eurad 2
European Partnership
on Radioactive Waste Management

3.4.2 Co-Disposal, Domain Insight

EURAD Roadmap

1. National Programme Management
2. Pre-disposal
3. **Engineered Barrier System**
    - 3.1 Waste forms
    - 3.2 Waste packages, for disposal
    - 3.3 Buffers, backfills, plugs and seals
    - **3.4 EBS system integration**
4. Geoscience
5. Disposal facility design and optimisation
6. Siting and Licensing
7. Safety Case

Authors: Nuria Marcos

Reviewers: John L. Provis and Quoc Tri Phung

Version: 0.1, 21/10/2025

DOI: 10.5281/zenodo.17407222

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

Co-disposal refers to the final disposal of radioactive waste (spent nuclear waste SNF, high-level radioactive waste HLW, low- and intermediate-level waste LILW) in different areas, and at the same or different depths in a single facility. A set of materials serving as engineered barriers (Engineered Barrier System, EBS) to contain and isolate the waste from the biosphere has been studied. The materials performance in the same disposal and the interactions between the ones used in the same disposal area and the materials used in different disposal areas and depths in the case of co-disposal of SNF, HLW and LILW is of utmost importance for long-term safety.

The focus of this deliverable is on interaction of materials used in the EBS in the case of co-disposal.

For the disposal of SNF and HLW, the materials considered for canisters containing the waste are copper with an iron insert (in Sweden and Finland) or iron/stainless steel (most other European countries, e.g. in France, Switzerland, Belgium). The canisters will be surrounded by buffer material, mostly a swelling clay (bentonite) or concrete (at least in Belgium). For the disposal of LILW, the most common materials used in the immobilization and containment of radionuclides are metals (steel or stainless-steel drums), cement, and concrete. Backfill materials (crushed rock, clay, sand, or mixtures, also high porous cementitious materials in some cases) are another barrier to use for the disposal of both kinds of waste. The host rock around the repositories can be crystalline rock (e.g. granite, gneiss as e.g. in Finland, Sweden, Czech Republic) or sedimentary (e.g. clay as in Belgium, France, Switzerland).

Keywords

Co-disposal, radioactive waste, engineered barrier system, EBS, interactions, bentonite, cementitious materials, disposal system, repository

Key Acronyms

engineered barrier system (EBS), spent nuclear fuel (SNF), high level waste (HLW), low and intermediate level waste (LILW), deep geological repository (DGR)

1. Typical overall goals and activities in the domain of Co-disposal

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	
3.4.2 Confirm that interactions between different EBS materials in disposal areas for different waste types do not compromise the performance of the disposal system (Co-disposal)	
Domain Activities	
Phase 1: Programme Initiation	Conduct SNF/HLW, and LILW inventory analysis. Characterization of waste and potential engineered barriers materials for SNF/HLW and LILW.
Phase 2: DGR Site Identification	Investigate the availability of enough space for disposal options (two repositories in one facility) and requirements to avoid interactions that could threat the operational and post-closure safety
Phase 3: DGR Site Characterisation	Perform (or use available) studies on interactions between the potential materials to be used in the EBS for the radioactive waste to be dispose of. Hydrogeological and hydrogeochemical investigations are on place.
Phase 4: DGR Construction	Confirmation of the result of hydrogeological and hydrogeochemical models. Update of modelling interactions between EBS materials accounting for hydrogeological and hydrogeochemical data; design and optimisation of transport options and construction step by step to avoid operational mishaps that could also have long-term safety implications.
Phase 5: DGR Operation and Closure	Confirm and preserve documentation for emplaced waste inventory, and at which depth. Details of the composition of the EBS (metallic components, bentonite, sand, crushed rock, concrete, etc) and the position of those components in the facility.

2. Contribution to generic safety functions and implementation goals

This section describes how co-disposal 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 Co-disposal that contribute to achieving storage safety as well as long-term safety of the disposal system

2.1.1 Primary goal – Ensure long-term stability with respect to internal evolution

INTERNAL STABILITY: The DGR is designed and implemented such that disposal system performance is not significantly affected by internal disturbances (e.g. temperature due to heat generation). Ensure first the compatibility of barrier components by the appropriate selection of materials. Then assess the evolution of the EBS with time accounting for potential hydrogeological and hydrogeochemical disturbances. Changes in groundwater flow and chemistry could affect the interactions between a repository for SNF/HLW and a repository for LILW, situated either at the same depth (as in case of the Swish repository (Figure 2) or at different depth (Figure 1).

BENTONITE STABILITY: Groundwater chemistry and hydraulic conductivity around the buffer need to be favourable so that swelling pressure is adequate. It is also important to avoid changes in composition and avoid erosion that could endanger bentonite mechanical stability. These changes could negatively impact sorption of radionuclides in bentonite. and microbial activity (MIND, 2019a) reaching the canister containing the waste. Microbial activity could generate corroding substances (e.g. sulphide) leading to a breach in the canister and leading to radionuclide releases.

CEMENT/CONCRETE STABILITY: Groundwater chemistry and microbial activity play a significant role in the degradation of cement and concrete contributing to their structural deterioration. According to Zhu & Dittrich (2016) microorganisms can form a biofilm in the surfaces of cracks and produce organic acids and carbon dioxide that deteriorate cement. Cement high pH leachates could contribute to destabilization of bentonite (e.g. ANDRA, 2005), should these leachates reach the repository areas where bentonite is used. Mechanical stability should be ensured to withstand mechanical loads in the expected repository conditions for as long as possible.

