **Identification of potentially suitable geological disposal concepts:** The choice of disposal concept depends on the available geological environment. For example, sedimentary formations may support different repository designs than crystalline bedrock. Disposal concept guides the rock suitability criteria. The concepts may be supported by natural analogue studies and studies within Underground Rock Laboratories (URLs). **Definition of exclusion criteria**: Exclusion criteria are used to eliminate unsuitable areas from consideration. These may include major faults, high seismic risk, volcanic activity, other natural hazards, unsuitable groundwater properties, or the presence of exploitable geological resources.
Phase 2: DGR Site Identification	**Screening and identification of potentially suitable areas** involves applying previously defined exclusion criteria to eliminate unsuitable regions. The goal is to narrow down areas or sites that may be geologically favourable for a disposal facility. In some countries the screening is restricted to voluntary municipalities while in others the screening is performed for the entire country. **Updating lineament interpretations:** Geological, geophysical, and topographical data will be integrated to refine interpretations of major lineaments (linear features that may indicate major faults). This approach supports the identification and updating of regional deformation zones and enhances delineation of potentially stable bedrock blocks. **Suitability analysis of identified areas:** The evaluation considers all available data on regional geology, hydrogeology, hydro geochemistry, tectonics, soil conditions, topography, geodynamics, and seismology. This integrated analysis supports the identification of areas with the highest potential for long-term geological stability. Stress measurements, geodesy and seismic monitoring is performed and used as input for modelling bedrock stability within different stress fields. Neo/Paleo seismic investigations are performed to extend the seismic catalogue and to identify possible capable faults. Site description and conceptual modelling is further depicting the geological evolution and characteristics of the site.

Phase 3: DGR Site Characterisation	Establishment of pre-construction baseline conditions from long-term monitoring. Detailed studies within outcrops, trenches and boreholes. Site specific geophysical surveys. Development of 3D site descriptive and evolutionary models (structural, stress, geomechanics, biosphere, hydrogeology and hydrochemistry). Development of system on host rock suitability classification based on disposal concept safety requirements. Rock characterisation and monitoring during construction of access routes. Geo-synthesis reporting.
Phase 4: DGR Construction	Detailed site characterisation, confirmation and testing of geological models. Comparison of predictions and outcomes. Updating of models. Availability of higher resolution data (from e.g., tunnels and pilot-holes) enables modelling of smaller-scale features important for identifying optimal volumes for placement of radioactive waste. Measurements and monitoring related to disturbances and to define long-term stability.
Phase 5: DGR Operation and Closure	Possible continuation of construction phase activities during operation. Optimisation of sealing strategy. Monitoring the surroundings of the repository and comparisons to models and baseline. Confirm and preserve documentation on geological and hydrogeological properties of the waste disposal facility. Final conclusions regarding long-term safety.

2. Contribution to generic safety functions and implementation goals

This section describes how geological and tectonic evolution (and its associated information, data, and knowledge) contributes to high level disposal system requirements using EURAD Roadmap Generic Safety and Implementation Goals (see, Domain 7.1.1 Safety Requirements). It further illustrates, in a generic way, how such safety functions and implementation goals are fulfilled. 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 functions 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 Features, characteristics, or properties of geological and tectonic evolution that contribute to achieving storage safety as well as long-term safety of the disposal system

Depth of repository: ISOLATION

Storing radioactive waste deep underground in a stable low-permeability geological environment is meant to keep it safely isolated, both from people and from natural changes. This ensures that if any radioactive materials are ever released and transported into the biosphere, they will be in such small amounts that they pose no risk to human health or the environment. The depth of the repository is carefully chosen to account for both slow geological processes (e.g., potential future glaciations, periglacial processes and erosion) and more sudden natural events (e.g., earthquakes). It also considers how geological and hydrogeological properties change with depth. While optimal repository depth is site specific, to reduce the risks from erosion, possible glaciation and future human intrusion, repositories are typically placed several hundred meters below the surface (IAEA, 2024).

Tectonic stability: EXTERNAL STABILITY

Tectonic stability is a critical factor in selecting and evaluating sites for radioactive waste disposal. The geological environment must be stable enough to ensure the long-term containment and isolation of the waste. Thus, a key aspect of the tectonic stability is having a well-understood and predictable geological setting (NEA, 2024). Sites that show little or no recent tectonic activity, such as earthquakes or volcanic events, and have a low chance of such events occurring in the future are considered more suitable. Tectonic stability strengthens the overall safety case by making it easier to model how the site will behave over time. This predictability builds confidence that the repository will remain a safe and secure environment for isolating radioactive waste, which is essential for gaining regulatory approval and public trust (IAEA, 2024).

