European Partnership
on Radioactive Waste Management

3.3.3 Plugs and Seals, Domain Insight

EURAD Roadmap

1. National Programme Management
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Overview

Plugs and seals are essential components of underground repositories for hydraulic isolation, gas management, and mechanical stability during both operation and long-term post-closure. Their design depends strongly on host-rock type (crystalline, clay, or salt) and on repository layout. Their primary safety function is to limit groundwater flow and prevent radionuclides from migrating along preferential pathways like tunnels and shafts. These systems typically consist of a swelling clay core (bentonite-based materials) to ensure tightness associated with concrete plugs to provide mechanical support.

Technology has reached a high level of maturity through international full-scale demonstration projects like DOPAS, ESDRED, and others, which confirmed the feasibility of constructing these large structures at repository depth. Current research focuses on long-term performance modeling (THMC), the impact of alkaline plumes from concrete on clay properties and adapting to low-carbon cement formulations. Despite these advancements, challenges remain in predicting behavior over thousands of years and optimising designs for cost and durability.

Keywords

plug, seal, bentonite, closure, backfill, gas production, low-carbon cement, water flow, swelling clay

Key Acronyms

ATEX = ATmosphères Explosives

DGR = Deep Geological Repository

DOMPLU = Dome Plug

DOPAS = Full-scale Demonstration of Plugs and Seals

EBS = Engineered Barrier Systems

EDZ = Excavation Damaged Zone

EPSP = Experimental Pressure and Sealing Plug

ESP = Enhanced Sealing Project

ESDRED = Engineering Studies and Demonstration of Repository Designs

FSS = Full-scale Seal

LILW = Low and Intermediate Level Waste

POPLU = Posiva Plug

RD&D = Research, Development, and Demonstration

THMC = Thermo- Hydro-Mechanical-Chemical

TRL = Technology Readiness Level

TSX = Tunnel sealing experiment

URL = Underground Research Laboratory

1. Typical overall goals and activities in the domain of *Plugs and seals*

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	
3.3.3 Identify appropriate seal/plug components, materials and designs under storage and disposal conditions, and confirm their properties, behaviour and evolution for the selected repository concept; Plug and sealing components (Plugs and seals)	
Domain Activities	
Phase 1: Programme Initiation	Define the strategy for closure at the end of operation phase or during operation to isolate some parts of underground disposal facilities for radioactive waste. Define requirements linked to performance and safety assessments.
Phase 2: Underground Repository Site Identification	During this phase of site identification, the previously defined strategy/requirements may need to be updated and adapted.
Phase 3: Site Characterisation	Characterisation of the host rock thermo-hydromechanical (THM) properties, mineral composition. First design of plugs and seals related to host rock properties. Depending on the host rock, development of several options for plugs and seals able to reach the safety and performance requirements. Possible interactions (THMC) with host rock have to be identified, extension and structure of damaged zone located where plugs and seals will be implanted need to be investigated related to water flow limitations requirements.
Phase 4: Repository Construction	Increase the TRL (Technology Readiness Level) of plugs and seals. Define the requirement for the zone (tunnel/shaft/ramp) where plugs and seals will be implanted (nature of lining, excavation techniques…) Include in safety assessment analysis the role of plugs and seals Optimise plug and seal components in terms of performance, design and cost.

Phase 5: Operation and Closure	Define acceptance criteria for closure components. Construct plugs and seals. Verify the conformity of installed plugs and seals, Confirm and preserve documentation for emplaced plugs and seals and their designs.

2. Contribution to generic safety functions and implementation goals

This section describes how plug and sealing components and their associated information, data, and knowledge contribute 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.) and account for stakeholder requirements. 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.

The openings in the repository (tunnels, disposal caverns, boreholes, shafts, and access ramp) must be backfilled and sealed during the operational and closure phases. The plugging and sealing might or might not have a safety function, depending on the disposal concept and the host rock. In the case that the plugs and seals have a safety function they are typically designed to create a mechanical and hydraulic decoupling between the repository and its environment, hence avoiding any preferential flow pathways (IGD-TP – SRA, 2020).

The engineering (design and construction) of plugs and seals shall be based on the safety strategy of the repository while relying on engineering standards and compliance with the existing national legislation. Several examples have been developed by advanced programmes that also include full-scale demonstrations. Some relevant tests can be found in DOPAS project (Hansen et al., 2013) for crystalline, salt and clay host rocks. Different kinds of materials (mainly cement-based, clay-based and salt-based) can be used in the construction of plugs and seals. Interaction (hydraulic, mechanical and chemical) and compatibility with other engineered and geotechnical barriers as well as with the geosphere needs to be assessed and ensured so that the safety functions of other components are maintained despite the interaction.