BACKFILL STABILITY: Backfill is a barrier that aims to provide mechanical stability. The material can be clay, cement, clay and sand, clay and crushed rock, or just crushed rock, or a mixed of these materials. It may have safety functions of its own or may help to maintain the safety functions of the other barriers. In helping to maintain the safety functions, interaction of backfill materials with other barriers should be understood.

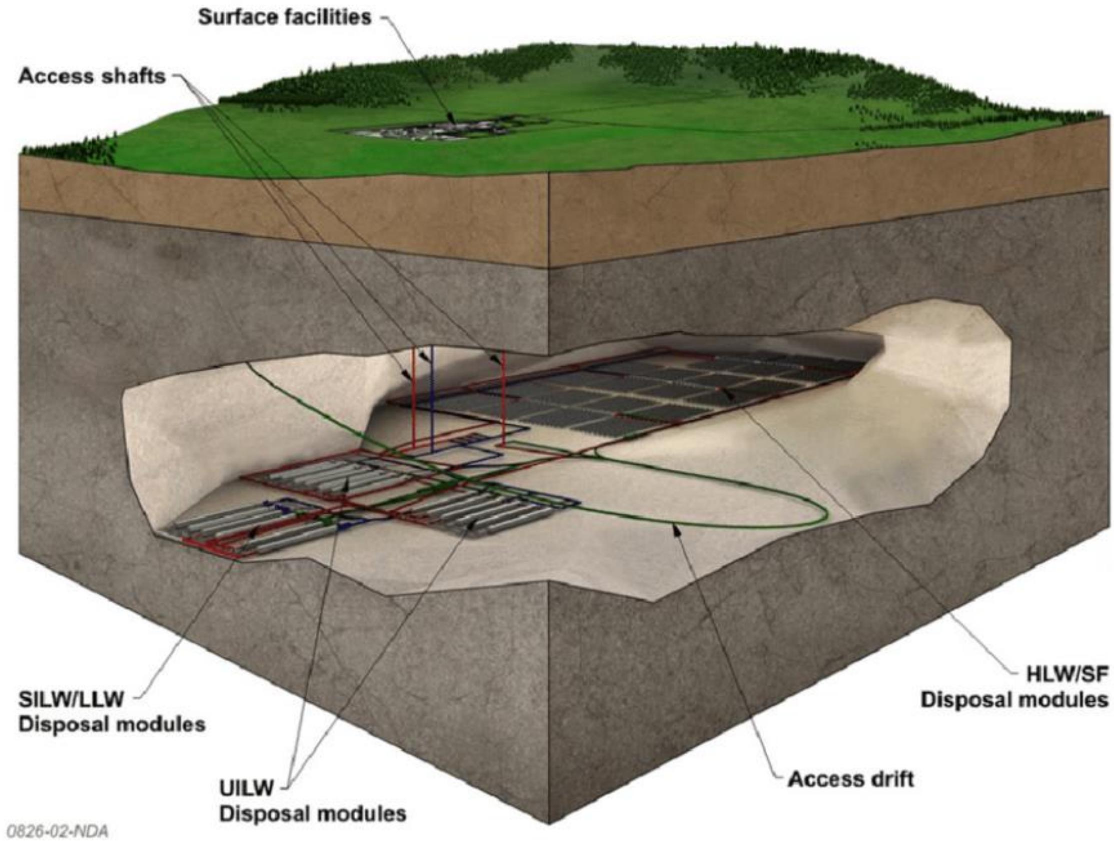

Figure 1. Generic co-located facility at two different levels (reproduced from DEFRA (2008)) and published in Wilson et al. (2011).