Mechanical stability: CONTAINMENT

Mechanical stability is essential to ensure that a geological repository remains structurally intact during operation and for hundreds of thousands of years after closure. This stability depends on selecting host rocks, like crystalline rock, consolidated clay, or rock salt, that can support underground excavations. Each rock type has distinct mechanical properties, such as strength and deformability, which influence the need for structural support. For instance, to guarantee containment, hard rocks may need some reinforcement or grouting. Softer and plastic rocks, however, such as salt formations, may slowly deform and self-seal, enhancing containment. A critical factor is avoiding faults or fractures that could reactivate over time, potentially damaging barriers and creating pathways for radionuclide escape. To reduce these risks, site selection and repository design aim to avoid areas with active faults and to manage excavation-induced damage zones that could compromise long-term safety (IAEA, 2003).

Low groundwater flow: CONTAINMENT

Low groundwater flow is a critical feature of a safe geological disposal environment, especially over long timescales, as it greatly limits the movement of water that could otherwise either change the favourable host rock conditions that might be detrimental to EBS and allow enhanced transport of radionuclides away from the repository. In host rocks such as plastic clays and rock salt, groundwater is either immobile or confined to isolated inclusions, making advective transport negligible (Berlepsch, 2017; Mazurek, 2017). Crystalline rocks are typically more fractured and therefore always require engineered barriers to limit water flow specifically around the waste packages, but also potentially in some sealing structures in the far-field. Low groundwater flow reduces the risk of waste corrosion and radionuclide migration, by allowing containment to rely primarily on the much slower process of diffusion. Over time, such geological environments also maintain chemical stability, which further supports the long-term performance of engineered barriers. Therefore, selecting sites with naturally low hydraulic gradients and stable hydrogeological conditions is essential for ensuring the long-term containment of radioactive waste (IAEA, 2003).

Rock matrix properties: RETENTION AND RETARDATION

The rock matrix consists of small mineral grains separated by pores or microcracks, which may form a continuous network. While porosity varies significantly between rock types, it is the connectivity of these pores that primarily governs transport processes outside fracture networks. In sedimentary rocks, such as clays, porosity can range from a few percent to over 30%. In contrast, crystalline rocks like granite and gneiss typically exhibit much lower porosities (0.1–0.5%), which restricts water movement and radionuclide transport primarily to fracture networks. Nevertheless, even in low-porosity rocks, the rock matrix acts as a radionuclide sink: slow matrix diffusion enables radionuclides to migrate from fractures into the surrounding rock matrix, thereby effectively slowing their movement. Additionally, mineral surfaces within the matrix can retain radionuclides through sorption processes, further enhancing retardation. The presence of microfractures increases surface area and may offer secondary pathways but also contributes to retention if filled with reactive minerals. Overall, the chemical composition, pore structure, and mineralogy of the rock matrix, shaped by the rock's geological evolution, are key factors that determine how effectively radionuclides are retained and delayed during subsurface transport (IAEA, 2003).

Stable groundwater chemistry: RETENTION AND RETARDATION

Stable groundwater chemistry is a fundamental attribute of a suitable geological disposal environment, as it ensures predictable interactions between groundwater, host rock, and engineered barrier system (EBS) over long timescales. In deep, low-permeability formations, groundwater often reaches geochemical equilibrium with surrounding minerals, resulting in chemically redox reducing, saline, and stable conditions. These conditions minimize the solubility and mobility of many radionuclides, reduce corrosion rates of waste containers, and support the long-term integrity of buffer and backfill materials. Moreover, the absence of oxygen and the presence of reducing minerals (e.g., pyrite) help maintain a chemically favourable environment that limits radionuclide concentrations in pore water. These stable hydrochemical conditions are strongly influenced by geological and tectonic evolution, which shapes the long-term isolation potential of the disposal system (IAEA, 2003).

2.2 Features, characteristics, or properties of geological and tectonic evolution that contribute to achieving long-term storage stability and feasible implementation of geological disposal

Level of characterisation: PRACTICABILITY

A high degree of understanding is required for the geological and tectonic characterisation for selecting and validating a repository site for radioactive waste. This detailed insight supports the practicability of repository development by ensuring that the site can be engineered and operated safely over long timescales. Investigations must assess rock structure, geodynamics, stress regimes, hydrogeology, and geochemistry through surface studies, boreholes, and underground laboratories. These data reduce uncertainties in safety and performance assessments and guide the design of engineered barriers. Ultimately, thorough site characterisation and underground investigations underpins confidence in the repository's ability to isolate waste effectively and sustainably (IAEA, 2003).

Safety case: RELIABILITY

The safety case for geological disposal must be grounded in a deep scientific understanding of both past geological and tectonic processes, as well as plausible future scenarios. This includes considering alternative ways the system might evolve over time. Its reliability depends on integrating data from multiple scientific disciplines to show that the repository can maintain its integrity during critical periods, such as thermal changes or future tectonic events, and over long timescales, often spanning tens of thousands of years or more. By systematically evaluating uncertainties and testing models against site-specific data, the safety case builds confidence in the long-term containment of radionuclides. This structured and conservative approach ensures that safety is not only theoretically sound but also demonstrably robust under a wide range of conditions (IAEA, 2011).