As with other repository components, the design and construction of plugs and seals are often done at laboratory scale to verify performance of individual components. The whole system is then later upscaled to be tested and demonstrated at full-scale at repository depth to confirm feasibility and reliability, generally in preparation for a construction licence. In this context, artificial or natural saturation with water is achieved and the behaviour of the components is tested under various stresses such as gas pressure, heat generation or chemical disturbance. Most of the time, artificial saturation is done due to the time needed to reach full saturation. For example, in clay host rock it takes more than 1000 years. Due to the fact that the functions of plugs and seals are mainly obtained after full saturation, this state need to be reached to reinforce the demonstration. In terms of performances to water and gas, this can't really be tested under partially water saturation state. Beyond this stage further optimisation for safety, robustness and cost is essential. Numerical modelling of plugs and seals is also needed to evaluate the behaviour and the long-term performance of manufactured components that could play a role throughout the life of the repository. Numerical modelling is essential for some very slow processes that are difficult to observe at a reasonable time scale such as chemical perturbation and its consequences on the THM behaviour.

2.1 Features, characteristics, or properties of plugs and seals that contribute to long-term safety of the disposal system

➢ **Primary goal - relied upon for long-term repository safety**

Plugs and seals contribute to the global closure system of a repository in complement of backfill and EBS (engineered barrier systems). The design of plugs and seals depend on the disposal concept, the host rock where the DGR is implanted, the water flow at the site location and the gas flows expected. They have generally a major role in limiting radionuclide migration along the tunnels and access shafts. In most cases, they are mainly involved in the long-term repository safety:

- **Contain contaminants within the total disposal system by retention or retardation**: Plugs and seals may be required following closure to limit groundwater flow and radionuclides migration along the tunnels and access shafts. Connections with the geosphere could constitute weak point for the requirement of contain the contaminants in the underground repository. In complement of the backfilling of the underground repository, specific parts will have to be plugged and sealed. One of the particularities of such engineering component is that their role is required on the total duration of the underground repository. They are needed to avoid fast migration pathways from underground repository to biosphere.
- **Ensure long-term stability with respect to internal evolution:** The underground repository is designed and implemented such that disposal system performance is not significantly affected by internal disturbances. In some underground repository configurations, mainly in clay host rock, requirements can concern gas migration due to the fact that gas pressure cannot easily dissipate through the rock. This is mainly due to presence of hydrogen that is generated by anaerobic corrosion of metallic components.
    - Plugs and seals can be designed to prevent unacceptable build-up of internal gas pressure by allowing the passage of gas through the tunnels, shaft and access ramps (mainly clay formations).
    - Plugs should also limit the exchange of gas between the deposition tunnel and the main tunnel (crystalline rocks).
- **Ensure long-term stability with respect to external events and environmental evolution:** Plugs and seals may be required to prevent inadvertent or unauthorised human access.

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

➢ **Primary goal - relied upon to Satisfy Operational Safety**

Depending on the repository design and the operations schedule, plugs and seals may be required during operations to isolate emplaced waste and other EBS components from the rest of the underground excavations.

- **Limit the exchange of gas during operation:** Plugs and seals can be designed and put in place to limit gas transfer between waste areas and main tunnels in link with radiological risk (contaminated gas) and ATEX risk (potential explosive atmospheres due for example to hydrogen generation).

- **Keep the backfill in place during operation:** Plugs can be designed to maintain backfill when a part of the waste zone is close, in link with a progressive closure strategy of the underground repository.

➢ **Primary goal - relied upon for implementation of geological disposal**

In most cases, the sealing system is constituted with a concrete plug associated with swelling clay core or swelling backfill. The main function of swelling clay is to assure the tightness of the system limiting water flow. The use of such material confers self-sealing properties to this component. It also contributes to the mechanical stability of the tunnel or confining system. The swelling clay core constitutes the heart of the seal.

Swelling clay is a bentonite that consists of swelling clay minerals (smectites), normally montmorillonite, and various accessory minerals. Mainly, two forms are used in underground repository: pre-compacted blocks with pre-defined shapes for specific applications and pellet/powder mixture useful to fill technological voids. Requirements for this component can concern the swelling pressure developed, the water permeability or gas entry pressure. They are used pure or with additive such as sand to adapt their properties.

The role of concrete plug is required to withstand the swelling pressure induced by this clay core or by the backfill.

In most cases, low-pH concretes are planned to be used for the concrete plug:

- To limit/avoid chemical interactions with swelling clay and/or clay host rock, in order to preserve their properties.
- To facilitate emplacement operations; the low-pH concrete produces low heat during curing. It will be possible to limit internal fracturing and shrinkage by using an appropriate low-pH recipe.

Depending on the type of excavation in which the plug is to be installed (e.g. a vertical shaft or a horizontal opening), the impact of the excavation on stress variations around the opening and the type of host rock, several shapes of concrete plug can be relevant (Figure 2-1) as well as the possible use of reinforcement.