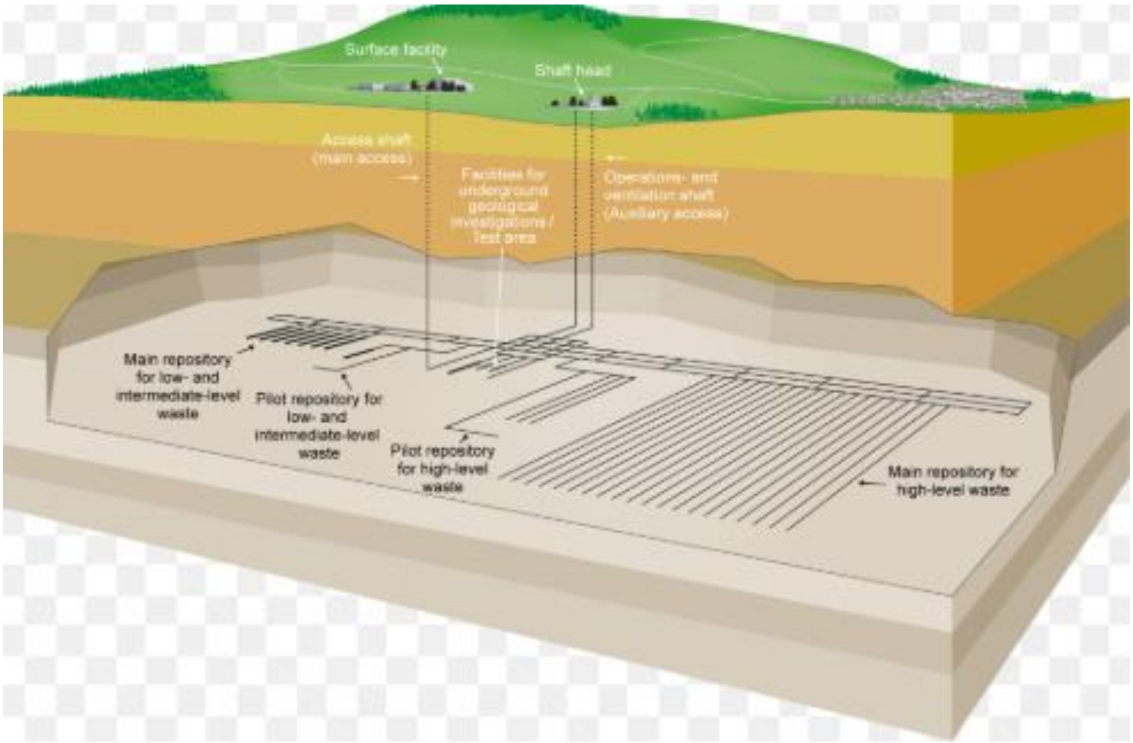

Figure 2. Co-disposal of HLW and LILW waste at the same level. Nagra, Switzerland (2020).

2.1.2 Secondary goal – slow transport of radionuclide releases and other substances through the engineered barriers in the geosphere

Slow transport through the engineered barriers is provided by the performance of the buffer bentonite and the performance of the concrete and cement that limits and retard the release of radionuclides. Buffer bentonite is the main barrier surrounding the waste canister in repositories emplaced in crystalline host rocks. As this barrier is only tens of centimetres thick, interaction with cement barriers used in other locations need to be considered, as noted in the section above. The less disturbances the longer time of adequate performance of the bentonite. In concepts where the host rock is clay or clayish, the main barrier surrounding the waste canister may consist of concrete/cement. Here the cement limits and retard potential radionuclide releases to the host rock. Therefore, the concrete-clay interface should not form a transport pathway. Thus, independent of the host rock or even of co-disposal, cement/bentonite interactions need to be accounted for. The slow transport of radionuclides and other substances in the geosphere is achieved by co-locating the repositories in a bedrock domain with a low hydraulic conductivity, either at the same depth or at different depths. To keep the bedrock domain with low hydraulic conductivity disturbances during construction and operation of the repositories should be minimised.

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

PRACTICABIITY – The materials selected to be used as engineered barriers are well known and well characterised. Their processing and their interactions have been tested successfully.

FLEXIBILITY –. Canisters and cases have been developed and suitable materials identified for a wide range of wastes and encapsulation tested following safe procedures. The use of cement and concrete to immobilise LILW has been widely tested.

OPERATIONAL SAFETY – Encapsulation of SNF/HLW and immobilisation of LILW can be totally automatised, so that there is no need to direct contact with the personnel involved in the task. The transfer of the waste to its destination can be also automated, or at a minimum it will be possible to offer radiation protection to the personnel involved. This applies nod only to the operations of one repository, but also to co-disposal of waste in two repositories at the same level or at two different levels. Co-disposal would need underground opening at different locations at the same or different depths. Mining works around the world have shown excavation and safety of underground openings can be achieved taking the proper measures.

2.2.1 Primary goals – relied upon for practicability, flexibility and operational safety

Co-disposal of the two waste classes will account for the host rock properties as well as the restrictions set by urban planning in the municipality or municipalities near the selected site. The repositories should be located such that they are isolated from the surface environment and from each other to avoid potential damaging interactions, though the access to both could be common. A LILW repository could potentially be excavated later than that for HLW to include decommissioning waste and allow a better estimation of the waste volumes.

The design of the repositories and the barriers (engineered and natural) should aim to provide the necessary degree of containment, for a duration that is sufficient in relation to the half-lives of the radioactive elements in the waste inventory.

The role of the natural and engineered barriers between the repositories should avoid the formation of new preferential flow paths. These flow paths could act to transport undesirable substances from one repository to another, damage the performance of the barriers and lead to radionuclide transport to the geosphere and biosphere.

3. International examples of Co-disposal

The co-disposal of low and intermediate level waste (LILW) is a common practice in many countries as they are isolated and contained by similar engineered barriers. However, the co-disposal of HLW/SNF and LILW has been planned in a few countries (e.g. Finland, Switzerland, United Kingdom). In France (ANDRA 2025) and Switzerland (OECD 2020) co-disposal of HLW and LILW has been planned for different areas at the same repository depth. In Finland (Posiva 2021) and United Kingdom co-disposal is planned at different depths (Norris & Williams 2012).

Norris & Williams (2012) presented an assessment of the potential for interaction of disposal modules (e.g. ILW/LLW and HLW/SF) in a co-located GDF – the study considered the potential for the interaction of an alkaline plume developed from an evolving ILW/LLW module post-closure to interact with an evolving HLW/SF module, and concluded that such interaction can be minimized by appropriate GDF design.

Implementation of appropriate GDF design to avoid interactions between two repositories is the development of plugs and seals, such as designed and implemented during the DOPAS project (The Full-Scale Demonstration of Plugs And Seals) was a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs)). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories were carried out in the project from 2012 to 2016. The DOPAS Project focused on tunnel, drift, vault and shaft plugs and seals for crystalline, clay and salt rocks. Plugs and seals were designed and tested successfully in Sweden's Äspö URF, France's Cigéo and Finland's Onkalo.

Previous full-scale emplacement of plugs and seals has been done in the Full-scale Emplacement (FE) experiment at the Mont Terri URL in Switzerland (Müller et al. (2015).

4. Critical background information

The section highlights specific components, 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 Co-Disposal.

Cement/Concrete durability: Though radiation may contribute to the degradation process of concrete in the low and intermediate level waste, it is mostly chemical degradation, whether induced by radiation or not, that affects the evolution of these components. Microbial activity also contributes to chemical degradation by inducing corrosion in case of metals, and degradation of e.g. cellulose in case of LILW.