Host rock volume: FLEXIBILITY

A sufficiently large and competent rock volume allows for adaptable repository layouts, enabling the safe placement of waste packages while maintaining appropriate spacing to manage heat output and, if needed, accommodate different waste types. The properties, locations, and distribution of brittle geological structures within this volume, such as faults, fractures, and joints, must be carefully assessed, as they can affect the suitability of the rock for geological disposal. A robust safety case therefore requires detailed characterisation of these structures to ensure that repository components are in geologically stable locations with minimal hydraulic connectivity. By integrating this understanding into the design process, the host rock volume can be used effectively to support both repository layout planning and the long-term safety of the disposal system (IAEA, 2003).

3. International examples of geological and tectonic evolution

Finland and Sweden are located within the Fennoscandian Shield, consisting of vast areas of ancient crystalline bedrock that has remained geologically and tectonically stable for hundreds of millions of years. Geological assessments for sites such as Forsmark in Sweden (SKB, 2008) and Olkiluoto in Finland (Aaltonen et al., 2016; Posiva 2021a) rely heavily on understanding both past and future glacial cycles. These assessments anticipate repeated glaciations over the next million years, which could influence groundwater flow, rock stress, and the structural integrity of repository systems. To investigate these potential impacts, the Greenland Analogue Project (Claesson et al., 2016) studied glacial processes at the edge of the Greenland ice sheet. Complementing this, the PGS-Dyn project (Ojala et al., 2019) focused on glacially induced faulting in northern Fennoscandia, providing insights into the seismic and structural responses of the bedrock to glacial loading and unloading.

Japan’s location at the junction of four tectonic plates makes it prone to earthquakes, volcanism, and uplift, posing challenges for long-term safety of radioactive waste disposal. However, some regions have remained geologically stable for over a million years, offering promising conditions for deep geological repositories. NUMO (Nuclear Waste Management Organization of Japan) is evaluating both crystalline (e.g., granite) and sedimentary rock formations, focusing on sites deeper than 300 meters with low permeability, reducing chemistry, and mechanical stability. Safety assessments prioritise a 100,000-year timeframe, with scenarios extending to 1 million years. To manage tectonic risks, NUMO uses a structured, probabilistic approach, developing scenarios, consulting experts, and applying logic trees to assess hazards like faulting and volcanism at repository-relevant scales. Sites with active faults or recent geological disturbances are excluded. Geological evolution is assessed through extrapolation, analogies, and modelling, with a strong focus on site-specific evaluations (NUMO, 2021).

In the national radioactive waste disposal programmes of Switzerland (Nagra) and France (Andra), clay formations are considered as potential host rocks. These formations are characterised by very low permeability (predominantly diffusive groundwater transport) and high sorption capacity (Gautschi, 2017). Additionally, fractures in such rocks tend to self-seal over time, enhancing their containment capabilities (Bock, 2010). Studies of faults within the Opalinus Clay formation in Switzerland suggest that aseismic slip is the dominant mode of fault reactivation, rather than earthquake nucleation, which contributes positively to the safety for this host rock option (Orellana et al., 2018). Furthermore, no major fault zone intersects the future Cigéo storage site.

The Gorleben site in northern Germany (BGE) was developed as a potential geological repository for high-level radioactive waste, situated within a large, homogeneous salt dome. Salt is considered an ideal host rock due to its low permeability, high thermal conductivity, and ability to self-seal through creep, which enhances long-term containment. The repository design prioritises natural geological barriers to ensure isolation for up to one million years. The Gorleben salt dome has evolved over approximately 250 million years through diapirism, where buoyant salt rose through overlying sediments, with uplift slowing significantly over the past 20 million years. Geological evidence suggests that diapiric activity will continue to decline due to reduced tectonic stress in the region. Although the dome has experienced dissolution of salt by groundwater this process is now limited to shallow depths. Glacial erosion channels have affected the overburden but are unlikely to reach repository depths in future glaciations. Overall, the geological and tectonic evolution indicates a stable environment at repository depth, supporting the long-term safety of nuclear waste disposal (Berlepsch & Haverkamp, 2016).

In the UK, integrating geological, climatic, and hydrological data is essential for anticipating future environmental conditions and mitigating risks to DGRs. Although the UK lies in a relatively stable intraplate setting with very low seismicity and no volcanic activity, its complex geological history presents unique challenges. Processes such as glacial isostatic adjustment, uplift, subsidence, and erosion, especially during future glacial cycles, could impact DGR integrity. Climate models predict recurring glaciations and permafrost development, which may affect both engineered and geological barriers. Glacial loading and unloading may also increase seismicity near ice margins, while sea-level changes may alter groundwater flow and erosion dynamics. Due to the complexity and uncertainty of these processes, site-specific studies and probabilistic modelling are crucial (McEvoy et al., 2016). As part of the ongoing EURAD CLIMATE work package, the impact of climate change on nuclear waste management is investigated, and knowledge gaps are actively identified.