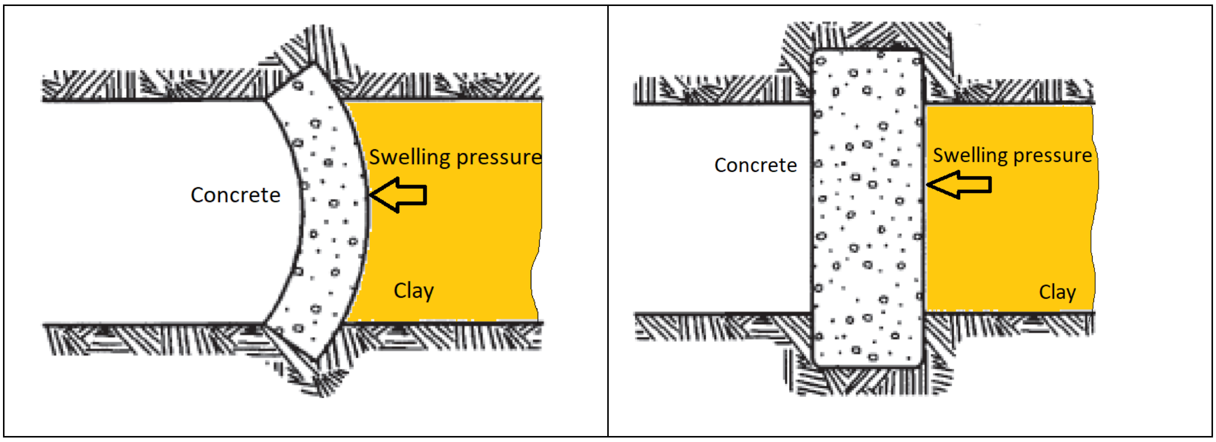

Figure 2-1 Examples of concrete plug shape (from Auld, 1996) in contact with swelling clay

The type of host rock and the disposal concept play an important role in defining the design requirements for plugs and seals:

- Crystalline rocks can be highly impermeable but usually exhibit fractures that increase their hydraulic conductivity. The objective of plugging/sealing shafts and tunnels in crystalline rocks is to achieve a hydraulic conductivity comparable to that of the rock mass ensuring a good contact is established between the plug/seal material and the rock.
- Clay rocks generally have very low permeabilities. One of the favourable properties of clay host rock is its self-sealing ability. Water permeability of cracks induced during operations (mainly excavation and ventilation) is largely reduced after water saturation. Underground openings in repositories located in clay rocks may require lining or mechanical stabilisation, which may need to be removed in a plug/seal location to ensure a tight rock-plug interface. The objective of plugs and seals in clay rocks is to limit the flux of groundwater by ensuring that very low permeabilities are reached.
- Salt rocks are characterised by an extremely low hydraulic conductivity, and creep properties that can contribute to the closure of a repository. Some salt host rocks also have extremely low water/brine content. Therefore, any openings within the salt rock may have to be backfilled in such a way that this rock's containment function is not compromised due to fracture initiation and growth. The main safety function of seals is to avoid brine migration through the underground opening to the waste canisters as long as possible. This allows the backfill to be compacted until its hydraulic conductivity is so low that brine migration is no longer possible.

Plugs and seals are also envisaged to close boreholes drilled within the repository site perimeter, whether they are exploratory boreholes or boreholes designed to transport gasoline or concrete to the repository for supporting purposes.

3. International examples of plug and sealing components

This section provides an overview of typical examples for the different types of plugs and seals being considered in underground repositories covering deep geological repositories mainly dedicated to high level wastes and repository dedicated to low and intermediate level wastes across Europe.

Although the attributes, characteristics and safety requirements of plugs and seals vary from country to country, there are similarities between the programs.

3.1 Crystalline host rock

Some examples of plug and seal concepts for crystalline host rock.

Swedish DGR (SKB-TR-21-03): In the Swedish concept, there are two types of plugs: "deposition tunnel plugs" and "plugs in other parts of the repository". The plugs in the deposition tunnels are designed with respect to the properties and function of the buffer and backfill. The plug consists of several parts that in different ways will contribute to maintaining its functions during the curing phase, the sealing phase and the post-closure phase. The main purpose of this plug is to keep the backfill in place during the operation of the repository.

The detailed design of the tunnel plug has a watertight seal of highly compacted bentonite and a concrete dome installed into a slot deepened from the excavated tunnel contour with a non-damaging technique so deep that all possible flow paths caused by excavation disturbance are cut off. The concrete dome is cast from low-pH concrete without reinforcement but it contains cooling pipes to limit the temperature during curing. The bentonite seal consists of compacted bentonite blocks and pellets (see Figure 3-1).

Plugs in the repository, other than the deposition tunnel plugs, have different purposes. They separate closed and open underground openings by keeping the closure material in place until the opening on the other side of the plug is filled with closure material. The design of the different types of plugs depends on the properties of the surrounding rock. The plugs contain no materials that can impair the barrier functions of other barriers and the concrete used for all plugs have the same composition as the concrete in the deposition tunnel plugs.