The chemical processes involved in the degradation processes of concrete structures are various:

- dissolution (e.g. Ca-leaching),
- alkali-silica (alkali-aggregate) reaction
- thermally induced alteration especially in case concrete is near HLW/SNF container
- Sulphate attack
- Chloride attack

The rate and extent of dissolution and precipitation processes in the concrete structures is influenced by:

- The rate and composition of groundwater flow carrying dissolved species (e.g. chloride, sulphide)
- The rate of diffusive transport of dissolved species
- The composition of the concrete including the assemblage of hydrated cement and supplementary cementitious materials
- Any changes in the chemical composition of the concrete induced by chemical reaction with groundwater (see above) and the surrounding materials (*i.e.* vault backfill, waste, and waste packages). This may in turn influence the microstructure of the concrete that would affect its transport properties
- The composition of concrete porewater. This is in turn determined by local thermodynamic equilibria between the porewater and the solid hydrated cement minerals

- Kinetic factors casing metastable equilibria or slow establishment of equilibria

The long-term leaching of concrete has been reported to follow a dissolution and precipitation sequence involving the following phases (see Figure 3) according to Atkinson (1985). Berner (1992) and Pointeau (2001) proposed similar sequences:

- Phase I: corresponds to fresh cement. Pore water has pH values over 12.5, high ionic strength and high K+ and Na+ concentrations. These features are the result of the dissolution of alkali hydroxides. The duration of this phase depends on the water flow through cement.
- Phase II: Soluble salts of Na+ and K+ have been completely dissolved and major phases are C-S-H and portlandite. The dissolution of portlandite buffers the pH to values around 12.4.
- Phase III: Portlandite has been completely dissolved and the C-S-H phases control the chemical evolution of the system. pH decreases from 12.4 to 10, and the ionic strength decreases. In this stage the Ca/Si ratio decreases from 1.7 to 0.85.
- Phase IV: Ca/Si ratio of C-S-H phases decrease in this stage to 0.83 buffering the pH at a value of 10.
- Phase V: Concrete has been completely altered, and the pH of the pore solution will be determined by the pH of the infiltration water and by calcite as the final alteration product.

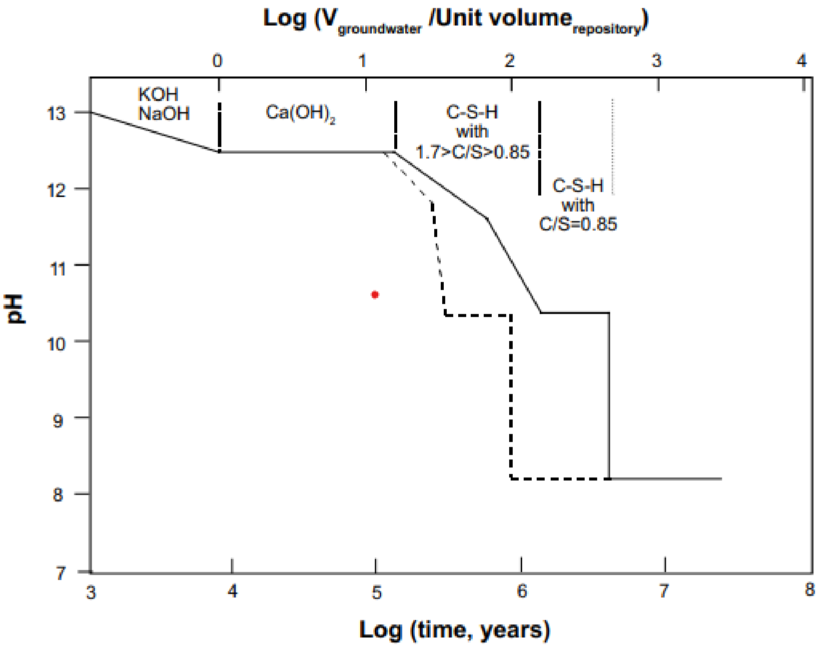

Figure 3. Evolution of pH as a function of degradation of the hydrated phases of cement. Results obtained by modelling tests (Atkinson 1985).

Savage (1998) developed a conceptual model (Figure 4) for the evolution of hyperalkaline leachates from conventional cements and their interaction with the host rock. This model assumes that the leachates are released from the cement following mixing of groundwaters with the cement porewater. As the plume reacts with the host rock, the pH decreases, as Na, K, Ca, Al and Si in groundwater equilibrate with the cement leachates (Figure 7-3). The extent of the cement/rock interaction depends greatly on the groundwater composition and the mineralogy of the rock.

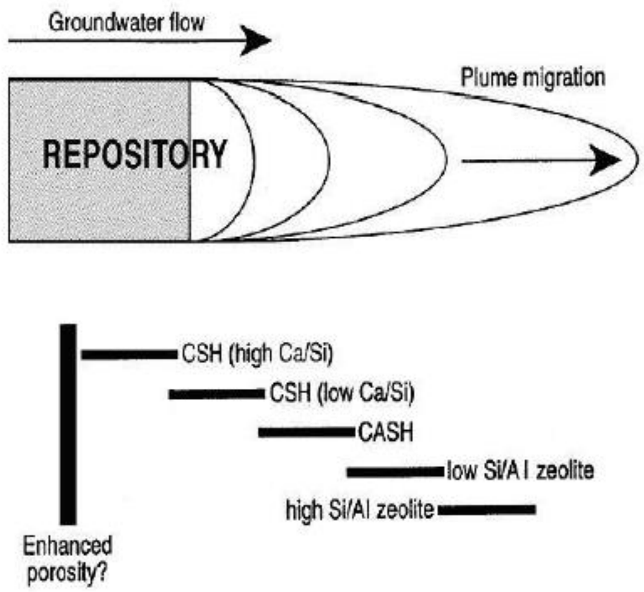

Figure 4. Conceptual model of hyperalkaline plume evolution in the aluminosilicate host rock from a cementitious repository. CSH = calcium silicate hydrates, CASH = calcium, aluminium silicate hydrates. From Savage (1998).

