EBS

Domain Insight 3.4.1

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Overview

The fundamental objective of disposing of radioactive waste is the protection of people and the environment from harmful effects of ionising radiation (IAEA 2006). Adequate safety standards for planning, development, operation and closure of a disposal facility have been defined by IAEA (2011). The disposal planning bases on the regulatory framework as well as on the definition of a safety approach and adequate design concepts for safety. A general requirement of the safety approach is that the safety of the closed disposal facility should rely on passive means that do not need any further actions. The safety strategy will be implemented by the Engineered Barrier System (EBS) consisting of diverse technical and geo¬technical barriers, which provide – in combination with the geological barrier – an acceptable level of safety.

Understanding of the components of the repository system and their future evolution is fundamental for the development of a suitable safety concept and an adequate multi-barrier system. The multi-barrier system consists of a combination of the geological barrier and the EBS. The EBS is defined as a system of man-made components including the waste form, the waste canisters, the disposal containers, the buffer, the backfill, the repository seals and other engineered features, e.g. supercontainers (Belgium, Swedish/Finnish KBS-3H). Isolation and containment of radionuclides in the disposal system are principal safety functions that have to be met by the multi-barrier system for a safe geological disposal of long-lived radioactive waste (IAEA 2011). To comply with these safety objectives, the components of the multi-barrier system have to combine multiple safety functions and provide a high level of diversity and redundancy, so that the overall safety is not dependent upon any safety function, i.e. safety is maintained even if one or more safety functions underperform. The safety functions will be provided by physical and chemical properties of the barrier components, such as low water permeability to, limited corrosion, dissolution, leach rate and solubility, high retention of radionuclides and retardation of radionuclide migration.

Due to comprehensive RD&D (research, development and demonstration) work especially in underground research laboratories (URL), maturity of knowledge and technology of EBS components is increased and their interaction with the geosphere have significantly advanced. But optimisation is a key issue in any deep geological repository (DGR) work and therefore corresponding future work may focus on increasing the functionality and efficiency of the barrier. Furthermore, outstanding uncertainties have to be analysed. These could include, for example the detailed characterisation and evolution of the geosphere, as well as climate evolution. Where uncertainties are addressed in models by simplifications and abstractions, these need to be evaluated and justified. With increasing progress of RD&D work on EBS, operational aspects and feasibility assessments and demonstrations will become more important as complements to performance and safety assessments as well as for associated RD&D work.

Keywords

Engineered Barrier System, safety functions, performance assessment

Key Acronyms

Engineered Barrier System (EBS)

1. Typical overall goals and activities in the domain of EBS

The fundamental safety objective for radiological safety is the protection of the public and the environment from radiation risks and avoidance of undue burdens from the repository (IAEA 2006~~b~~). The strategy to comply with this safety objective includes – especially for high-level radioactive waste and spent fuel considered as waste – its geological disposal (cf. the Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste) and the isolation, containment, retention and retardation of the radionuclide inventory by means of a multi-barrier system (IAEA 2011). This barrier system has to be stable on a long-term basis with respect to internal and external impacts. The goal breakdown structure of the European Joint Programme on Radioactive Waste Management (EURAD) project relies on those fundamental recommendations of IAEA and NEA.

The adequate basic safety concept requires a diverse and redundant multi-barrier concept that will consist of a geological barrier in combination with engineered barriers. Therefore the compatibility between the host rock and the engineered repository components is an important issue. A general requirement of the safety approach is that the safety of the closed disposal facility should rely on passive means that do not need any further societal actions (IAEA 2011). The adequate understanding of the components of the repository system and their evolution in the future is a fundamental issue to develop a suitable safety concept. The EBS will consist of a system of physical barriers with adequate properties contributing to waste containment, e.g. low permeability, chemical compatibility and stability and retention or retardation of radionuclide migration. Components of the EBS may be the waste form, the disposal container, buffer, backfill and different sealing constructions. The barrier components and their safety functions can be complementary and work in combination. Depending on the host rock type and the safety concept, different requirements have been defined for the properties of the different barriers, e.g. in salt and clay formations the host rock is the long-time barrier, while the disposal containers and the sealing constructions are most relevant for a limited period of time defined by requirement from safety strategy, e.g. period for recoverability of containers, keep integrity during the thermal phase of HLW or duration of backfill compaction to adequately seal the former mine excavations. In many safety strategies for crystalline rock, the disposal container in combination with geotechnical barriers (buffer) is stipulated as the most important barrier for long-time containment of the radionuclides. In any case, the comprehensive understanding of the EBS system and the interactions between the barriers and the repository nearfield are fundamental issues for the design of barriers and for evaluating their performance.

As mentioned in EBSSYN (2010), there was generally good consistency amongst national EBS designs for spent fuel and HLW disposal, but less for ILW (because of greater range of ILW waste streams, disposal sites and disposal programmes).

The table below gives a high-level overview on strategies to develop an adequate EBS for a DGR. Requirement management is a key issue during EBS development for the different phases of the DGR roadmap. Deviations occur dependent on the respective national context and programme.

Domain Goal
3.4.1 Confirm complete and integrated EBS system understanding, including the design of an optimised interface EBS/repository and the understanding of the interaction with the repository nearfield environment (EBS system); domain insight.
Domain Activities

Phase 1: Programme Initiation	Starting point for developing an EBS-system is the identification of the safety goals from an analysis of the corresponding regulatory framework (incl. radiological and non-radiological requirements (mining, occupational safety, environmental protection etc.) and the development of corresponding safety strategies (host rock, EBS). The inventory to be accounted for forms another important basis. Safety functions for the different components of the barrier system and strategies to implement the barrier system through an adequate design concept have to be defined (compiled in a safety concept). R&D programmes to develop a general understanding of the future evolution of a potential host rock type and its interaction with repository components should be initiated. At this time, generic repository and EBS concepts will be developed. Investigations of the functionality and constructability of geotechnical barriers will be performed.
Phase 2: DGR Site Identification	Based on rock type specific safety concepts, requirements for potential host rocks have to be identified. During the site selection process, the compliance with the safety requirements has to be analysed and demonstrated through the results of exploration. After site selection, important boundary conditions for the safety concept can be specified by using site specific data (e.g. type of host rock and overburden and their corresponding properties incl. groundwater). The additional exploration data will be used to specify input data for the safety assessments and to revaluate and possibly optimise the specified safety strategy. Furthermore, the generic repository design and the EBS concept have to be adapted to site-specific boundary conditions.
Phase 3: DGR Site Characterisation	For site characterisation, an expanded surface exploration programme in combination with an underground exploration programme will be implemented. During this phase, a comprehensive set of rock data will be acquired to verify the compliance with the requirements for host rock properties and to get further data to optimise the safety concept and the corresponding EBS concept. The adaption of EBS design to the increasing knowledge on host rock properties is a persisting process during site characterisation, repository construction and operation. The host rock properties as well as important processes for the future repository evolution will be analysed by performing in situ tests in the exploratory mines (focus on rock properties) or URLs (supplementary analysing the interaction between repository components and the host rock). The in situ tests in URL will be performed to analyse the functionality and constructability of the EBS and to investigate the interactions between the host rock and the repository components. Results of the in situ tests will be also used to evaluate, verify and optimise the safety concept, the repository design as well as the disposal and the barrier concept

Phase 4: DGR Construction	During DGR construction, further information will be acquired on the geosphere. Based on the mine excavations, the ‘as built state’ of the repository and the corresponding components/installations will be captured and used for design verification. The properties of components and installations can be specified. After the completion of the construction of the shafts or ramps, infrastructure and connection drifts, mining work at the disposal areas will be done in retreating mode, which means that construction, operation and closure will run simultaneously in different areas of the repository. Due to radiation protection requirements, the mining work and waste package handling will be radiologically separated i.e. no waste packages will be handled in the construction areas. As mentioned above, acquired data will be continuously compared with former assumptions and used for further optimisation of the repository design and disposal strategy as well as the closure concept.
Phase 5: DGR Operation and Closure	Operation phase will start with the first emplacement of a disposal canister. During DGR operation and closure, the information on the geosphere will be continuously updated and confirmed. If the repository will be constructed and operated in retreating mode, the void volume of the mine excavations will be minimised. When the emplacement of the waste packages in a disposal borehole/drift has been completed, the local EBS will be installed; possible components are: the buffer (surrounding the waste package), the backfill and the borehole or drift-seals. For an adequate functionality of the barriers, the geology and the excavation damaged zone (EDZ) at the construction site have to be analysed in-depth. After installation, the specific properties of each barrier have to be verified (as built state). During the operational period, the EBS will contribute to operational safety; especially the waste packages assure the safe containment of the radionuclides and – if shielded – reduce radiation exposure of the staff. The main objective of the geotechnical barriers is the containment of the radioactive waste and the retardation of radionuclide migration during the post-closure period.