4. Critical background information

Ensuring the stability of the geological environment is essential for the safe isolation of radioactive waste over the extended timescales required for geological disposal. However, stability does not imply that the environment remains completely unchanged. Natural geological processes (both gradual and episodic) will continue to occur.

Although long-term predictability of geological and tectonic processes is inherently uncertain over long timescales decades of earth science research have provided a strong understanding of these processes. This enables experts to model how geological settings may evolve and to assess how such changes could impact the performance of natural and engineered barriers. These insights are fundamental to evaluating the long-term safety of a geological repository. The following aspects of geological and tectonic evolution are considered critical for the successful implementation of geological disposal (IAEA, 2003; 2011; NEA, 2024):

Geological setting and host rock characteristics

- Stability over geological timescales (thousands to millions of years)
- Favourable mechanical, hydrogeological, and geochemical properties.
- Depth and lithological characteristics of host rock to ensure containment and isolation.

Tectonic and Seismic Considerations

- Assessment of tectonic stress and stability, seismicity, and fault activity.
- Historical and instrumental earthquake records.
- Evaluation of neotectonics and the potential impact on repository integrity.
- Fault displacement rates and recurrence intervals.

Volcanism and Igneous Activity

- Distribution and history of Quaternary volcanism.
- Magma intrusion pathways and thermal anomalies.
- Assessment of risk of future volcanic activity near repository sites.

Uplift, Erosion, Sedimentation, Climate and Landscape Evolution

- Long-term uplift and denudation rates.
- River incision, glacial cycles, and sea-level changes.
- Impacts on repository depth and overburden stability.
- Use of natural analogues to understand long-term changes in site conditions.
- influence of glacial cycles and postglacial rebound on regional and local stress field variation and potential fault reactivation

Hydrogeological conditions

- Low permeability and slow groundwater movement to limit radionuclide transport and to ensure geochemical stability at repository depth.
- Fracture networks and their influence on radionuclide transport.
- Understanding of hydraulic gradients, recharge/discharge zones, and aquifer systems.
- Hydrothermal activity

Geochemical environment

- Evolution of groundwater chemistry over geological timescales.
- Conditions that retard radionuclide migration (e.g., sorption, precipitation).

- Compatibility with engineered barriers and waste forms.

Modelling and Scenario Development

- Use of natural analogues to assess long-term stability.
- Evidence of geochemical and hydrogeological stability over millions of years.
- Use of numerical models to simulate geological evolution.
- Scenario-based risk assessments incorporating probability estimates, uncertainty quantification and logic trees.

4.1 Integrated information, data or knowledge (from other domains) that impacts understanding of geological and tectonic evolution

International Cooperation and Shared Foundations (1.3.1)
While geological conditions vary between countries, many similarities exist in the subsurface environments that are suitable for deep geological repositories. Importantly, the fundamental principles and technologies that underpin the long-term safe disposal of radioactive waste and spent nuclear fuel are universally applicable. This common foundation encourages to international cooperation and knowledge sharing to develop internationally accepted, robust, science-based disposal solutions.

Understanding and Designing for Geological and Climate-Induced Impacts
Disposal system design must account for both geological and climate-induced processes, such as glacial activity. The potential impacts of glacial cycles, including mechanical stress and chemical perturbation from groundwater changes, must be carefully considered during EBS design (3.4.1).

Site Descriptive Models and Natural Barrier Assessment
A site descriptive model (4.1.1) plays a central role in demonstrating how the host rock and surrounding geological formations (the natural barrier) contribute to long-term safety. This model compiles geological, hydrogeological, and geochemical data to support safety assessments and guide repository design.

To enhance understanding of potential perturbations (4.2.1), studies of natural analogues are employed. These help to predict how geological and tectonic stability may be affected by repository construction and operation, and how such impacts can be managed.

Climate Change and Long-Term Geological Stability
Climate change (4.3.2) may introduce additional complexities, including glacial rebound, permafrost degradation, eustatic variation (i.e. sea-level change), and shifts in groundwater systems. These processes can impact both geological and tectonic stability, making it essential to evaluate their potential influence on the safety and integrity of the repository system.

To improve predictive capability and uncertainty management, numerical models, including advanced tools like digital twins and virtual reality simulations (5.2.5), can be used to visualize and simulate geological evolution over time.

Conceptual Models and Design Principles
Conceptual models (4.4.1) integrate data and understanding of long-term geological and tectonic evolution into the design and layout of the repository. These models form the backbone of the safety case by visualizing how natural and engineered systems interact over time.

The disposal concept (5.1.1) must be selected in alignment with the long-term stability of the site's geology and tectonic setting. This ensures that both natural and engineered barriers will perform as intended under evolving conditions.