Hydrogeology: In crystalline bedrock, groundwater flow takes place in hydraulically active deformation zones (hydrogeological zones) and fractures. The location of the LILW and HLW/SNF repositories should not be intersected by any known hydrogeological zones connecting both repositories. In sedimentary rocks, e.g. claystones and salt the avoidance of hydrogeological zones and fractures should be easier, as in these formations fracture zones are rare or non-existent.

Groundwater chemistry: Should be favourable to cement/concrete durability and to the stability of other EBS materials, like metal and bentonite.

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

Waste package performance – the performance of LILW waste packages is important in understanding the interaction of the potential degradation and corrosion products with the EBS in the LILW repository and with the EBS in the HLW repository. For example, the degradation of cellulose as part of LILW can occur through two main competing pathways in the LILW repository: abiotic alkaline degradation with the formation of isosaccharinic acid (ISA) and microbial activity driven degradation, which is accompanied by the formation of gas. In both cases degradation is dependent on pH. The abiotic and biotic degradation rates have been reported by Höglund et al. (2018) and found that the rate constant for microbial cellulose degradation of 1.5×10^{-7} h^{-1} is faster than all the abiotic cellulose degradation rate constants estimated for pH 13 and below. Therefore, when microbial degradation is possible (pH < 11), it is likely to be the dominant process.

Once ISA forms, its dissolved concentration is dependent on sorption to available cement, precipitation as a calcium salt, dilution and microbial degradation. According to Höglund et al (2018), at high pH ((pH~12-13) microbial degradation of ISA will be inhibited, as will the degradation of cement. Therefore. there will be a minor local interaction between the EBS and waste packages and even less with the EBS of an HLW/SNF repository. The major concert is the potential interaction between cement degradation products and the EBS of an HLW/SNF repository, but for this purpose low-pH cements have been developed.

The performance of HLW/SNF packages depends on hydrochemistry of groundwater and the interaction of groundwater with EBS components. Corrosion is the main process to affect metal packages. For this reason, the thickness of the packages is planned to last long times. Even if corrosion takes place, a passive corroded layer protects the package from further advances. Steel/iron corrosion products might interact with bentonite and damage its properties (swelling) as a barrier. In case of repositories in crystalline host rock, this is a major concern, as the thickness of the bentonite barrier in the EBS is at most few ten centimetres. Nonetheless, many studies have shown that most of the corroded Fe occur within a 10 mm-thick clay layer adjacent to the corrosion layer (e.g. Wersin et al. 2015 and references therein).

Cement-clay interactions and iron-bentonite interactions are of importance in the co-disposal of two repositories in crystalline rock, but of less concern in repositories, where host rock is mostly clay, because of the thickness of clay/sediments is not limited of a few tens of centimetres.

5. Maturity of knowledge and technology

This section provides an indication of the relative maturity of information, data and knowledge for disposal of Co-disposal. 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

The interactions between EBS materials used in different repositories have been studied in national and EU-projects (e.g. ECOCLAY, CEBAMA, MAGIC). An environmental safety case on cement-clay interactions was presented by Norris & Williams (2012) and a safety case, where co-disposal of a LILW and a SNF repository is accounted for (Posiva (2021). There is a wealth of information about concrete degradation and degradation of cemented LILW (e.g. Höglund et al. 2018, Seetharam & Jacques 2015, IAEA 2013, Wilson et al, 2021).

5.2 Optimisation challenges and innovations

Co-disposal of LLW and short-lived intermediate level waste (SL-ILW) has long been a common practice in many countries and cement-waste interactions addressed widely in experiments and modelling. Ordinary Portland Cement (OPC) has been up to now the cement most used. Low-pH cements have also been developed, but mostly for use in repositories for ILW (e.g. Cau-dit-Coumes et al. 2006) and SNF/HLW (e.g. Savage & Benbow 2007). Mg-K-P cements have also been developed for immobilisation of ILW (e.g. Pyo et al. 2021). As in the following years, when disposal and co-disposal of all kinds of waste will become a common practice, the challenges are upon the supply of the materials used in EBS, especially cement, bentonite, metals (copper, steel, iron) and the demonstration of long-term safety if co-disposal of large amount of radioactive materials became also a common practice (see discussion in NAGRA 2020).

In co-disposal, the timing of construction and operation of the repositories is important in considering potential interactions. In case of Posiva (2021), where the SNF and LILW repositories is at two different levels, it is assumed that the LILW repository will be constructed a few tens of years later than the SNF repository, already in construction phase.