2. Contribution to generic safety functions and implementation goals

This section describes how EBS (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.

As mentioned above, the principle safety functions of disposal systems of long-lived radioactive waste are isolation and containment. The natural (geological) barrier system as well as the EBS are basic elements to meet those safety goals. The chapter illustrates, in a generic way, how the safety functions and implementation goals are fulfilled in different ways, depending on the particular waste and the provided disposal site (different host rock types), through appropriate repository design and operation as well as by using an adequate EBS (EBSSYN 2010). The EBS consists of man-made components of the disposal system and may include the waste form, the disposal canister, the buffer, the backfill, the repository seals and other engineered features. In general, their safety functions are to provide the required level of waste containment and to retard the radionuclide release to the host rock. In addition, functions might be defined for certain components which aim at protecting other components. Each EBS component has its specific requirements to fulfil the safety functions for different timescales.

The relevance of the different EBS components may vary during the different phases of repository lifetime and dependent on the rock-type specific safety concept: so, the waste form, waste canister and the disposal containers (if unshielded in combination with a transfer cask) are of high safety relevance during the operation phase of all repositories (e.g. criticality safety, radiation protection, minimisation of accident consequences). The waste form depends on the waste type and the conditioning strategy, e.g. vitrified reprocessing waste is filled in waste canisters (CSD-V, CSD-C, CSD-B). The corresponding requirements are generally defined as waste acceptance criteria. Radiation shielding and accident prevention may be provided by the disposal container or by a transfer overpack. The disposal container design has to consider requirements from repository operation and long-term safety. Typically, the disposal containers for salt or clay formations have a relatively shorter functional period - the initial phase of the post-closure period (to ensure containment during the thermal phase of HLW and to fulfil the requirements for retrieval/recoverability), while the disposal containers in crystalline host rocks are key barriers and have to ensure waste containment for the whole demonstration period.

In contrast to this, the design requirements for geotechnical barriers mainly address the post-closure period. The safety functions mentioned above result in EBS design requirements referring to the sealing function as well as to the barrier stability/integrity. EBS performance assessment requires consideration of chemical/biological, thermal, hydraulic and mechanical loads.

Because the EBS works is an integrated system, requirements for a barrier may also consider the need of a neighbouring barrier, e.g. in many disposal systems the buffer protects the disposal canister from mechanical damage and corrosion. The relevance of a barrier in an EBS is dependent on the boundary conditions during the demonstration period, on regulatory requirements and on the host rock properties.

To be effective, an EBS must be tailored to the specific environment. So designing an EBS requires the integration of on-site data and waste characterisation studies, RD&D studies on barrier properties and experience gained during demonstration tests and repository operation.

A broad spectrum of EBS adoptions are possible referring to different safety strategies and boundary conditions. For engineered barriers, construction materials should be compatible with the geological setting and resist chemical impairments during the functional period. So, favourable construction materials should have chemical and mineralogical properties similar or stable to the corresponding host rock resp. in the hydrochemical environment. This applies to bentonite in clay formations or to salt resp. magnesia concrete in salt formations. In crystalline rocks, bentonite is a preferred barrier material, because of its long-term stability in that hydrochemical environment and its swelling capacity ensuring the rapid fixation in mine contour and other retention properties.

It is recognised that the various national disposal programmes adopt different approaches on how disposal system requirements are specified and organised. Each programme must develop its own requirements, to suit national constraints (national regulations, safety strategy, different waste types, different packaging concept options, different host rock environments, etc.). The generic safety functions and the 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 EBS that contribute to achieving storage safety as well as long-term safety of the disposal system

The first step for initiating an adequate disposal concept is the development of a safety strategy which incorporates all high-level requirements and identifies additional lower level requirements (IAEA 2011). Those requirements and constraints are the key issues to identify the first generic EBS that will be continuously upgraded by safety and performance studies, engineering design studies as well as tests of constructability and compliance with the requirements. During this process, reasonable assumptions made at the beginning increasingly evolve into detailed specifications. Furthermore, constraints for the EBS design are related to disposal site characteristics, the properties of existing waste packages, the waste inventory, available technologies, understanding of processes and uncertainties, and the need for operational safety and flexibility (IAEA 2011).

There are different levels of design requirements that have to be translated into an adequate and technically feasible design. High-level regulatory requirements may be derived e.g. from:

- Nuclear regulations including radiation protection provisions
- Additional specific legal requirements for radioactive waste management (e.g. retrievability of waste packages during the operation period or recoverability during the early phase of the post-closure period),
- Mining regulations
- Other legal fields dealing with environmental protection, water management (constraints for release of harmful substances), health and safety regulations

Lower level requirements may result from the site characteristics, the waste properties or the construction materials for the EBS, eg. a temperature limit of 100 °C at the surface of the waste package in disposal concepts with a bentonite buffer or in a clay host rock may be defined to avoid a thermal alteration of the clay minerals in buffer and in the host rock.

Requirement management systems and accessory software tools are useful means (Bennett 2010) of demonstrating that the EBS design adequately addresses the various requirements and constraints of the disposal system and increase transparency in indecision-making. Requirement management is based on the subdivision of design objectives. At each level of requirements, a test will verify the compliance with the objectives. Results from the requirement management system are detailed specifications for the EBS construction. The requirement management system interacts and iterates with safety and performance assessment techniques and has to be performed throughout a project. The comparison of alternative design options against requirements is an important part of the decision-making process (multi-criteria options appraisal, see Bel et al. 2003, UKAEA 2004).

The development of the safety case for a DGR is based on a comprehensive compilation of the site-specific data and integration in a conceptual site descriptive (SDM) model or geosynthesis. SDM describes especially the features contributing to long-term isolation, containment and retardation of radionuclides but also potentially detrimental features.

The basic design concept for a DGR refers to the following safety functions (IAEA 2011):

1. Isolation of the waste from the biosphere.

2. Long-term containment of the waste to allow radioactive decay.

3. Retardation of the dispersion of radionuclides in the geosphere and biosphere.

4. Protection of the waste from any undue impacts originating from large-scale geological and climate processes or unfavourable evolutions in the repository system that could compromise the integrity of the barrier system (internal and external stability).

The safety goals and safety functions for the DGR system components are also included in many corresponding national regulations for the disposal of radioactive waste and siting of a DGR (e.g.

German Disposal Safety Requirements Ordinance 2020, German Site Selection Act 2017). It has to be ensured that there is adequate defence in depth, so that safety is not unduly dependent on a single element of the disposal facility. This can be demonstrated by multiple safety functions, the robust fulfilment of individual safety functions and the adequate performance of the various physical components of the disposal system and the fulfilment of their safety functions.

2.1.1 Primary goal - relied upon for isolation

In the context of final disposal of radioactive waste, IAEA (2018) defined “isolation” as:

The physical separation and retention of radioactive waste away from people and from the environment.

Isolation of radioactive waste with its associated hazards in a disposal facility involves the minimisation of the influence of factors that could reduce the integrity of the disposal facility; provision for a very low mobility of most long lived radionuclides to impede their migration from the disposal facility; and making access to the waste by people difficult without special technical capabilities.

Design features are intended to provide isolation (a confinement function) for several hundreds of years for short lived waste and for at least several thousands of years for intermediate level waste and high level waste.

Isolation is an inherent feature of geological disposal.

In compliance with the basic safety principles compiled in IAEA (2011) the disposal facility shall be sited, designed and operated to provide features that are aimed at isolation of the radioactive waste from people and from the accessible biosphere. The features shall aim to provide isolation for several hundreds of years for short lived waste and at least several thousands of years for intermediate and high level waste. Consideration shall be given to both the natural evolution of the disposal system and events causing disturbance of the facility.

IAEA (2011) compiles some fundamental strategies with regard to the waste isolation in a DGR:

- For near surface facilities, isolation has to be provided by the location and the design of the disposal facility and by operational and institutional controls. For DGR, isolation is provided primarily by the host rock in combination with the adequate depth of disposal
- Isolation means the separation of the waste and the avoidance of associated hazards for the biosphere. Furthermore the design should minimise any external and internal impacts that could reduce the integrity of the disposal facility, e.g. geological environments with higher hydraulic conductivities have to be avoided.
- The DGR should be sited in a stable geological formation to protect the facility from the impact of geomorphological processes, such as erosion and glacial channelling. To reduce the hazard of future human intrusion the DGR site should not provide significant mineral resources.