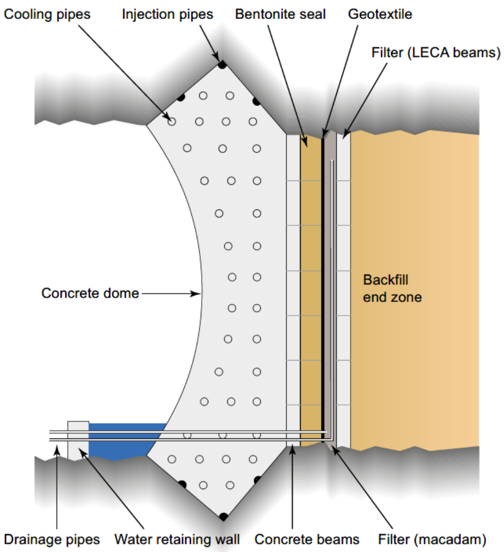

Figure 3-1 Schematic section of the reference design of the depositional tunnel plug in Swedish DGR (SKB TR-21-03)

Finnish DGR: Plugs and Seals in the Finnish Reference Disposal Concept differ depending on the requirements and their location. The sealing structures of horizontal deposition tunnels consist of the backfill and plugs. Plugs will be placed at the entrance of deposition tunnels. These plugs are referred to as "deposition tunnel plugs". In openings other than deposition tunnels, the sealing structures are named "closure backfill" and "closure plugs". The closure plugs envisaged in the Finnish repository are of different types depending on the associated function.

- *Mechanical:* a concrete or other rigid structure physically isolating installed backfill and a neighbouring opening. In central tunnels, access tunnels and shafts, mechanical plugs will be installed to hold the closure backfill in place.
- *Hydraulic:* a concrete structure with a clay component preventing water flow through the plug over the long term. A hydraulic plug will be placed in a tunnel or shaft to both sides of a fracture zone; the tunnel volume that is intersected by a fracture will be backfilled with rock material.

3.2 Clay host rock

French DGR: In the French repository, the principle of sealing is identical whether you're considering a horizontal drift seal, the entrance to a deposition tunnel, a shaft seal or a ramp seal. It consists in placing a swelling clay core between two concrete plugs (see Figure 3-2). To adjust and control the expected swelling pressure, water permeability and gas properties, the swelling core is composed with a mixture of bentonite and sand.

The concrete plugs are cast from low heat concrete to avoid concrete degradations and without reinforcement to limit gas production.

All underground structures (drift, shaft, ramp) are supported by a concrete lining to ensure stability during operation. This lining is partially (horizontal tunnels) or completely (shafts and ramps) removed depending on the location of the sealing to obtain a good contact between the host rock and the swelling clay core. This point is particularly important to reach the requirements in terms of limitation of water flow. The same types of seals are positioned in areas containing high-level waste as well as in areas containing long-lived intermediate-level waste.

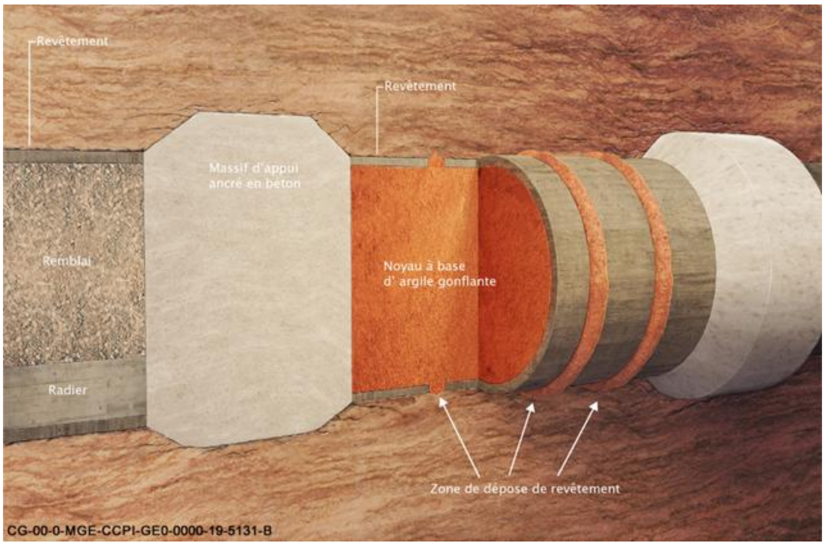

Figure 3-2 Schematic representation of the reference design of a horizontal seal with plugs in French DGR (Andra 2020)

Swiss DGR: Seals are defined as elements that hydraulically isolate parts of the repository system and/or the repository from the geosphere and biosphere. Seals are composed of a sealing element (e.g. bentonite) and mechanical supporting elements (e.g. concrete plug and gravel). Plugs are defined as temporary mechanical seals and have no long-term safety functions. Suitable materials are chosen ensuring low hydraulic conductivity, high conductivity for gas, high radionuclide retention, and a swelling behaviour to compress excavation damage zone after resaturation of the system The materials chosen for the seals may vary depending on their location in the DGR. For the LILW, gas permeable seals require a sealing element consisting of a sand/bentonite mixture. Seals with a pure bentonite sealing element (particularly in shaft) aim at limiting both water and gas flow to a minimum.

3.3 Salt host rock

Main seals and plugs are installed in the shaft. They must provide their sealing function during the early post closure phase until the backfill in the repository drifts and emplacement zones has sealed in response to compaction induced by the creep of the surrounding rock. This compaction leads to a low permeability for the backfill, typically in the same order of magnitude as the host rock. Due to the environmental conditions, specific materials are envisaged to obtain a compatibility with the salt. Bentonite used should have chemical stability when exposed to the magnesium and sodium brines found in salt domes. Salt concrete or sorel concrete are used instead of classical concrete. The sorel concrete consists of cement produced from magnesium oxychloride phases and crushed salt as aggregate. An important component of the seal is made with crushed salt.