5.3 Past and ongoing (RD&D) projects

Past (RD&D) Projects:

- ECOCLAY Effects of cement on clay barrier performance
  - https://cordis.europa.eu/project/id/FIKW-CT-2000-00028

- CEBAMA: Cement-based materials, properties, evolution, barrier functions
  - https://cordis.europa.eu/project/id/662147

- ESDRED: Engineering Studies and Demonstrations of Repository Designs
  - https://cordis.europa.eu/project/id/508851

- MIND: Development of the safety case knowledge base about the influence of microbial processes on geological disposal of radioactive wastes
  - https://cordis.europa.eu/project/id/661880

- Chemo-Mechanical AGIng of Cementitious materials (MAGIC) - IGD-TP | Safe Solutions for Radioactive Waste

Ongoing (RD&D) Projects:

- EURAD-2 Work Package ANCHORS: Hydraulic mechanical chemical evolution of bentonite for barriers optimisation
- EURAD-2 Work Package OPTI: HLW repository optimisation including closure
- EURAD-2 Work Package InCoManD: Durability of Traditional and Innovative Disposal Container Materials and Coatings

5.4 Lessons learnt

ECOCLAY is the project from which we learnt most about cement-bentonite/clay interactions. The studies performed on the alkaline plume indicated that it did not jeopardise the integrity and functionality of the bentonite barrier in the case of a repository in fractured rock and even less in case of co-disposal as learnt in Posiva (2021). For repository concepts of co-disposal in clay rocks the extent of the effects of the alkaline plume is limited.

In CEBAMA, experimental and modelling data helped to improve understanding of the evolution of cementitious materials in radioactive waste management applications (Duro et al. 2020). Comparisons between the performance of traditional OPS mixes and “low-pH” cement blends showed the benefit of the latter material in terms of lowering the pH and the extent of alteration of the contacting clays. Here the lesson learnt applies also to co-disposal of different wastes and packages.

The MIND project investigated the impact of microbial processes on the performance of repository components including clay and canister materials (MIND 2019). The project contributed to increase knowledge of microbial processes and their importance in setting safety requirements for engineered barriers in the disposal and co-disposal of different wastes.

ESDRED contributed to demonstrate the technical feasibility, at industrial scale, of activities carried out to construct, operate, and close a deep geological repository (ESDRED 2009). This applies also for the construction of two repositories in case of co-disposal.

MAGIC aims to increase confidence in chemo-mechanical numerical models by reducing uncertainties in input data and understanding key coupled processes (for both young (not early-age) and aged materials). Specific conditions for waste disposal (microbial activity, chemical and mechanical stress, variable saturation, etc.) are accounted for by addressing implementation needs and safety aspects, e.g., regarding the selection of materials, dimensioning, and (long-term) behaviour of seals and plugs. Several laboratories, mock-ups, and in situ experiments (mainly existing) dedicated to identifying the mechanical behaviour of concrete under various stresses are developed. Interactions between the different EBS materials in the same repository and in case of co-disposal are also addressed.

6. Uncertainties

There are uncertainties in the evolution of the repositories and in the timing and extent of unlikely events (e.g. human intrusion), and related consequences. These are usually accounted for in scenario formulation and in the analysis of potential radionuclide releases further in safety assessments.

The dimension of cracks/fractures that can be formed in concrete and go unseen after closure can be accounted for in the parametrisation of hydraulic conductivity and diffusivity of the concrete. This is also related to the availability of novel cements and alkali-activated materials that could be used in the overall construction of the repositories.

Also, uncertainties in groundwater flow rates and groundwater chemistry can be considered in setting parameter values when modelling interactions between two repositories in case of co-disposal.

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 *Co-disposal*.

Guidance
https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1908_web.pdf
Training
EURAD2 Anchors PhD school_Aug2025-1.pdf *Workshop of CODE_BRIGHT — Department of Civil and Environmental Engineering — UPC. Universitat Politècnica de Catalunya* *CODE_BRIGHT ONLINE COURSE — Department of Civil and Environmental Engineering — UPC. Universitat Politècnica de Catalunya* *Jyväskylä Summer School Course Programme | University of Jyväskylä*
Active communities of practice and networks
https://cordis.europa.eu/project/id/FI4W950006 *https://forum.gidsimulation.com* *CODE_BRIGHT - GiD forum*
Capabilities (Competences and infrastructure)
https://www.grimsel.com
https://skb.com/research-and-technology/laboratories/the-aspo-hard-rock-laboratory/
https://www.mont-terri.ch/en/rock-laboratory
https://www.posiva.fi/en/index/finaldisposal/researchandfinaldisposalfacilitiesatonkalo.html

8. Further reading, external links and references

8.1 Further reading

Alexander, W. R., Milodowski,A. E., Pitty, A. F., Hardie, S. M. L., Kemp, S. J., Korkeakoski, P.,Rigas, M., Rushton, J. C., Sellin, P., Tweed, C. J. 2012. Reaction of bentonite in low-alkali cement leachates: an overview of the Cyprus Natural Analogue Project (CNAP). Mineralogical Magazine, 76, 3019-3022. https://doi.org/10.1180/minmag.2012.076.8.17

Andra (2005) Ecoclay II: Effects of Cement on Clay Barrier Performance – Phase II. Final Report. EC project N° FIKW-CT-2000-00028; Andra report N° CRPASCM04-0009, 381 pp.

Hidalgo, A., Petit, S., Domingo, C., Alonso, C., Andrade, C. 2007. Microstructural characterization of leaching effects in cement pastes due to neutralisation of their alkaline nature: Part I: Portland cement pastes. Cement and Concrete Research 37, 63–70. https://doi.org/10.1016/j.cemconres.2006.10.002.

Höglund, L.O. 2014. The impact of concrete degradation on the BMA barrier function. SKB R-13-40, Svensk Kärnbränslehantering AB (SKB).