As mentioned before, isolation of the waste in a DGR from biosphere will be mainly ensured by an appropriate geological barrier consisting of the host rock and protective overburden formations. Therefore, corresponding requirements are included in the site selection criteria for many national programmes.

With regard to the DGR roadmap, ‘isolation’ has to be addressed during all phases. But the most important decisions for compliance with requirements have to be made at early stages, including the safety strategy as well as the selection of the host rock and the site. The safety strategy also includes basic requirements for the DGR and the EBS design that contribute to waste isolation.

2.1.2 Primary goal - relied upon for confinement/containment

Containment and confinement are two closely related items. They are defined and delimited by IAEA (2018) as follows:

- Containment describes methods or physical structures designed to prevent or control the release and the dispersion of radioactive substances.

- Confinement means the prevention or control of releases of radioactive material to the environment.

Based on those definitions, confinement refers to the safety function of preventing the release of radioactive material, whereas “containment” refers to the means for achieving that function (i.e. the EBS).

Therefore, the EBS (incl. the waste form and the disposal containers), will be designed to provide containment of the radionuclides in combination with the host rock (IAEA 2011). Radionuclide containment shall be provided until radioactive decay of short-lived radionuclides has significantly reduced the radiological hazard. Another requirement for heat generating, high-level waste demands containment during the thermal phase, to avoid a migration of radionuclides outside the disposal system during that time and to prevent an impairment of the disposal system performance. As explained above, for concepts in crystalline host rocks, containment requirements for the EBS might cover much longer timeframes.

To comply with the requirement of radionuclide containment, all engineered components of the DGR should be adequately designed to avoid or minimise the release of radionuclides (IAEA 2011). Performance and safety assessment for EBS will demonstrate the containment capability of the barriers being appropriate for the waste type and the overall disposal system. Releases of small amounts of gaseous radionuclides and other highly mobile species pollutants may be inevitable and have to be evaluated in the safety assessment. For EBS design, referencing the application of the best available technology for preventing releases, rather than reducing calculated dose consequences, may be an appropriate safety demonstration strategy (Baltes et al. 2008). It was observed that this approach could work well for salt or clay host environments, where containment in the near field is a prominent feature. A different approach is favoured for crystalline formations where greater reliance is placed on containment by the EBS und calculations of releases from the EBS are of greater importance.

Confinement is the most important safety strategy for intermediate level waste (ILW), for vitrified waste from fuel reprocessing (HLW), and for spent nuclear fuel (SNF). With regard to the retention of radionuclides, the durability of the waste form is important. The EBS should be adequately designed to retain barrier integrity for the period of decay of the shorter lived radionuclides and for the decrease of the associated heat generation.

In some national regulations, isolation and containment are the key issues rather than potential hazards (e.g. Baltes et al. 2008; BMU 2020). The “containment providing rock zone” is the key issue in the German concept. The concept is that a portion of the host rock with favourable containment properties surrounds the repository and can maintain crucial properties over a timeframe of 106 years. If the “completeness of containment” can be demonstrated for expected evolutions, the radionuclide releases should not significantly exceed natural radioactivity resp. the variation of the radiological background. Therefore, the calculated radionuclide concentrations in the accessible environment are seen as primary safety indicators. With regard to the confinement function, the relevance of the different components of the multi-barrier system changes in the different phases of DGR evolution.

During the planning phase, the safety strategy defines the safety functions and the requirements for the host rock and the EBS. These issues are the fundamentals for the development of adequate generic concepts for the repository and the EBS that comply with the safety goals.

During the siting phase, adequate criteria ensure the selection of a suitable site and a host rock with adequate containment properties (BMU 2017). The specific knowledge on the host rock properties will progressively increase during surface exploration and subsequent underground exploration. At an advanced stage of underground exploration, in situ tests may give indications for the understanding of relevant processes during potential DGR evolution. Early time preliminary safety assessments of the initial evolutions give indications for potential site-specific hazards and support the identification of requirements to design appropriate EBS components.

During the construction phase, the repository design (as derived from the safety strategy) will be adequately implemented. Construction measures such as excavation techniques to minimise the EDZ and minimisation of the void volume (for example, if disposal areas are excavated on demand and immediately backfilled and sealed after completion of disposal), will reduce the disturbance of the host rock and obtain the barrier function New exploration data as well as experiences/results from construction of DGR components will be used to upgrade the safety strategy and optimise the design.

It is likely, that construction, operation and closure activities will be performed simultaneously in different, separated areas of the DGR. During the operation period, radionuclide containment is provided by the combination of waste form, waste canisters and disposal containers (although of course the geotechnical barriers will also be installed). Most barriers need some chemical/physical processes to completely accomplish their provided safety functions to achieve their low permeability, e.g. needs chemical conversion of magnesia concrete, saturation of bentonite or closure via convergence of the contact zone and EDZ of geotechnical components. The performance of the EBS (as-built-state) is a very important boundary condition for the post-closure phase and for compliance with the safety goals.

2.1.3 Primary goal - relied upon to retard the dispersion of radionuclide in the geosphere and biosphere

Retention and retardation of radionuclide migration are key safety functions of EBS to limit long-term releases of radionuclides below regulatory limits. Releases of gaseous radionuclides and of small fractions of other highly mobile species from waste of some types cannot be excluded for disposal periods of several hundred thousands of years. Uncertainties in the prognosis of future system evolutions (e.g. future climate impacts) may influence the barrier performance. Retention and retardation of radionuclide releases will be considered in all stages of the DGR roadmap.

With regard to DGR siting, a geological barrier with low hydrogeological dynamics is seen as a favourable host rock. The corresponding host rock properties include a low permeability, low amounts of groundwater and limited local and regional groundwater fluxes as well as no recent or future flow paths between the host rock and the biosphere. The host rock and the potential disposal level of the DGR have to be arranged at a depth that cannot be impaired by any surface impacts, like climate effects (e.g. glaciation) or physical effects (e.g. erosion). If the host rock is seen as a main barrier (e.g. containment providing rock zone), advective flow should be minimised and slow diffusive transport processes should be dominating. Slow, long lasting transport processes foster the decay of short-lived nuclides during transport. Some rock minerals (e.g. in clay) have high sorption capacities for radionuclides and therefore strengthen radionuclide retardation. Fractured crystalline rocks only have a low containment capacity. Therefore, the containment concepts for those rock types rely on engineered barriers (container, buffer).

There are two principal approaches to how EBS supplement the geological barrier function: first, by sealing the mining induced perforations of the geological barrier, and second, by adding an additional barrier (e.g. disposal canister). In the repository system, the barriers can be arranged in series or parallel. Requirements and safety functions (containment, retardation of radionuclide-release) for the EBS components will be defined in the safety concept (ESK 2019). In many disposal concepts, the functional period of the barriers is staggered – starting with the disposal container and the waste form/waste canister during the initial post-closure phase. Their corrosion rate and the solubility of radionuclides can be reduced by minimising water access and implementing a favourable hydrochemical environment. This can be achieved by adequate construction materials (buffer of clay or concrete). The geotechnical barriers are provided for a longer period bypassing the time until the backfill works as a long-time barrier (Mönig et al. 2013). The low permeability of the sealing elements of the geotechnical barriers should be stable in the long-term. Therefore, the construction materials should be adapted to the geological environment and to the expected hydrochemistry. Their functionality should be demonstrated by in situ tests. Some construction materials resp. their corrosion products (e.g. clays, metal corrosion products) have a high sorption capacity for radionuclides and thus also contribute to radionuclides retention and retardation of migration.

2.1.4 Primary goal - relied upon to ensure long-term stability with respect to internal and external impacts

Long-lived radionuclides have half-lives of several hundred thousand to millions of years, therefore a long-term isolation and containment of radionuclides is necessary for a HLW repository. IAEA proposed a safety demonstration period for a HLW repository of 1 Ma.

Stability against external mechanical impacts is linked to the geosphere properties. If geological impacts or rock properties occur in a region that could result in an impairment of the geological barrier, the region should not further be considered as a potential DGR site. Therefore, site selection procedure is a key issue to ensure external stability. The corresponding requirements are connected with the site selection criteria in many national regulations, like active fracture zones as stated earlier in this work.