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 plug and sealing components.

A number of factors need to be taken into account when critically analysing plugs and seals.

- Technological factors:
    - The construction of these components is constrained by the nature of the host rock, the functions assigned to these components and their expected durability.

  - Construction materials need to be compatible with geosphere to limit its interactions with plugs and seals and don't compromise long-term safety. Materials used in the underground repository have to be resistant to degradation under the conditions prevailing in the facility (e.g. conditions of chemistry and temperature) and selected also to limit any undesirable impacts on the safety functions of any element of the disposal system.
  - Clear definition of component acceptance criteria in relation to requirements.
- Safety and long term behaviour factors:
  - External events like earthquakes need to be studied to verify that the component continues to perform its specified functions after being subjected to seismic stresses. .
  - Corrosion of reinforcement of concrete plug when reinforced concrete is used. This point is to assess the durability of concrete in particular when using low pH concrete in link with the degradation process of the passive layer of steel reinforcement concrete structures.
  - THMC evolutions of plug and seals in relation to long term safety requirements such as:
    - Host rock/plug and seals interactions,
    - Water flow and consequences in terms of erosion, and piping of bentonite-based materials,
    - Concrete/bentonite chemical interactions to assess the influence of alkaline plume on bentonite characteristics such as swelling capacity or transfer properties,
    - Microbial activity related to bentonite properties evolution.

4.1 Construction of a disposal facility

Component acceptance criteria: Acceptance of plugs and seals is based on objective criteria to ensure that the construction complies with the expected functions. As mentioned in §2.2, most of the time, to ensure water tightness of the seal (if required), a material such as bentonite is envisaged in association with the concrete plug.

- In the case of concrete plugs, these include mechanical stability, quality of anchoring in rock (when relevant), nature and homogeneity of the concrete, level of temperatures reached during curing.

- For the swelling clay core made with bentonite-based materials, the main indicators or criteria are water content and dry density of the material. The performances in terms of swelling pressure, water permeability, or gas breakthrough pressure are related directly to the dry density of the chosen bentonite and the environmental conditions. Despite the use of additives in order to adapt bentonite properties to certain specifications such as sand to increase gas permeability (for example, in the case of seals for LILW in Nagra's repository), the criterion on dry density is still applicable. Even if the bentonite materials are able to fill initial technological voids; the volume of the total cavity need to be estimated. In this context, homogeneity of the material can be important.

Interface with host rock: EDZ should be limited in the zone where plug and seals will be implanted and especially where the plugs will be anchored or in the contact zone between the bentonite core and the host rock in clay formations. Rock excavation methods have to be chosen to limit damage in these zones. For crystalline rock, the strength and properties of the rock in the area where the concrete plug is embedded have to be suitable for construction. This means that long fractures should not be present at the plug location to prevent water transport to the biosphere.

Concrete plug: The thermal, viscoelastic and shrinkage properties of the concrete shall be such that internal cracking in the young concrete will not compromise the ability of the plug to achieve its functional requirements. The curing of the concrete plug shall take place without the formation of crack. In that perspective, low heat of hydration concretes are good candidates for plugs in most underground repository.

4.2 Long term behaviour of disposal facility

Concrete plug/bentonite-based material interface: An alkaline plume associated with concrete leaching can have an impact on the bentonite properties. The main effect is related to ion exchange and smectite transformations with potential consequences on swelling pressure and water permeability. This needs to be evaluated depending on the nature of the concrete used and the type of bentonite. This evaluation is underground repository design dependent and depends on the expected requirements. Low-pH concretes are good candidates for limiting such effects.

Limitation of water flow: The design of plugs and seal is made to limit water flow in the tunnels, drifts, shafts and ramps. This is induced by requirements on radionuclides migration in all underground repository designs. For the crystalline rock cases, limitation of water flow is needed to avoid piping and erosion of the deposition tunnel backfill or EBS.

4.3 Integrated information, data or knowledge (from other domains) that impacts understanding of plugs and sealing components

Improving material formulations (domain 2.3.2 optimisation) studies on concrete-based material can lead to improved performance of concrete plugs, reduced chemical impact on the other underground repository components and reduced cost.

Plugs and seals are directly in interface with buffer components (domain 3.3.1), backfill (domain 3.3.2) and EBS system (domain 3.4.1). They contribute to preserving requirements on these components.

Implementation of plug and seals has to be done in the way to reduce perturbations (domain 4.2.1). Perturbations may be caused by facility construction, operations or closure and they have impacts on long-term disposal system evolution.

Seals in shaft or access ramps contribute directly to limiting human intrusion in underground repository (domain 4.3.3).

The safety criteria, and a high-level safety strategy contribute to requirements on the plug and seals in terms of Design requirements (domain 5.1.1).

Demonstration that plugs and seals can be practically manufactured, constructed and installed in accordance with detailed design requirements and specifications is an essential item for these manufactured components (Constructability, demonstration and verification testing) (domain 5.2).