Höglund, L., Sidborn, M., Crawford, J., Keith-Roach, M., Hoek, J. & Grundfelt, B. 2018. Modelling of chemical influences from Posiva's low and intermediate level waste repository on the spent nuclear fuel repository. Eurajoki, Finland: Posiva Oy. Working Report 2017-03. https://www.posiva.fi/media/raportitjajulkaisut.html

Kaufhold, S., Dohrmann, R., Ufer, K., Kober, F. 2018. Interactions of bentonite with metal and concrete from the FEBEX experiment -mineralogical and geochemical investigations of selected sampling sites. Clay Minerals. 53. 1-37. 10.1180/clm.2018.54.

OECD 2003. Engineered Barrier Systems and the Safety of Deep Geological Repositories; Report EUR 19964 EN.; OECD: Issy-les Molineaux.

Smart NR, Rance AP, Fennell PAH and Kursten B, 2013. The anaerobic corrosion of carbon steel in alkaline media – Phase 2 results. The European Physical Journal (EPJ) Web of Conferences 56, Paper 06003.

Smart, N.R., Rance, A.P., Fennell, P.A.H., Gaggiano, R., Padovani, C. 2020. Further studies on the anaerobic corrosion of carbon steel in alkaline media in support of the Belgian supercontainer concept. Materials and corrosion 72. https://doi.org/10.1002/maco.202011827Seidler, W.K. (2009) ESDRED: Final Summary Report and Global Evaluation of the Project. ESDRED Deliverable D6 of Module 6, WP4. European Commission Contract Number FI6W-CT-2004-508851.

Smellie. J.A.T. (ed), 1998. MAQARIN natural analogue study: Phase III. SKB TR 98-04, Vols I and II, Svensk Kärnbränslehantering AB

Sneyers, A., Grambow, B., Hernán, P., Alheid, H. J., Aranyossy, J. F., & Johnson, L. (2007). The integrated project NF-PRO: Recent advances in European research on the near-field system. In *Proceedings of the ICEM2007: 11th International Conference on Environmental Remediation and Radioactive Waste Management* (PART B ed., pp. 861-866). (Proceedings of the ICEM2007 - 11th International Conference on Environmental Remediation and Radioactive Waste Management; No. PART B). https://doi.org/10.1115/ICEM2007-7269

Soler J, Mäder U, 2007. Mineralogical alteration and associated permeability changes induced by a high-pH plume: Modeling of a granite core infiltration experiment. Applied Geochemistry, 22(1), pp.17-29, http://dx.doi.org/10.1016/j.apgeochem.2006.07.015

Soler, J. & Mäder, U. 2010. Cement-rock interaction: Infiltration of a high-pH solution into a fractured granite core. Geologica Acta, 8(3), pp.221-233, http://digital.csic.es/bitstream/10261/31843/1/vol0803a01.pdf

Wang, L., De Cannière P., Jacques, D., Moors, H., Van Gompel, M., Aertsens. M. 2004 Experimental and modelling studies of Boom Clay exposed to an alkaline perturbation. SCKCEN-R-4019, Mol, Belgium. 35 pp. (Mentioned in https://doi.org/10.1016/j.apgeochem.2010.03.002).

Watson, C., Benbow, S., Savage, D. 2007. Modelling the interaction of low pH cements and bentonite. SKI Report 2007:30.

8.2 External links

https://www.oecd-nea.org/jcms/pl_19150/cementitious-materials-in-safety-cases-for-geological-repositories-for-radioactive-waste-role-evolution-and-interactions?details=true

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

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

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

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

https://www.nagra.ch/downloads

https://www.drbg.ch/

https://www.drbg.ch/erkunden/vertiefte-recherche-in-der-pdf-bibliothek/rbg-gtl/gtl-referenzberichte/302-ntb-23-03-geochemical-evolution-of-the-l-ilw-near-field/file

https://www.drbg.ch/erkunden/vertiefte-recherche-in-der-pdf-bibliothek/rbg-gtl/gtl-referenzberichte/180-ntb-23-02-the-geochemical-evolution-of-the-near-field-in-the-hlw-section-of-the-combined-repository-at-noerdlich-laegern/file

8.3 References

Alonso, M.C., García Calvo, J.L., Cuevas, J., Turrero, M.J., Fernández, R., Torres, E., Ruiz,A.I. 2017. Interaction processes at the concrete-bentonite interface after 13 years of FEBEX-Plug operation. Part I: Concrete alteration, Physics and Chemistry of the Earth, Parts A/B/C, 99, 38-48, ISSN 1474-7065, https://doi.org/10.1016/j.pce.2017.03.008.

Andra (2005) Ecoclay II: Effects of Cement on Clay Barrier Performance – Phase II. Final Report. EC project N° FIKW-CT-2000-00028; Andra report N° CRPASCM04-0009, 381 pp.

ANDRA 2025. https://international.andra.fr/projects/cigeo/cigeos-facilities-and-operation/project-siting-and-facilities-overview

Atkinson, A, 1985. The time dependence of pH within a repository for radioactive waste disposal. AERE Report R-11777, Harwell, UK.

Berner, U.R. 1992. Evolution of pore water chemistry during degradation of cement in a radioactive waste repository environment, Waste Management, 12, 201-219, ISSN 0956-053X, https://doi.org/10.1016/0956-053X(92)90049-O.