Internal stability considers the compatibility between the DGR components and the geological environment due to repository excavation, operation and closure. The mining work results in significant stress changes in the surrounding host rock. Furthermore, the thermal impact by the disposal of heat generating waste and the resulting thermo-mechanical (TM) stresses have to be considered. Construction materials and their alteration products have to be compatible with the host rock. Additionally, the waste packages will be corroded. The resulting gas generation will increase fluid pressure that may impair the EBS and the host rock. Therefore, DGR design will provide preventive measures to avoid unacceptable high gas pressure (high corrosion resistivity, minimisation of water influx, favourable hydrochemistry, barrier design tolerating gas flow etc.) Furthermore, post-closure criticality should be excluded or the consequences should be tolerable. Corresponding measures may comprise fissile material controls/limits (including burn-up credit for SNF) and detailed understanding of the evolution of waste packages’ evolution over relevant post-closure timescale.

2.1.5 Secondary goal – acknowledged but not relied upon for implementing an EBS

The EBS of the DGR system consists of multiple barriers with an adequate spectrum of safety functions that has been designed in a step-by-step approach to meet the primary goals described above. Additionally, secondary goals have been defined relating to the step-by-step implementation of the planning, that are necessary for safety and to assist in developing confidence in the safety of DGR. As necessary, each step can be supported by iterative evaluations of the site, of the options for design and management, and of the performance and safety of the geological disposal system. Based on the secondary goals, requirements for the development, the operation and the closure of the DGR can be defined. These requirements are linked with quantifiable parameters to check compliance.

The first secondary goal is the demonstration of the “technical feasibility”. In this context, it has to be shown that the repository components have been adequately designed, constructed and (buildings) installed to assure effective repository operations as well as to comply with their safety functions during the different phases of repository lifetime. Flexibility of the system should be provided to enable optimisation or adaptions/corrections of the system. For components of the EBS, laboratory tests (small-scale, specific investigations), processing tests (construction materials, barrier elements (e.g. highly compacted bentonite blocks)) and in situ tests (construction and performance) are common procedures. In situ tests provide a broad spectrum of information with regard to barrier/host rock interactions and functionality of the barrier.

“Reliability” means the demonstration, that the barrier design complies with the design requirements and thus fulfils the safety functions. The reliability of the barrier construction is based on a robust design process that has been adequately supported by a safety case. The compliance with corresponding requirements can be checked by a performance assessment analysing the consequences of chemical and thermo-hydro-mechanical (THM) loads imposed by chemical and physical processes occurring in other parts of the EBS and the demonstration of the barrier integrity for the provided functional period.

“Flexibility”: Basic requirements for the design of the EBS include the compatibility with standardisation and the reliable availability of the construction material. In principle, the EBS should be designed to resist a broad spectrum of potential thermal, hydraulic, mechanical and chemical impacts. That's due to the fact that even if homogeneous host-rock formations are preferred options for siting a DGR, some variability in the geological environment has to be expected. This may include changes of mineralogical/chemical properties or texture of the rock, tectonic properties (fractures and faults) as well as occurrence and properties of ground water. Especially for extended mine excavations, the geological properties may vary at the repository site. During mine construction, additional geological data will be acquired. If those new data are not compatible with the assumptions for the barrier design, it may be necessary to adapt the barrier design to the site-specific boundary conditions.

Furthermore, "optimisation" of technical safety measures is a basic requirement for all DGR work. Experiences from construction work may give indications how to increase the functionality and the effectiveness of a barrier. In addition, legal requirements may be changed resulting in an adaption of the safety strategy and the corresponding closure measures.

"Safeguards" and the corresponding monitoring may have an impact on the strategy and the time schedule for EBS construction. Many DGR projects provide waste disposal in retreating mode which means that disposal areas completely filled with waste packages are backfilled and sealed immediately. This work has to be done in parallel with construction and emplacement work in other areas of the DGR. The corresponding interactions during DGR operation have to be reflected in an adequate safeguards monitoring procedure.

Other potential secondary goals resulting from some national regulations are "retrievability" of waste packages during operation period and/or "recoverability" of waste package disposal during the initial phase of the post-closure period.

"Retrievability" may have an impact on EBS design on the one hand and on the planning and time schedule for DGR operations on the other hand. But it has to be ensured that measures for waste retrieval do not impair the containment function for the EBS. The waste packages have to be adequately designed to maintain their integrity and tightness during the operation period. Furthermore, technical installations (e.g. borehole liners) may be necessary to enable the retrieval of the waste packages. In addition, it has to be demonstrated that the backfill and the EBS components can be removed and the waste package picked up and recovered with acceptable effort.

Other secondary goals for the operation period refer to "operational safety" and mostly address the reduction of radiological risks by an adequate shielding of the waste packages (or their containment in adequate overpacks) and a robust container design to resist potential impacts from accidents and thus prevent or minimise corresponding radiological consequences. Another aspect related to operational safety is the installation of drift liners in host rocks with low mechanical strength. This has a significant impact on the installation of EBS components, because for effective drift sealing the lining has to be removed at least at the location of sealing elements.

2.2 Key processes in the DGR's evolution and their impact on features, characteristics, or properties of EBS

A fundamental understanding of potential evolutions in DGR system including the interactions between geosphere, biosphere and repository system is a basic issue to develop an adequate safety and closure concept and a prerequisite for an adequate Safety Case (Bennett, 2010; Schäfers et al. 2014). In this context, especially the functionality and effectiveness of the multi-barrier system implemented in the EBS has to be evaluated. During the last decades, comprehensive international investigations have been performed to study the complex interaction of THMCB processes in clay host rocks. In this context, the knowledge and understanding of the EBS evolution have been deepened, a quantitative basis for the relation between the long-term EBS evolution and their safety has been provided and the relevance of residual uncertainties for long-term performance assessment has been clarified. The key processes impacting the EBS and affecting their long-term performance during the post-closure period are similar for all high-level concepts. The relevance of the impacts and their treatment in the safety assessment may be different for the concepts, e.g. the saturation of the clay buffer has a higher relevance in fractured crystalline rocks than in clay rocks.

The range of materials proposed for the use in EBS comprises copper, titanium, steel and other alloys for HLW/SF disposal canisters as well as cement (broad spectrum of concrete materials), bentonite-based materials and asphalt for buffers, backfills (also crushed salt or barren rock mixed with bentonite), seals and plugs. The key pre-closure processes for future repository evolution are:

- The development of the EDZ (incl. rock spalling)
- Effects of ventilation on the host rock and the EBS materials
- Water influx, erosion, and piping of bentonite-based materials
- Effects of grouting and high-pH solutions resulting from concrete alteration
- Effects of residual materials from operation (e.g. oils)
- Microbiological activity

Those key processes influence the initial boundary conditions for post-closure safety and therefore have to be considered for EBS design (Bennett 2010).

An important group of key processes refer to the thermal phase of the waste packages resulting from the radionuclides’ decay in SNF and HLW. Therefore, temperature is an important constraint for repository layout and EBS design. Peak temperatures will occur in some tens of years after waste disposal and may remain above the geothermal temperature for several hundreds to thousands of years. The consequences of the thermal impact on the DGR system also refers to the different thermal properties of the host rock types, e.g. salt has a high thermal conductivity (allowing higher temperatures of waste packages) while clay is characterised by a low thermal conductivity (demanding lower temperature limits for the waste packages). For shaft seals also climate induced low temperatures and freezing may be a significant impairment.

Especially in fractured crystalline rocks, water circulation is an important issue for thermal evolution of the DGR system. So water intrusion into the EBS can increase the thermal conductivity, thereby reducing temperatures. Due to their low hydraulic conductivity, water flow is of lower relevance in clay and salt formations. Thermo-chemical processes are also important for system evolution. In this context couplings between temperature, water flux, chemistry and mechanical effects have to be considered. In fractured crystalline rocks for example, spalling may occur due to mechanical and thermo-mechanical stresses. Another example for an important thermal impact on the EBS refers to salt creeping (convergence) that enhances at high temperatures. This process is important for enclosure of the waste packages in the disposal areas, fixes the geotechnical barriers in the mine contour and compacts the backfill in the mine openings.