Balancing and Optimising Safety Functions
Design optimisation (5.2.2) involves balancing risks between the natural barrier and the EBS. An overreliance on either component can introduce vulnerabilities and additional costs; hence, a harmonised safety strategy is necessary.

Monitoring and Verification of Geological Conditions

Baseline monitoring (5.5.1) is conducted before and during repository development to establish a detailed understanding of geological and tectonic conditions. This monitoring tracks parameters such as seismic activity, rock movement, groundwater behaviour, and temperature gradients.

During onsite investigation, construction, and operational phases (5.5.2), continuous monitoring is essential to verify that the geological environment behaves as expected and that the assumptions made during design remain valid.

Site Selection and Regulatory Compliance
The long-term geological stability of the host environment is a cornerstone of conceptual planning (6.1.1). Area survey and site screening (6.1.2) use predefined exclusionary and suitability criteria to eliminate geologically unstable regions (such as those with high seismicity, active faulting, complex structural context or susceptibility to glaciation or erosion) from further consideration.

Following this, the process moves to site investigation (6.2.1) and detailed site characterisation (6.2.2), where data is refined, and site suitability is confirmed with greater precision.

Ultimately, regulatory licensing (6.3.2) demands a well-documented and scientifically supported understanding of the site's geological and tectonic stability. This knowledge is essential to meet legal requirements and ensure long-term safety of the disposal facility.

5. Maturity of knowledge and technology

5.1 Advancement of safety case

Disposal in deep geological repositories (DGRs) is a globally recognized solution for the long-term safety of spent nuclear fuel. These facilities combine EBS with the natural stability of deep underground rock formations. This layered defence strategy is designed to isolate radioactive materials for thousands to millions of years.

A post-closure safety case is a structured and evolving argument that explains why a geological repository for radioactive waste can remain safe over extremely long timescales, even after it's been sealed and is no longer monitored. Early on in a project, safety cases may rely on general assumptions about geology and design but as research, construction, and testing progress, the safety case becomes more detailed, drawing on site-specific data and modelling (NEA, 2004). Here, it is vital that site characterisation programme serves safety case process (IAEA 2024).

The concept of geological disposal for radioactive waste has reached a high level of maturity especially in countries with advanced nuclear programs. Several countries have made significant progress in DGR implementation. For example, Posiva Oy (waste management organization (WMO) in Finland) received construction licence in 2015 and started constructions in 2016 with plans to begin final disposal in the 2020s. Sweden's WMO SKB is also advancing its own licensing process, while France is developing its deep geological repository concept with a construction licence application submitted in 2023. Other countries such as Canada, the UK, and Germany are engaged in formal site selection efforts. Some nations, including the Netherlands, Denmark, Norway, Belgium, Slovenia, Italy and Croatia, are also exploring the possibility of multinational disposal solutions. A key element supporting DGR programs is the global network of underground research laboratories (URLs). These facilities serve as testing grounds to support safety case and repository designs and help build public and regulatory confidence in long-term safety strategies (IAEA, 2022b).

Geological studies from other than the actual disposal sites can be used to support the safety cases. These include URL and various types of natural analogue studies (e.g. site analogues, process studies etc.). Natural analogues have provided a powerful tool in advancing the safety case for geological disposal of radioactive waste. They offer real-world examples of how materials and processes like those in a repository behave over geological timescales, something no laboratory experiment can fully replicate. For instance, by studying uranium ore bodies, scientists have observed that radionuclides have remained immobilized in natural rock formations for millions of years (Gauthier-Lafaye et al., 1996). This helps validate models predicting how spent nuclear fuel might behave in a repository. Similarly, the discovery of native copper sheets preserved in clay-rich rocks for over 170 million years supports the idea that copper canisters used to contain waste will remain intact for comparable durations (Alexander et al., 2015).

5.2 Optimisation challenges and innovations

Optimisation in geological disposal of radioactive waste is a multi-dimensional challenge, balancing safety, cost, engineering feasibility, environmental impact, and public acceptance over timescales of up to a million years. One of the biggest challenges is that geological and tectonic processes, such as faulting, uplift, or glaciation, can alter the stability of a repository site over time. This means that early decisions, like where to place the repository and how to design its engineered barriers, must be informed by robust models of how the subsurface might change.

To meet this challenge, disposal programmes are increasingly turning to digital innovations (Gaus et al, 2023). Virtual simulations and digital twins allow engineers and geoscientists to test how different repository designs and engineered barriers would perform under various geological scenarios. These tools help identify potential weaknesses early and support more resilient, flexible designs. Thus, understanding of geological and tectonic evolution feeds directly into safer, more efficient repository designs.