Cau Dit Coumes, C., Courtois, S., Nectoux, D., Leclercq, S., Bourbon, X. 2006. Formulating a low-alkalinity, high-resistance and low-heat concrete for radioactive waste repositories, Cement and Concrete Research, 36, 2152-2163, https://doi.org/10.1016/j.cemconres.2006.10.005

Daniel E. González-Santamaría, D.E., Fernández, R., Ruiz, A.I., Ortega, A., Cuevas, J. 2020. Bentonite/CEM-II cement mortar INTERFACE EXPERIMENTS: A proxy to in situ deep geological repository engineered barrier system surface reactivity, Applied Geochemistry, 117, ISSN 0883-2927, https://doi.org/10.1016/j.apgeochem.2020.104599.

Dauzeres, A., Le Bescop, P., Sardini, P., Cau Dit Coumes, C. 2010. Physico-chemical investigation of clayey/cement-based materials interaction in the context of geological waste disposal: Experimental approach and results, Cement and Concrete Research,40, (8), 1327-1340, ISSN 0008-8846, https://doi.org/10.1016/j.cemconres.2010.03.015.

DEFRA 2008. Managing Radioactive Waste Safely—A Framework for Implementing Geological Disposal. A White Paper by Defra, BERR and the devolved administrations for Wales and Northern Ireland (London: HM Stationery Office)

Hidalgo, A., Petit, S., Domingo, C., Alonso, C., Andrade, C. 2007. Microstructural characterization of leaching effects in cement pastes due to neutralisation of their alkaline nature: Part I: Portland cement pastes. Cement and Concrete Research 37, 63–70.

Höglund, L., Sidborn, M., Crawford, J., Keith-Roach, M., Hoek, J. & Grundfelt, B. 2018. Modelling of chemical influences from Posiva's low and intermediate level waste repository on the spent nuclear fuel repository. Eurajoki, Finland: Posiva Oy. Working Report 2017-03. https://www.posiva.fi/media/raportitjajulkaisut.html

IAEA 2013. International Atomic Energy Agency. The Behaviours of Cementitious Materials in Long Term Storage and Disposal of Radioactive Waste. IAEA-TECDOC-1701 (IAEA, 2013).

MIND 2019. Microbial activity and the physical, chemical and transport properties of bentonite buffer (Microbiology in Nuclear waste Disposal). Deliverable D2.16. (In igtdp.eu/documents/.

Müller, H.R., Garitte, B., Köhler, S., Vogt, T., Sakaki, T., Weber, H. and Vietor, T. (2015). LUCOEX – Final Report of WP2. LUCOEX Deliverable D2.6.

NAGRA 2020. Standortunabhängiger Vergleich eines Kombilagers mit zwei Einzellagern hinsichtlich Bau- und Betriebsabläufe sowie Umwelt. Report NAB 19-15.

Norris, S. & Williams, S. 2012. Environmental safety case and cement-related issues for intermediate level waste in a co-located geological disposal facility. In Appendix C of NEA/RWM/R(2012)3/REV.

OECD 2020. https://www.oecd-nea.org/upload/docs/application/pdf/2020-07/switzerland_report_web_2020.pdf

Pointeau, I, 2001. Etude mécanistique et modelisation de la retention de radionucléides par les silicates de calcium hydratés (CSH) des ciments. Thèse Doctorale Université Reims Champange-Ardenne, Collection Les Rapports, ANDRA.

Posiva 2021. Safety Case for the Operating Licence Application – Low and intermediate level waste repository assessment (LILW-RA). POSIVA 2021-07. Eurajoki, Finland: Posiva Oy.

Pyo, J-Y., Um, W. Heo, J. 2021. Magnesium potassium phosphate cements to immobilize radioactive concrete wastes generated by decommissioning of nuclear power plants, Nuclear Engineering and Technology, 53, 2261-2267, https://doi.org/10.1016/j.net.2021.01.005.

Savage, D. 1998. Zeolite occurrence, stability and behaviour. In: Smellie J. (ed.) Maqarin Natural Analogue Study: Phase III. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co. (SKB). Technical Report TR 98-04. 281-316 p. 401 p + app. 306 p. ISSN 1404-0344.

Savage, D. & Benbow, D. 2007. Low pH cements. SKI-Report 2007:32

Seetharam S & Jacques D, 2015. Potential Degradation Processes of the Cementitious EBS Components, their Potential Implications on Safety Functions and Conceptual Models for Quantitative Assessment, OPERA-PU-SCK514 (2015).

Wersin, P., Jenni, A,, Mäder U.K. 2015. Interaction of Corroding Iron with Bentonite in the ABM1 Experiment at Äspö, Sweden: A Microscopic Approach. Clays and Clay Minerals. 2015;63(1):51-68. doi:10.1346/CCMN.2015.0630105 <div></div>

Sun, Z., Chen, Y., Ye, W. 2022. A systematic review of bentonite/concrete interaction system in HLW disposal repositories: Theoretical, experimental and geochemical modelling analysis, Construction and Building Materials, 353, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2022.129075.

Wilson, J., Bateman, K. & Tachi, Y. 2021. The impact of cement on argillaceous rocks in radioactive waste disposal systems: A review focusing on key processes and remaining issues. Appl. Geochem. 130, 104979 (2021).

Yokoyama, S., Shimbashi, M., Minato, D., Watanabe, Y., Jenni, A., Mäder, U. 2021. Alteration of Bentonite Reacted with Cementitious Materials for 5 and 10 years in the Mont Terri Rock Laboratory (CI Experiment). Minerals 2021, *11*(3), 251; https://doi.org/10.3390/min11030251

Zhu, T. & Dittrich, M. 2016. Carbonate Precipitation through Microbial Activities in Natural Environment, and Their Potential in Biotechnology: A Review. Frontiers Bioeng Biotechnol, 2016. 4. https://doi.org/10.3389/fbioe.2016.00004.