Chemical and microbiological processes can initiate and/or intensify the corrosion of disposal containers and the alteration of geotechnical barriers. The functional requirements on the different barriers depend on the host rock and site-specific safety concept. While the disposal container is the main barrier in many concepts for crystalline rocks and therefore has to keep its integrity for the whole safety demonstration period, the functional life time for disposal containers in clay and salt formations is mostly restricted to the thermal phase (and the period for the retrieval/recovery of containers). The characteristics and the intensity of metal corrosion processes depend on the construction materials and the hydrochemical properties of groundwater. The high relevance of container corrosion for safety assessment arises from the impairment of the waste containment and the resulting radionuclide mobilisation and transport. For HLW/SF disposal, there are two main categories of container materials that have a different resistance to metal corrosion:

- Materials including carbon steel, low-alloy steels, cast irons and copper corrode in geological environments in well predictable corrosion rates (corrosion-allowance materials).
- Materials including austenitic stainless steels, N-Cr-Mo-alloys and titanium alloys passivate by formation of a protective oxide layer (corrosion-resistant materials). Those protective layers reduce the corrosion rate, but pitting or crevice corrosion may occur if the protection layer has local defects.

Metal corrosion is also important due to the gas generation and the resulting increase of hydraulic pressure. The corrosion processes are controlled by the chemical properties of the metals and by the hydro-chemical properties of the ground water. Due to their high sorption capacity for radionuclides, some metal corrosion products contribute to the retention of radionuclides in the repository.

Gas generation may be also caused by microbial degradation of organic components in EBS components or waste.

The geochemical evolution of the geotechnical (non-metallic) barriers will be affected by temperature and the reactions between construction materials and hydrochemistry of groundwater (Bennett 2010). The temperature influence will be especially relevant in the disposal areas, but climate impact (glacial periods) also influences the properties of the overburden formations and the DGR access seals (shaft/ramp) e.g. by freezing.

In principle, different chemical reactions and chemical species occur at different temperatures and reactions are typically faster at elevated temperatures. Thermal loads may reinforce chemical/mineralogical processes (e.g. illitisation, redistribution of trace elements, crystalline phases in concrete, precipitation of minerals). Thermal gradients may initiate hydraulic processes, like water/brine flux and convection. The relevance of thermo-hydro-chemical (THC) effects in disposal areas is dependent on temperature, the duration of thermal phase and the thermal gradients.

At low fluid flow rates, the presence of a reactive solid phase (e.g. clay) will tend to buffer the chemistry of the associated pore fluids (Bennett 2010). Therefore heterogeneous fluid-solid reactions will only generate narrow zones of alterations. This can be considered for EBS design by providing an appropriate thickness of the barrier components.

The most relevant chemical impacts on clay-based EBS materials refer to iron, bentonite and concrete (Bennett 2010). The corrosion of iron under anaerobic conditions releases Fe2+ to the pore water that interacts with bentonite and results in a reduced sorption capacity, a transformation of smectite to non-swelling clays (reduced swelling capacity) and an increased hydraulic conductivity. Those interactions are coupled in a non-linear way, so some uncertainties remain in process understanding.

Cement-bentonite interactions result in various mineral dissolution, precipitation and alteration reactions. They may cause changes in porosity, permeability and mechanical properties of the bentonite. Concrete alteration may result in a release of hydroxyl-ions and cations (e.g. Ca2+) and a high pH and thus initiate an alteration of bentonite.

The very low humidity is a favourite property of salt formations (Roedder 1984). Brines are predominately accumulated in other intercalated rock types like anhydrite, carbonates or clay layers and are in equilibrium with the geological environment. Alterations of the EBS depend on the volume and hydrochemistry of the availability of intruding brines (Babel & Schreiber 2014). To ensure long-term stability of the EBS, the construction materials will be adapted to the mineralogy of the surrounding salt formations resp. the saturation level of the intruding brine in NaCl-, K- and Mg-salts. Therefore, salt concrete or sorel-concrete are favoured construction materials in this geological environment (Freyer et al. 2015).

The performance assessment for an EBS system is based on laboratory and modelling studies as well as on demonstration tests. Modelling can increase the process understanding, evaluate uncertainties (e.g. in barrier degradation rates) and assess disposal system performance (Bennett 2010). The methodical approach may be based on detailed or simplified models, realistic or conservative assumptions and deterministic or probabilistic models. In the context of the EBS design process, models as well as safety assessment and performance assessment strategies are most relevant. Process models can help to increase and demonstrate understanding and thus build confidence in the safety case. Furthermore, they can be used to assess the significance of processes and thus help for the screening of Features, Events and Processes (FEPs) within the safety assessment (Lommerzheim 2022). Performance assessment may consider just parts of the EBS and does include the evaluation of radiological impacts, while the safety assessment refers to the functionality of the whole disposal system and the evaluation of radiological consequences. Furthermore, those models contribute to integrate knowledge and information of FEP that may influence the behaviour of the disposal system. Uncertainties and variability within the disposal system will be evaluated.

In compliance with the results of the EBSSYN project (Bennett 2010), key processes in clay barriers provided for disposal concepts in crystalline rock and clay rocks have been specially addressed in PEBS project (Schäfers et al. 2014). For the early stage of the post-closure phase, the following key processes were identified:

- Saturation and swelling of EBS clay components (buffer, drift//shaft/borehole seals),
- Mechanical evolution (incl. convergence//creeping, THM stresses),
- Alteration of hydro-mechanical properties (alteration of EBS and surrounding rock).

The saturation of clay will initiate swelling of the construction material, which expands up to the contour of the mine openings. Then, the barrier is restrained in the drift/borehole contour. As a result, the swelling pressure increases and the hydraulic conductivity decreases. Therefore, the process is decisive for the sealing function of the barrier. The clay saturation depends on the availability of water and on hydrochemistry. The hydraulic and mechanical properties of the clay barrier significantly change from the status after installation (blocks, pellets, technical voids) to final situation after saturation (homogenisation).

Apart from swelling, the mechanical processes of the EBS include thermal expansion, creeping and – in the disposal fields – interactions with the canisters and the pore water. Canister corrosion has different consequences on the bentonite buffer: first, metal corrosion results in solid corrosion products with a larger volume (pressure increase) and on large amounts of hydrogen gas (increase of fluid pressure in the pores).On the other hand, mobilised ions from corrosion process or bacterial activity will decrease the swelling capacity of the clay. Based on the results of large-scale demonstration tests, material models for the simulation of swelling processes have been verified. Uncertainties mainly concern to the very complex material model and the corresponding parameter values.

Basing on a transformation of montmorillonite to clays with no or low swelling capacity, shrinkage of clay materials may arise from hydro-chemical alteration at the canister-buffer and liner-buffer interfaces (Schäfers et al. 2014). Other processes promoting this evolution include congruent dissolution of clay minerals, reduction/oxidation of iron in mineral structure, atomic substitutions in mineral structure, layer charge elimination by small cations at high temperatures and ion-exchange. Concrete corrosion and resulting changes of hydrochemistry will also alter the swelling pressure of clay materials. The reduction of swelling may be compensated by convergence or by the volume expansion of the metal corrosion products.

For multi-component barriers (e.g. composed of a large number of bentonite blocks) potentially imperfectly installed elements have to be considered. A preliminary evaluation has shown that the effect of those faults is attenuated by swelling and plasticity of the bentonite (Schäfers et al. 2014).

In the framework of the PEBS-Project several in situ experiments have been performed to analyse the THMC processes mentioned above (Schäfers et al. 2014). The results confirmed assumptions for key processes interacting with EBS and increased the knowledge and understanding on the processes. Numerical models were developed and verified and the uncertainties could be reduced. Criteria for performance assessment of EBS were identified.

Coupled HM, THM and THMC investigations have been performed to analyse the hydration of clay materials, including a heater test, analyses of processes in a bentonite buffer in the Swedish concept (FEBEX in situ Test), container-bentonite interactions and concrete-bentonite interactions and model extrapolation to repository long-term evolution and model uncertainty.

The results of the PEBS experiments have been used to calibrate and verify numerical tools and to develop new or improved constitutive laws for HM, THM and THMC analyses. Furthermore, the test results were extrapolated to repository long-term evolution. The progress in modelling includes the consideration of non-Darcy-flow and thermos-osmosis, the implementation of a special porosity model and a modified strategy for uncertainty management (Schäfers et al. 2014). For the long-term extrapolation exercise, four simulation cases were defined: (1) isothermal buffer evolution (early stage), (2) THM evolution of buffer at temperatures up to 100 °C or (3) above 100 °C and (4) geochemical evolution at canister-bentonite and bentonite-concrete interfaces.