5.3 Past and ongoing (RD&D) projects

Past (RD&D) Projects:

- The Kiruna Natural Analogue (KiNa) project aimed to investigate the formations of smectite-rich clay as a natural analogue for the long-term evolution of bentonite components of a geological disposal system for radioactive waste. 2019 – 2022
  - https://igdtp.eu/activity/kina-kiruna-natural-analogue/
- PGSdyn project focused on glacially induced faulting in northern Fennoscandia, providing insights into the seismic and structural responses of the bedrock to glacial loading and unloading. 2014 – 2018
  - https://www.researchgate.net/publication/332801798_Postglacial_faults_in_Finland_-_a_review_of_PGSdyn_-project_results
- The Greenland Analogue Project (GAP) studied the impact of glacial conditions on the long-term safety of deep geological repositories for nuclear waste. 2008 – 2013
  - https://www.skb.com/publication/2484498/
- GASNET - A thematic network on gas issues in safety assessment of deep repositories for nuclear waste. 2001 – 2004
  - https://cordis.europa.eu/project/id/FIKW-CT-2001-20165
- Biosphere models for Safety Assessment of radioactive waste disposal based on the application of the Reference Biosphere Methodology. 2001 – 2003
  - https://cordis.europa.eu/project/id/FIKW-CT-2001-00184/factsheet
- CATCLAY: Processes of cation migration in clayrocks. 2010 – 2014.
  - https://igdtp.eu/activity/catclay-processes-of-cation-migration-in-clayrocks/
- CROCK: Crystalline rock retention processes. 2011 – 2013.
  - https://igdtp.eu/activity/crock-crystalline-rock-retention-processes/
- FUNMIG: FUNdamental processes of radionuclide MIGration. 2005 – 2008.
  - https://igdtp.eu/activity/funmig-fundamental-processes-of-radionuclide-migration/
- NF-PRO: Understanding and Physical and Numerical Modelling of the Key Processes in the Near-Field and their Coupling for Different Host Rocks and Repository Strategies. 2004 – 2007.
  - https://igdtp.eu/activity/nf-pro-understanding-and-physical-and-numerical-modelling-of-the-key-processes-in-the-near-field-and-their-coupling-for-different-host-rocks-and-repository-strategies/

Ongoing (RD&D & Strategic Studies) Projects:

- CCSC: Climate Change in the Safety Case. 2021 –
  - https://igdtp.eu/activity/ccsc-climate-change-in-the-safety-case/

- EURAD-1 Work Package HITEC: Improved THM description of clay based materials at elevated temperatures
    - *https://www.ejp-eurad.eu/implementation/impact-climate-change-nuclear-waste-management-climate*
- EURAD-2 Work Package CLIMATE: Impact of climate change on nuclear waste management
    - https://www.ejp-eurad.eu/implementation/impact-climate-change-nuclear-waste-management-climate
- EURAD-2 Work Package HERMES: High fidElity numeRical siMulations of strongly coupled processes for rEpository syStems and design optimisation with physical models and machine learning
    - *https://www.ejp-eurad.eu/implementation/high-fidelity-numerical-simulations-strongly-coupled-processes-repository-systems*
- EURAD-2 Work Package RAMPEC: Radionuclide mobility under perturbed conditions
    - *https://www.ejp-eurad.eu/implementation/radionuclide-mobility-under-perturbed-conditions-rampec*
- The ERDO Deep Borehole Disposal Project is a strategic initiative led by the European Repository Development Organisation (ERDO) to assess the feasibility of deep borehole disposal (DBD) as a solution for high-level radioactive waste (HLW) and spent nuclear fuel, particularly for countries with small waste inventories.
    - https://www.erdo.org/deep-borehole-disposal/

5.4 Lessons learnt

Geological and tectonic stability

Studies on nuclear waste disposal consistently demonstrate that understanding the geological and tectonic evolution of a site must be site-specific, as no two locations share identical geological histories or characteristics. However, a regional understanding is also essential to provide a holistic framework for interpreting local data. Lessons learned from projects in Finland, Sweden, the USA., France, and Germany highlight the importance of detailed assessments of rock formations, seismic activity, groundwater systems, and long-term geochemical stability. Collectively, these experiences have matured the domain's understanding of Earth's deep-time processes and reinforced the need for multidisciplinary, localised investigations to ensure the long-term safety of nuclear waste repositories.

Natural analogues

Studies on natural analogues provide convincing real-world evidence supporting the safety of geological disposal for nuclear waste. These analogues are naturally occurring systems that mimic key features of nuclear waste repositories, where radioactive materials, groundwater or substances like those used in EBS have remained stable. They offer valuable insights into how nuclear waste, EBS or the site itself might behave in deep geological environments over long timescales. Natural analogues of faulting (see e.g. PGSdyn project above) can provide crucial information that is needed for the long-term assessment (see Posiva 2021b). Similarly, the Mont Terri URL in Switzerland, had long served as an analogue site for the Opalinus clay repository studies (https://www.mont-terri.ch/en). Furthermore, the behaviour of trace elements in a rock can be used as a proxy for long-term radionuclides and toxic chemical migration (Grangeon et al., 2023).