5. Maturity of knowledge and technology

This section provides an indication of the relative maturity of information, data and knowledge for disposal of plugs and seals. It includes the latest developments for the most promising advances, including innovations at lower levels of technical maturity where ongoing RD&D and industrialisation activities continue. Several large-scale experiments have been done in underground research laboratory to show the feasibility of such component and to evaluate the performance of the sealing system. These experiments demonstrate a good maturity for both construction and technological ability to build the components with the expected properties. Several examples of plugs and seals can be found in DOPAS project (White et al, 2016). Most representative structures for crystalline rocks developed in particular during DOPAS project were DOMPLU (SKB), POPLU (see Figure 5 1a from POSIVA), EPSP (SURAO, CTU) and Prototype Repository (SKB, TR13-22).

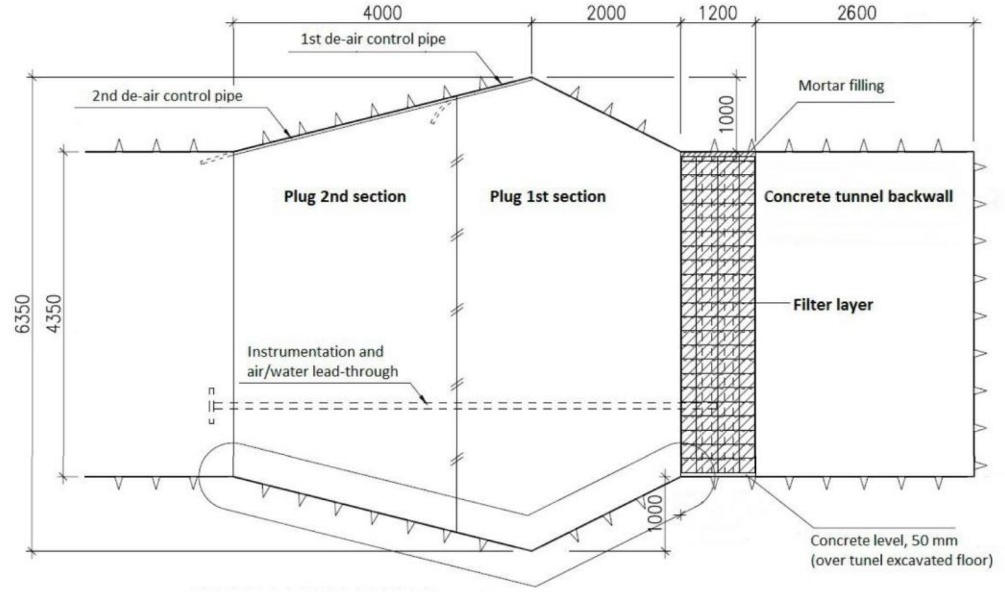

Figure 5-1 Schematic representation of (a) POPLU experiment (Posiva, Finland)

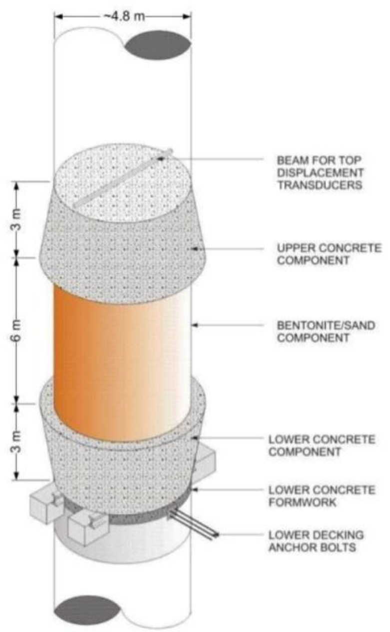

Figure 5-2 ESP experiment (NWMO), Canada.

Full-scale seals in a shaft (ESP, see Figure 5-2) (Priyanto et al., 2016) and tunnel (TSX) (Martino et al, 2007) were designed and installed in rock at Underground Research Laboratory (URL) near Lac du Bonnet, Manitoba, Canada by AECL. The ESP experiment showed the capacity to seal a shaft (4.8 meters diameter) and to obtain the expected performances in terms of water flow.

In clay formation, the Full-scale seal (FSS) experiment in France developed in the DOPAS project demonstrates the ability to build a full-scale seal in an about 8 meters diameter gallery. This test also demonstrates the capacity to cast a large-scale (7.6 diameter, 5 meters length) concrete plugs with low pH concrete and with the expected requirement.

Feedback from large-scale tests carried out in URL shows a high level of maturity in terms of technology. Some tests have also demonstrated the capacity of these structures to meet the expected requirements.

5.1 Advancement of safety case

Plugs and seals contribute to overall safety after closure, with their main roles being hydraulic cut-off, limiting contaminant migration and generally isolating underground repository from the biosphere.

Regarding the safety function of the ramp seal or shaft seal for underground repository, long term behaviour of such components relies on a good understanding of the physical and chemical processes that drive the evolution over time of the materials that make up these structures.

Part of understanding comes from characterising the behaviour of materials at different scales. It is also based on the use of large-scale demonstrators that allow to observe the behaviour of the structure under conditions similar to those encountered in storage.

The analysis and supporting numerical modelling constitute a part of demonstration that the repository is working properly, and at a first level involves integrating the behaviour of concrete, backfill, swelling clays and the Excavated Disturbed Zone (EDZ) surrounding the plugs and seals.