The results of the PEBS project gave implications for long-term safety, repository design and construction. During the early stage of the repository evolution, THM processes in the EBS affect bentonite hydration process. This process depends on buffer properties and local hydraulic conditions. The first scenario considered a location with relevant heating. When the barrier is restrained in the excavation contour, swelling pressure will increase. After final saturation, the hydraulic conductivity of the barriers is very low and the swelling pressure high. The duration of bentonite saturation strongly depends on the boundary conditions. Although, there is a principle conformity between the results of experiments and modelling, at later stages of hydration the progress of saturation is slower in tests than expected by numerical modelling. The reasons for this discrepancy could not yet be identified. But performance assessment has shown, that the safety functions of the bentonite barriers will be met - due to a sufficient swelling pressure - even at a saturation level of 85-90 %. Thus, uncertainty with regard to the later stages of saturation process seems not to be relevant for long-term safety.

Due to the high temperatures at an early stage, system evolution is different in the disposal areas. The consequences of an initial transient stage with high temperature and a low water saturation to lower temperatures and full resaturation for the long-term behaviour of bentonite barriers have been analysed in the PEBS-project (Schäfers et al. 2014). Above 120 °C, a significant reduction of the swelling pressure in unsaturated conditions occur, but minor thermal transient effects have been observed at <130 °C in saturated conditions. Furthermore, plasticity and hydraulic conductivity may be decreased at high temperatures.

The thermally induced transformation of the clay mineralogy proceeds very slowly and thus is of low relevance for short thermal phase of the disposal areas. Below 130- °C, limited alteration of smectite will occur. Thermally induced mineralogical changes will be relevant for temperatures above 150 °C that will not be reached in the analysed repository designs (Bennett 2010).

In principle, the high temperatures during the short thermal phase seem to have only a limited impact on the performance of the barriers, but the impact of temperatures above 125 °C on the swelling and properties is still uncertain (Schäfers et al. 2014).

Alterations of the bentonite in contact with corrosion products of concrete or metal (disposal containers) have to be considered. The main effects of geochemical evolution will take place at the interfaces between bentonite and surrounding materials. Interactions between corrosion products and bentonite will not significantly impair the main properties of bentonite. Under unsaturated conditions, iron corrosion products will only intrude the bentonite for less than 1 mm. In saturated conditions, the canister-buffer interface shows a reduced porosity by the precipitation of magnetite and siderite in an altered zone of 7 cm for a repository in crystalline rock and an altered zone of 4 cm in a clay repository. That is caused by the different pore water chemistry in the two host rock types (Schäfers et al. 2014).

The interaction between bentonite and concrete will produce an altered layer of < 5 mm that is sealed by the precipitation of new minerals in the pores. In the long-term, the reaction zone can increase to some centimetres. The hydration will not be significantly retarded by the cementation of pores. Coupled THMC numerical models reflect the main trends in mineral dissolution-precipitation. Chemical alteration has an impact on the THM-properties of the EBS and therefore has to be included in the performance assessment.

Close to the concrete surface, pore sealing is expected 5 cm in the concrete-bentonite interface. Furthermore, mineral dissolution and precipitation will occur throughout in the buffer and in 25 cm of the adjacent host rock.

The observed cementation process is not kinetic, i.e. it will be the same throughout time. Especially at temperatures above 100 °C, cementation during heating-cooling cycle can increase the strength of dense bentonite, but decrease the swelling pressure. The safety relevance of those processes depends on the impact on the canister (e.g. shear across a borehole).

During saturation, bentonite pellets and bentonite block will homogenise. Experiments have shown that even under non-optimum boundary conditions swelling of mixtures of blocks and pellets will achieve effective sealing.

In the Swedish SR Site Safety Case (Hedin 2006), the following uncertainties for system evolution of a bentonite barrier have been identified: mass-loss due to piping or erosion in early stage evolution; swelling and homogenisation of components with different density; sealing after mass loss; the relevance of friction in the bentonite, between the bentonite components and other materials; and the effects of temperature on the mechanical properties.

3. International examples of EBS

Several European countries (e.g. Belgium, Finland, France, Germany, Sweden and Switzerland) have advanced programmes for radioactive waste disposal in different host rocks. Considering the country specific waste inventories, national regulations and the geological boundary conditions, safety strategies and corresponding EBS concepts have been developed. In the following chapter, a short compilation of key characteristics of some examples and specific EBS is given.

3.1 Examples for EBS in salt formations

In Germany, salt formations were the favoured option for radioactive waste disposal for some decades. Therefore, comprehensive R&D work has been done on this rock type (Asse URL, Gorleben exploration mine) and a former salt production mine was converted to a LILW repository (ERAM, now in licensing procedure for closure). In the course of the R&D work, a site specific EBS concept (incl. shaft seals and drift seals) was developed for the Gorleben salt dome. Referring to German regulations (EndlSiAnfV 2020) the barrier system bases on the “containment providing rock zone” in combination with geotechnical barriers to seal the mine excavations. One important goal is to prevent inflow of liquids to the emplaced waste. This is possible due to the impermeability of the host rock if the EBS performs the way it is designed for. Only if liquid inflow cannot be prevented (e. g. due to failures of EBS components) scenarios with contaminant release and liquid-driven migration are taking place. If any waste package fails (due to production failures or unexpected impacts (e.g. intensive corrosion) volatile radionuclides can be released and transported via gas flow (gas production by metal corrosion or microbial processes.

The geotechnical barriers include shaft seals (concrete and bentonite seals) and drift seals (salt/magnesia concrete) designed for a lifetime of 50,000 years and compacted salt backfill for the long-term. All sealing components have been designed referring to the technical regulations of EUROCODE (DIN-EN-1997-1) and numerical simulations have been performed to demonstrate the sealing capacity and the integrity (Bollingerfehr et al. 2017). In the German safety concept for HLW/SNF disposal in salt formations, the disposal containers are especially relevant for operational safety as well as for retrieval during operation and recoverability for the first 500 years of the post-closure period (EndlSiAnfV 2020).

Apart from the disposal containers, the EBS for the closure of the Morsleben LILW repository is similar. Due to the geological structure and the hydrochemistry of the expected brine, magnesia concrete has been selected as construction material for the drift seals. At locations that need instantaneous sealing after closure, the concrete components will be combined with asphalt components (Mauke et al. 2012, Mauke 2016). The two shafts and a sliding hole will be sealed by gravel columns grouted with asphalt in the salt formations. Additionally, the shafts will be plugged by bentonite seals in the overburden formations.

In the former Asse URL, more than 40 seals of sorel concrete have been installed in drifts and blind shafts as emergency measures to retard the brine inflow in the disposal areas.

The technical feasibility and functionality of the EBS in salt formations have been proven by in situ tests at pilot-seals at the Morsleben repository and the Asse mine. Large-scale demonstration tests for shaft seals have been performed in the course of the DOPAS project (White et al. 2016a), at the Morsleben repository (gravel column with asphalt sealing) and in the salt production mine Salzdetfurth (Kudla & Herold, P. 2021).

3.2 Examples for EBS in clay formations

In all safety concepts for clay formations, due to its low permeability and favourable sorption behaviour the host rock is – in combination with geotechnical barriers to close the mine openings - the key barrier. The disposal containers are relevant for operational safety as well as for confinement during the thermal phase of the waste (as well as for potential retrieval). For most clay concepts a temperature of 100 °C has been defined to avoid a thermal degradation of the clay minerals. Usually, the geotechnical barriers consist of bentonite seals/buffers in combination with concrete abutments.

Two fundamental issues of the French disposal strategy are the emplacement in retreating mode (filled disposal areas are abandoned) on the one hand and the retrievability of the waste packages on the other hand (Andra 2005b). The French host rock for the combined LLW/HLW repository is the consolidated Callovo-Oxfordian clay formation. In the disposal areas, a waste-specific spectrum of carbon steel disposal canisters for HLW (temperature limit 100 °C) will be emplaced in horizontal disposal boreholes. If filled, the disposal boreholes will be sealed with bentonite-concrete plugs (Andra 2005a). The borehole steel liners are perforated to enable the saturation of the bentonite by water inflow from the host rock. LILW drums will be stacked in disposal cells, which will be backfilled with concrete after completion of disposal. Bentonite and low pH-concrete are the most relevant construction materials for drift seals and shaft seals. The EDZ in the drift contour will be interrupted by clay-filled grooves with a width of 0.3 m and a depth of up to 3 m. Other parts of the mine will be backfilled with a clay-sand-mixture. The technical feasibility and functionality of the EBS components has been analysed in large-scale in situ tests, e.g. for drift seals (TSX-test: AECL 2005, ANDRA 2005a, Chandler et al. 2002; ESDRED project: ANDRA 2005a, Gatabin et al. 2008) and shaft seals (RESEAL project: Volckaert et al. 2000, Kudla & Herold 2021).