Public acceptance

The process and options for choosing a final site for a deep geological repository varies from country to country. In some cases, the decision is made by the WMO, the national government, a geological institute, a dedicated siting commission, or a mix of these actors. Regardless of the setup and geological environment, involving local communities is crucial, especially during the siting phase. Experience shows that getting approval to build a repository usually depends on earning the trust and consent of the host community. This is much more likely if residents are engaged from the outset and if the site is shown through transparent research to be geologically and tectonically stable (van Est & Arentsen, 2023).

6. Uncertainties

To ensure the long-term safety of a DGR, the surrounding geological environment must be stable and predictable. This allows scientists to assess potential risks over very long timescales, up to one million years. Natural processes that could influence the site include tectonic activity, as well as climate-driven changes such as erosion, land uplift, and glaciation. One of the main challenges is the uncertainty in how these processes will evolve. Their rates can vary widely, and unexpected shifts may occur, making future predictions difficult. From a geological perspective, one million years is a short period, and current data may not capture the full range of possible tectonic changes. Similarly, forecasting climate patterns beyond 200,000 years is highly uncertain. Therefore, scientists must rely on models that estimate the range of possible climate conditions, rather than precise outcomes (McEvoy et al., 2016). These projections are based on a range of scenarios that account for possible trajectories of anthropogenic forcing, primarily driven by greenhouse gas emissions.

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 geological and tectonic evolution.

Guidance
https://www.oecd-nea.org/ https://www.iaea.org/
Training
https://euradschool.eu/events/category/eurad-training-course/ https://igdtp.eu/research-area/education-and-training/
Active communities of practice and networks
https://www.ejp-eurad.eu/ https://igdtp.eu/
Capabilities (Competences and infrastructure)
https://nucleus.iaea.org/sites/connect/urfpublic/SitePages/Home.aspx

8. Further reading, external Links and references

8.1 Further Reading

INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Site Investigations for Radioactive Waste Disposal Facilities, IAEA Nuclear Energy Series No. NW-T-1.40, IAEA, Vienna (2024), https://doi.org/10.61092/iaea.jy3v-m5p4

NEA (2024), International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste, OECD Publishing, Paris https://www.oecd-nea.org/jcms/pl_97739

8.2 External Links

https://www.posiva.fi/en/index/media/reports.html

https://www.skb.com/publications/

https://www.andra.fr/documents-et-ressources

https://nagra.ch/downloads/

https://www.ondraf.be/general-publications

https://www.enresa.es/eng/

8.3 References

Alexander, W.R., Reijonen, H.M. & McKinley, I.G. Natural analogues: studies of geological processes relevant to radioactive waste disposal in deep geological repositories. Swiss J Geosci **108**, 75–100 (2015). https://doi.org/10.1007/s00015-015-0187-y

Berlepsch, T. (2017): Salt repository systems: design development approach at the example of the Gorleben salt dome. In: Apted, M.J. & Ahn, J. (Eds): Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive (2nd ed.), Woodhead Publishing Series in Energy, 145-162.

Berlepsch, T. & Haverkamp, B. (2016): Salt as a Host Rock for the Geological Repository for Nuclear Waste. Elements 12/4, 257-262. https://doi.org/10.2113/gselements.12.4.257

Bock, H., Dehandschutter, B., Martin, C. D., Mazurek, M., De Haller, A., Skoczylas, F., & Davy, C. (2010). Seal-sealing of fractures in argillaceous formations in the context of geological disposal of radioactive waste: Review and Synthesis, Nuclear Energy Agency - Organization for Economic Co-Operation and Development. https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/nea6184-self-sealing.pdf

Claesson Liljedahl, L; Kontula, A; Harper, J; Näslund, J-O; Selroos, J-O; Pitkänen, P; Puigdomenech, I; Hobbs, M; Follin, S; Hirschorn, S; Jansson, P; Kennell, L; Marcos, N; Ruskeeniemi, T; Tullborg, E-L; Vidstrand, P. (2016). The Greenland Analogue Project: Final report, SKB TR-14-13. https://www.skb.com/publication/2484498/TR-14-13.pdf

van Est, R., Arentsen, M. (2023). European Lessons for the Governance of Long-Term Radioactive Waste Management. In: Arentsen, M., van Est, R. (eds) The Future of Radioactive Waste Governance. Energiepolitik und Klimaschutz. Energy Policy and Climate Protection. Springer VS, Wiesbaden. https://doi.org/10.1007/978-3-658-40496-3_12

Gauss, I., Blechschmidt, I., Hansen, J., Jon, M., Van Geet, M. & Jalonen, T. (2023): The Role of Optimization in Geological Disposal Programmes for Radioactive Waste, IGD-PT Position paper. https://igdtp.eu/wp-content/uploads/2023/04/IGD_TP-The-role-of-optimisation-in-geological-disposal-programmes-for-RW-2023.pdf