Nevertheless, safety/performance assessment cases should be built to take into account uncertainties in the properties of such materials. These analyses are made to support the expectation that the plugs and seals will provide the expected performance and the principal radionuclide release pathways will be not along tunnels/shafts/ramps.

5.2 Optimisation challenges and innovations

The goal of limiting the environmental impact of concrete is currently leading to the consideration of low-carbon concrete. At the same time, some cement components, such as fly ash produced in coal-fired power plants, will no longer be available, and the composition of blast furnace slag will evolve with technological changes in furnaces. In this context, regulation is evolving to include new types of materials (metakaolin, calcined clays, sulfo-aluminate cements, alkali-activated binders…) and the rate of additions (like silica fume) and recycled aggregates in use for common concrete formulations. Given national-based requirements for plugs and seals, particularly in terms of the durability of some concrete components used in repositories, further studies will be necessary to support these changes, qualify these new materials and develop physical and chemical models to predict their long-term evolution.

Reinforcing concrete with non-metallic reinforcement or replacing metal reinforcement with metallic or non-metallic fibres are ways of improving the durability of concrete plugs and limiting the quantities of metal used in order to reduce gas production.

Improving THMC constitutive models for swelling clays, whether or not they interface with a concrete plug, and implementing them in computer codes remains a challenge in order to improve both the scientific understanding of the processes that determine their evolution and the assessment of their performance.

For clay/sedimentary host rocks and also for LILW waste repositories, gas is an important issue. To prevent gas pressure building up to values close to the gas fracturing pressure, gas-related requirements can be assigned to plugs and seals. In that case, in complement of limitation of water flow, these components can be designed to offer pathways to gas. Constitutive materials have to be selected and characterised in this perspective. For example, the use of bentonite/sand mixture for seal can allow to have swelling pressure development, low water permeability and low gas breakthrough pressures.

5.3 Past and ongoing (RD&D) projects

Some past (RD&D) projects are relevant for the thematic of underground repository closure and give a good overview of construction of Plugs and seals, materiel properties, modelling and safety assessment:

- DOPAS, the Full-Scale Demonstration of Plugs and Seals (DOPAS), including national projects of POPLU, FSS, DOMPLU, and EPSP (https://cordis.europa.eu/project/id/323273).

- PEBS, the Long-term Performance of Engineered Barrier System (https://cordis.europa.eu/project/id/249681)
- ESDRED: Engineering Studies and Demonstrations of Repository Designs (https://cordis.europa.eu/project/id/508851)
- CEBAMA, Cement-based materials, properties, evolution, barrier functions (https://cordis.europa.eu/project/id/662147)
- BEACON: Bentonite mechanical evolution; (https://cordis.europa.eu/project/id/745942)
- EBSSYN Engineered Barrier System Project (https://www.oecd-nea.org/jcms/pl_48805)
- LUCOEX: Large Underground Concept Experiments (https://cordis.europa.eu/project/id/269905)
- ECOCLAY II - Effects of Cement on CLAY barrier performance - phase II (https://cordis.europa.eu/project/id/FIKW-CT-2000-00028)
- Prototype repository: A full scale experiment at Äspö HRL (https://cordis.europa.eu/docs/projects/files/FIKW/FIKW-CT-2000-00055/projrep-prototype-repository_en.pdf)
- DECOVALEX - DEvelopment of COupled models and their VALidation against Experiments (https://decovalex.org/
- TSX: The tunnel sealing experiment (Martino et al, 2007) (https://inis.iaea.org/records/pfdwx-vha69)
- ESP: Enhanced Sealing Project (Dixon et al, 2010) (https://inis.iaea.org/records/nqgm1-b8313)

Ongoing (RD&D) Projects:

Most of the new R&D projects are included in EURAD, in addition to the following:

- DECOVALEX 2023/2027– https://decovalex.org
- GAST - Gas-Permeable Seal Test https://www.grimsel.com/gts-projects/gast/gast-introduction
- Large-scale testing of a sandwich shaft-sealing system at the Mont Terri rock laboratory (Wieczorek et al., 2021) (https://www.grs.de/en/news/new-shaft-seal-as-geotechnical-barrier)

5.4 Lessons learnt

Extensive research work has been performed in recent decades on plugs and seals in the context of nuclear waste disposal.

Different approaches have been conducted to first demonstrate the technological feasibility of building such components, and to evaluate their performance in regards of the requirements during operation and for long-term safety. As mentioned in §5.3, several international projects contributed to a considerable improvement in knowledge of the processes affecting these components and to acquire confidence in the ability to build them under repository conditions.

Large experimental programs conducted in underground laboratories around the world have demonstrated the ability to build these essential components of DGR. This has been achieved by laboratory scale tests, modelling and eventually setting up full-scale experiments in all types of host rock.

Large scale experiments carried out in crystalline rocks in Sweden, Czech Republic, Finland and Canada have not only demonstrated the ability to build the structures, but also to achieve the performance targets. A very relevant case is the closure of the underground laboratory in Canada (ESP), with operational shaft seals (access and ventilation shafts) that fulfil the requirement concerning limitation of water flow.