In Switzerland, an EBS concept has been developed for the combined disposal of LILW and HLW/spent fuel in Opalinus clay (Nagra 2021). The temperature limit in the disposal areas for HLW/Spent fuel is 125 °C. The reference canister type for the disposal of HLW and spent fuel is a stainless steel canister with a minimum lifetime of 1,000 years that will be emplaced in disposal drifts and surrounded by a bentonite buffer. The EBS concept includes five categories of geotechnical barriers and backfill for the different disposal areas, connecting drifts and shafts and ramp. The basic barrier concept relies on bentonite seals and concrete or gravel abutments. For feasibility and functionality demonstration, NAGRA was also involved in many in situ tests mentioned above at ANDRA (NAGRA 2002, Nold 2006). Furthermore, a heater test and an in situ barrier test has been performed in the Mont Terri URL (Schäfers et al. 2014).

The Belgian EBS concept has been developed for drift disposal of HLW and spent fuel in plastic clay (Boom clay) (Gens et al. 2011). A special component of the EBS is the supercontainer that is an overpack for a HLW/spent fuel container. It consists of an inner carbon steel container (thickness 3 cm) surrounded by a concrete buffer (thickness 70 cm) and an outer stainless steel envelope (thickness 0.6 c) (Bel et al. 2011). The temperature limit is 100 °C and the functional lifetime should cover the thermal phase of HLW. Advantages of prefabricated barriers, like supercontainers, are the favourable boundary conditions for fabrication and quality verification in plants. Supplementary barriers of the Belgian EBS concept include drift seals and shaft seals made of bentonite sealing elements and concrete abutments. Feasibility and functionality tests have already been mentioned above (RESEAL, PEBS). Furthermore, specific tests for the Belgian EBS concept have been performed in PRACLAY project including mine-by-tests, seal test and heater test (Dizier et al. 2016).

3.3 Examples for EBS in crystalline rocks

Crystalline rocks are characterised by a high mechanical and thermal stability making them favourable for repository operation and protecting the waste packages in the disposal areas during the post-operational period. Crystalline rocks, however, are often intensively fractured and may be water-bearing. Therefore, the safety function of long-term confinement of radioactive waste has been mostly assigned to the disposal containers. The surrounding buffer retards and limits water influx, cares for favourable hydrochemistry and reduces mechanical loads. Other geotechnical barriers restrict and retard water influx and radionuclides migration via the drifts. These are the basic safety issues for the Finnish and the Swedish disposal strategies that are quite similar and compiled in the following paragraph.

The Finnish project at Olkiluoto is the most advanced HLW repository project worldwide: in 2015 the construction license has been granted, at the end of 2021 Posiva applied for an operation licence, a cold commission test (TRFD) will be performed in 2023, and the start of operation is foreseen for 2025. Safety functions, performance targets and technical design are compiled in Posiva & SKB (2017). Main design requirements include a lifetime of the copper canisters of at least 100,000 years, resistance to mechanical and hydraulic impacts from glaciation, a temperature limit of 100 °C at the canister surface, and retrievability of waste packages. The copper canister and the surrounding bentonite buffer in the deposition boreholes are the key elements of EBS. In the reference concept “KBS-3V” emplacement in vertical boreholes is foreseen, but an alternative option (horizontal emplacement of supercontainers, KBS-3H) was also investigated. Other technical measures of EBS include a bentonite backfill of the access drifts of the disposal areas and drift seals and shaft seals to limit water intrusion in the repository. For operating license application, Posiva prepared a new safety case including a performance assessment of the EBS (Posiva 2021a, b, c, d, e). Numerous large-scale in situ tests for feasibility and functionality of EBS components have been performed e.g. for buffer/backfill (Martikainen & Niskanen 2022), shaft seals/drift seals (ELSA, FEBEX: Schäfers et al. 2014; DOPAS (DOMPLU, POPFLU): White et al. 2016a,b). Furthermore, POSIVA started a full scale in situ test of the disposal system (FISST test) in 2019. Two test canisters (heaters) were installed in deposition holes in a 50 m long tunnel. The tunnel was backfilled with bentonite and closed with a steel-reinforced concrete plug (Haapala 2020a,b). Temperature changes and pressure of the canisters, deposition holes and surrounding bedrock and behaviour of tunnel backfill will be monitored with approx. 500 sensors for years to verify that the EBS is operating according to the initial assumptions. The FISST test will be used to develop the preparedness for the integrated system test related to the commissioning phase of the disposal facility (Trial Run of Final Disposal, cold commissioning).

4. Critical background information

The EBS is the technical realisation of a safety strategy that has been developed based on a specific radioactive waste inventory and geological boundary conditions as well as a prognosis of future system evolution. Therefore, a broad spectrum of information is necessary to implement deep geological disposal including the corresponding EBS. In principle, starting point of any approach to develop a DGR system is the development of an overall safety strategy on a generic level and considering national and international experiences on mining and disposal-specific R&D. The key data for this work have to be derived from the fields described in the next chapters.

4.1 Geosphere

Description of the geosphere is a basic issue for the characterisation of the properties of the geological and its potential evolution in future. In this context, not only the properties of the rocks and groundwater should be analysed but also recent processes and events should be identified. Geological properties that are relevant for the potential host rock’s barrier functions (confinement of radionuclides) include hydraulic, mechanical, thermal and mineralogical-chemical features. In many countries, criteria and requirements for rock properties have been defined for a site selection procedure to evaluate the suitability of potential host rocks. Furthermore, recent processes in geosphere should be identified and monitored, e.g. groundwater flow or tectonic movements. As a base for the prognosis of the evolution of the geosphere, a site-descriptive model or geosynthesis comprising the relevant geoscientific information and a geoscientific long-term prognosis should be performed. This prognosis is based on an analysis of the geological evolution in the past that can be reconstructed from the properties of the geological sequence and an interpolation of long-ranging processes into the future (actualism principle). This also considers climate evolutions, e.g. glacial periods, that can also have significant impact especially on the overburden formations and ground water (e.g. glacial channels, glacial sediments (glacial loams/tillites, loess, fluviatile gravel). Geosphere defines important boundary conditions for EBS design: litho- and hydrostatic pressures, chemical impact as well as events like earthquakes will be basic loads for EBS design. Furthermore, construction materials and the thermal input of the disposal canisters have to be compatible with the host rock properties. Therefore, a good understanding of geosphere evolution and its interaction with the repository properties are key issues to evaluate long-term safety. The hydraulic properties of the mining induced EDZ significantly influences the sealing properties at the construction sites of the barriers.

4.2 Waste inventory

Many requirements for the operational and the post-closure phase of the repository have to be derived from the provided waste inventory incl. their waste matrices (e.g. borosilicate glass from vitrified reprocessing waste). For the operational period, the waste inventory defines requirements for the radiation protection of the staff and public as well as for corresponding technical measures, e.g. cooling requirements or shielding constraints for disposal casks. During the post-closure period, the properties of the waste inventory influences the temperature development and the radionuclide mobilisation. The species of radionuclides define the decay and the properties relevant for mobilisation and transport in liquid and gas phases, e.g. the solubility and the half-lives. Ionising radiation may result in a radiolysis of fluids and gas generation in the nearfield. Furthermore, the radionuclide species are important with regard to the safety function “retention and retardation of radionuclides transport”, e.g. for the evaluation of the sorption capacity of the construction materials.

Another important characteristic of the waste inventory is the heat generation resulting from radionuclides decay. The limitation of decay heat from the waste packages is a key requirement to ensure compatibility between the waste inventory and the surrounding geological and geotechnical barriers. To avoid for example an alteration of clay minerals in the buffer and the host rock which would result in an impairment of the barrier properties, the maximum temperatures at canister surface have been mostly restricted to 100 °C for disposal in clay formations and crystalline rocks. Those restrictions of canister temperature can be met by adequate interim storage periods for HLW/spent fuel and corresponding canister loading. For salt formations, the potential thermal degradation of carnallitite causing a release of crystal water at temperatures above 167 °C, is a limiting factor to be met by safety distances between disposal areas and carnallitite layers and restrictions of maximum temperature at canister surface. Due to their high safety relevance, requirements for waste packages have to be defined in the waste acceptance criteria. Those requirements have to be met by an adequate waste conditioning and packaging as well as by interim storage for radionuclide decay and temperature decrease. An important aspect for radionuclide release is the occurrence of the volatile radionuclide fraction that can be set free immediately after container failure (Instant Release Fraction (IRF). Those radionuclides are directly released from the waste matrix or are converted to volatile form upon dissolution of the fuel. C-14 is an important component of that fraction. For high burnup UO_2 and MOX fuel, limited information is available on the IRF.