F. Gauthier-Lafaye, Holliger, P., Blanc, P. (1996). Natural fission reactors in the Franceville basin, Gabon: A review of the conditions and results of a “critical event” in a geologic system, Geochimica et Cosmochimica Acta, Volume 60, Issue 23. https://doi.org/10.1016/S0016-7037(96)00245-1

Grangeon, S., Roux, C., Lerouge, C., Chardon, P., Beuzeval, R., Montavon, G., Claret, F., & Grangeon, T. (2023). Geochemical and mineralogical characterization of streams and wetlands downstream a former uranium mine (Rophin, France). Applied Geochemistry, 150, 105586. https://doi.org/10.1016/j.apgeochem.2023.105586

INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Site Investigations for Radioactive Waste Disposal Facilities, IAEA Nuclear Energy Series No. NW-T-1.40, IAEA, Vienna (2024) https://doi.org/10.61092/iaea.jy3v-m5p4

INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic hazards in site evaluation for nuclear installations, IAEA safety standards series, ISSN 1020–525X; no. SSG-9 (Rev. 1), IAEA, Vienna (2022a) https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1950_web.pdf

INTERNATIONAL ATOMIC ENERGY AGENCY, Status and Trends in Spent Fuel and Radioactive Waste Management, IAEA Nuclear Energy Series No. NW-T-1.14 (Rev. 1), IAEA, Vienna (2022b) https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1963_web.pdf

INTERNATIONAL ATOMIC ENERGY AGENCY, Geological Disposal Facilities for Radioactive Waste, IAEA Safety Standards Series No. SSG-14, IAEA, Vienna (2011) www.pub.iaea.org/MTCD/Publications/PDF/Pub1483_web.pdf

INTERNATIONAL ATOMIC ENERGY AGENCY, Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes, Technical Reports Series No. 413, IAEA, Vienna (2003) https://www-pub.iaea.org/MTCD/Publications/PDF/TRS413_web.pdf

Gautschi, A. Safety-relevant hydrogeological properties of the claystone barrier of a Swiss radioactive waste repository: An evaluation using multiple lines of evidence. Grundwasser 22, 221–233 (2017) https://doi.org/10.1007/s00767-017-0364-1

Mazurek, M. (2017). Far-field process analysis and radionuclide transport modelling for saturated media. In: Apted, M. J.; Ahn, J. (Eds.) Geological repository systems for safe disposal of spent nuclear fuels and radioactive waste (2nd ed.). Woodhead Publishing Series in Energy, 229-266.

McEvoy, F. M., Schofield, D. I., Shaw, R. P., & Norris, S. (2016). Tectonic and climatic considerations for deep geological disposal of radioactive waste: A UK perspective. Science of the Total Environment, 571, 507–521. https://doi.org/10.1016/j.scitotenv.2016.07.018

NEA (2024), International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste, OECD Publishing, Paris https://www.oecd-nea.org/jcms/pl_97739

NEA (2004), Post-closure Safety Case for Geological Repositories, OECD Publishing, Paris https://www.oecd-nea.org/jcms/pl_13678/post-closure-safety-case-for-geological-repositories?details=true

NUMO, (2021). The NUMO Pre-siting SDM-based Safety Case, NUMO-TR-21-01. https://www.numo.or.jp/technology/technical_report/pdf/NUMO-TR21-01_rev220222.pdf

Ojala, A. E.K., Mattila, J., Ruskeeniemi, T., Markovaara-Koivisto, M., Palmu, J-P., Nordbäck, N., Lindberg, A., Sutinen, R., Aaltonen, I., Savunen, J. (2019). Postglacial faults in Finland: A review of PGSdyn project results. Posiva. https://www.researchgate.net/publication/332801798_Postglacial_faults_in_Finland_-_a_review_of_PGSdyn_-project_results

Orellana, L. F., Scuderi, M. M., Collettini, C., & Violay, M. (2018). Frictional properties of Opalinus Clay: Implications for nuclear waste storage. Journal of Geophysical Research: Solid Earth, 123, 157–175. https://doi.org/10.1002/2017JB014931

Posiva (2021a). Olkiluoto Site Description 2018. POSIVA 2021-10. Eurajoki, Finland: Posiva Oy. available at: https://cms.posiva.fi/

Posiva (2021b). Posiva 2021. Safety Case for the Operating Licence Application - Performance Assessment and Formulation of Scenarios (PAFOS). POSIVA 2021-06. Eurajoki, Finland: Posiva Oy. available at: https://cms.posiva.fi/

SKB. (2008). Site description of Forsmark at completion of the site investigation phase, TR-08-05, Svensk Kärnbränslehantering AB. https://www.skb.com/publication/1868223/TR-08-05.pdf