In clay formation, several large-scale experiments have been conducted or are still running in Belgium, Switzerland, and France. In Boom clay, tests carried out in Hades (Belgium) such as RESEAL or Bacchus (Li et al, 2023), provided essential information on both the construction, with the particularity of managing the linings required to support the rock in place, and the demonstration of the performance achieved. In France, the FSS full scale demonstrator (White et al, 2016) improved the confidence in terms of building such components and especially the capacity to set up large volume of low pH concrete in line with what it is expected (low temperature during curing, no fracture in the plug). The GAST experiment installed in Grimsel in Switzerland, dealt with the performance of the seals to handle gas release requirements by using a bentonite /sand mixture with a high sand content (80%).

Many studies have been done about the behaviour of each individual material used for plug and seals. Large amounts of experimental tests have been conducted to characterise the bentonite-based material and to improve knowledge on their THMC behaviour. Several research programs have also been conducted to develop concrete formulations for the concrete plug materials. Interactions between all the materials of the plugs and seals also receive special attention. In particular, the interaction between concrete and clays is still an important subject of study for assessing the long-term consequences on the swelling pressures and permeabilities of bentonite subjected to an alkaline plume (see for example CEBAMA or ECOCLAY).

In most of the projects launched addressing plugs and seals, and their constitutive materials, an important effort has been made to develop numerical models able to simulate the THMC long term behaviour of such components. EC projects such as BEACON illustrated the difficulties to model the complexity of bentonite components in a underground repository environment.

6. Uncertainties

Given the R&D programs developed in the past, construction of plugs and seals in the context of underground repository reached an important level of maturity. However, uncertainties and knowledge gaps remain concerning long-term behaviour of these components.

Even though the THMC processes of these components are generally well understood, enabling us to describe the main long-term evolutionary trends of the plugs and seals, some points need to be improved with a view to optimising the performance of the components, increasing the margins with regard to repository safety and optimising costs.

In this context, some challenges remain about numerical tools that allow a detail representation of plugs and seals evolutions. The robustness of the tools and their predictability capacity concerning coupling THMC processes needs to be improved as was seen for example in the BEACON project. These improvements will lead to a better evaluation of long-term behaviour and performances of the components.

Cement/clay interactions and more generally interactions between the constitutive materials and the environment need to be better understood and/or better represented by the numerical models. In particular, concrete degradations, potential reduction of swelling pressure and increase of water permeability due to alkaline plume, evolution of damaged zone around plugs and seals. All need to be investigated in detail to be able to simulate long term behaviour.

Modelling choices depend on the design of the underground repository, the functions assigned to plugs and seals, and the host rock. The acquisition of specific parameters to describe the THMC evolution of these components and constitutive materials must be defined in this constrained context in order to reduce uncertainties in the simulation results.

The main challenge is induced by the requirements for the long-term isolation of radioactive waste and in some underground repository designs the necessity to keep some performances of plugs and seals on the whole lifetime of the repository. Tests, data acquisition and process observation are carried out over short periods of time and through the help of complex model simulations. Extrapolating these data or the physico-chemical processes over the very long term is complex and, in order to limit the uncertainties, it is needed to consolidate the knowledge base considerably.

7. Guidance, Training, Communities of Practice and Capabilities

This section provides links to resources, organisations and networks that can help connect people with people, focused on the domain of *Plugs and Seals*.

The main group that discusses need and advancements on plugs and seals for closure are within the bentonite communities of practice, as defined in the list of projects above and chapter 8 below. The waste management organizations have existing infrastructure related to plugs and seals based on earlier demonstrations within some of the projects listed above.

Guidance
IAEA: https://www-pub.iaea.org/MTCD/Publications/PDF/te_630_web.pdf
Training
Specific training sessions are organised during EU projects such as Work Package Eurad2-ANCHORS Training course (https://euradschool.eu/event/work-package-anchors-training-course/), *The next training course from this task is planned in 2029*

8. Further reading, external Links and references

Main references about plugs and seals have been produced during R&D international programs and most of the time by EC projects.

8.1 Further reading

Among all the large amounts of reports, *the following documents are recommended for the reader*:

- DOPAS deliverables are relevant concerning full-scale experiments (*https://cordis.europa.eu/project/id/323273/reporting/fr*).
- BEACON has a good state-of-the-art for modelling bentonite-based materials describing several types of models and their application to real cases. (https://www.beacon-h2020.eu/).
- Well Plugging – The technical solutions adopted by the oil and gas industry for long term closure of wells, are similar to those being tested for underground repository, particularly the use of bentonite-based cores. There is interesting feedback from experience in these areas. https://www.epa.gov/natural-gas-star-program/well-plugging

8.2 External Links of infrastructure facilities

- *https://www.sckcen.be/fr/infrastructure/hades*
- *https://www.mont-terri.ch/fr/page-d-accueil.html*
- *https://meusehautemarne.andra.fr/landra-en-meusehaute-marne/installations/le-laboratoire-souterrain*
- *https://decovalex.org/*
- *https://www.grimsel.com/*
- *https://skb.com/research-and-technology/laboratories/the-aspo-hard-rock-laboratory/*

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