4.3 Disposal canister

Disposal canisters are key components of the EBS in the safety concept and have to consider operational and post-closure requirements. For the operational period there are specific container requirements, e.g. dimensions, maximum weights, trunnions for handling, heat dissipation, and design measures for radiation protection and mechanical stability to mitigate radiological consequences of accidents. Radiation protection means compliance with legal requirements to limit the release of volatile radionuclides on one hand, and shielding to restrict the dose rate resulting from the packages. It has to be demonstrated that the container will resist a number of representative accidents during waste package handling, e.g. drop from a crane, a transport vehicle or into a disposal borehole, or fire loads resulting from the burning of equipment.

For long-term safety, there are different requirements referring to the host rock/disposal specific safety strategy. So the canisters have to resist all impacts from geosphere (chap. 4.1), from the waste inventory and other repository components (chap. 4.2: e.g. decay heat). In disposal concepts for salt and clay formations, the functional period of the disposal canisters is restricted corresponding to requirements for retrieval/recoverability resp. to the end of the thermal phase. Due to the limited retention properties of fractured crystalline rocks, the disposal canisters are the key barriers in those rock types and have to ensure the long-term containment of the radionuclides for the whole demonstration period. Corrosion of the disposal containers significantly influences the future system evolution. So metal corrosion or microbial degradation of organic components (e.g. poly-ethylen moderator material) results in gas generation, which is a transport medium for volatile radionuclides on the one hand and causes an increase of fluid pressure on the other hand. Elevated fluid pressure may impair the functionality of the surrounding buffer and must therefore be taken into account in barrier design. Furthermore, solid corrosion products have a high sorption capacity for different radionuclides and contribute to radionuclides retention. Finally, a corrosion-induced container failure may induce a water intrusion, a corrosion of the waste matrix and radionuclides mobilisation. Therefore, many key processes with regard to long-term safety result from properties and evolutions of the disposal containers.

4.4 Repository design

The repository design has to consider operational constraints as well as requirements from long-term safety, e.g. the EBS. Common strategies to minimise the impact of repository construction and operation on the geological barrier include gentle mining work (minimisation of EDZ), reduction of open excavations (excavate disposal areas on demand), and immediate backfill of completely loaded disposal areas. This strategy is called “mining in retreating mode”. Therefore, a repository includes areas, which are under construction (mining), areas with operation (disposal) work and closed (decommissioned) areas. With regard to the geotechnical barriers it is important to demonstrate that all necessary barrier components can be constructed properly in accordance with detailed design requirements and specifications (constructability, demonstration and verification testing) and that the allocated safety functions can be met (Posiva & SKB 2017). Although the geotechnical barriers will already be installed in decommissioned parts of the repository, there are no safety related requirements for the operation period.

4.5 Interfaces with the EURAD GBS structure

The knowledge on the key issues addressed before has been compiled in different domains of the EURAD Goals Breakdown Structure. The most important interfaces are given with the following domains:

- Domain 1.2.1 (licensing framework) and 1.2.2 (licensing criteria): Important requirements for the safety strategy may be enacted in regulations.
- Domain 1.2.5 (RD&D strategy): In the course RD&D work the understanding of rock-specific processes and the interaction with EBS will be analysed. Furthermore, the technical feasibility and functionality of the barriers will be demonstrated by in situ tests.
- Domains 2.1.1 Waste inventory, 2.2.1 waste characterisation, 2.2.3 waste conditioning define important boundary conditions for EBS planning.
- All domains related to the sub-theme “3.1 wasteform”: 3.1.1 – 3.1.4 SNF, HLW, LL-ILW: define important boundary conditions for EBS planning.
- All domains related to the sub-theme “3.2 waste packages for disposal”: 3.2.1-3.2.3 waste packages are key components of the EBS.

- All domains related to the sub-theme “3.3 buffer, backfill, plugs and seals”: 3.3.1-3.3.3 buffer, backfill and plugs and seals are key components of the EBS.
- 4.1.1 Site descriptive Model: Describe the geological barrier and the environment and loads to be considered in EBS design.
- 4.1.2 Aqueous transport and retention: EBS will contribute to radionuclide retention and transport by a low hydraulic conductivity and a high sorption capacity.
- 4.1.3 Gas generation and transport: Metal corrosion from waste matrices, waste canisters and disposal containers as well as the alteration of organic materials from waste and asphalt from EBS will be the key sources for gas generation in a repository. Gas transport will depend on the hydraulic properties of EBS.
- Domain 4.2.1 Perturbations: Chemical, hydrogeological, geomechanical, thermal, microbiological impacts from facility construction and operations define the boundary condition for installation of EBS. During the post-closure period such impacts may impair the function of the EBS.
- Subtheme “4.3 Long-term stability”: Geological and tectonic evolution (4.3.1) and Climate change (4.3.2) have been addressed. The corresponding geological and climate-induced (glacial) impacts have to be considered for EBS design.
- Domain 4.4.1 Geosynthesis provides a geoscientific synthesis including key information with respect to long-term safety and repository layout and construction. This information is very important with regard to long-term performance of the EBS.
- Theme 5 Disposal facility design addresses different basic issues for EBS, like design specification (5.1.1), design optimisation (5.1.2), constructability, demonstration and verification (5.2.1). Sub-themes 5.4 Operational safety and 5.5.3 Retrievability are especially important for canister design.
- Theme 7 Safety Case, Sub-theme 7.1 Safety strategy defines requirements and performance indicators for the EBS system.
- Domain 7.3.1 Performance assessment and system models quantify the behaviour and evolution of the DGR system incl. the EBS. In this context, uncertainties have to be considered that may deal with by adequate design measures (e.g. redundant multiple barrier system with diverse construction materials, “conservative” dimensioning) (7.3.2). In an iterative procedure, EBS will be optimised based on the results of performance assessment.

5. Maturity of knowledge and technology

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

The EBS is – in combination with the geological barrier – the technical key measure to implement the safety strategy for disposal of radioactive waste and ensures the safe long-time containment of the radioactive inventory. Due to this outstanding importance, great efforts have been directed to this topic in the last decades to increase the knowledge about the properties and future behaviour of barrier components as well as about their technical feasibility and functionality.

The Joint EC/NEA Engineered Barrier System Project (EBSSYN) (Bennett 2010), the Long-term Performance of Engineered Barrier System (PEBS) (Schäfers et al. 2014) and the Full-Scale Demonstration of Plugs and Seals (DOPAS) (White et al. 2016a,b) projects are the most recent compilations of the state-of-the-art of EBS. Summarising the results, international projects succeeded in the design development of EBS for different host-rocks and different disposal strategies. The corresponding investigations included large-scale in situ tests in URLs that demonstrate the technical feasibility and functionality of the barriers. The understanding of key processes in recent or future geosphere and in the mine excavations has been significantly improved.

5.1 Advancement of safety case

The EBS is the technical realisation of the safety strategy and therefore has a central role in the safety case for disposal. A basic issue for the EBS design and the performance/safety assessment is the comprehensive understanding of the evolution of the geosphere and the repository components as well as all relevant processes and events, that occurred recently and those that will occur in future. While most recent properties of geosphere and components as well as ongoing processes and events can be accurately and with sufficient completeness described, uncertainties significantly increase for the prognosis of future evolutions. The optimisation of the EBS is an iterative process referring to the results of numerical model calculations performed for the safety case.

The EBS components have to fulfil multiple safety functions in the safety case that may be diverse in the different phases of DGR evolution, e.g. disposal containers have to comply with several operational requirements for waste transport, handling and disposal as well as for worker protection (e.g. by shielding). Furthermore, depending on the host rock type and the corresponding safety strategy, disposal containers will ensure radionuclides containment for the initial post-closure period in salt and clay formations and for the whole demonstration period in crystalline rocks. To increase confidence in the safety of disposal, the safety case has to rely on a multiple barrier system to fulfil multiple safety functions and defence in depth. Furthermore, the EBS plays an important role in other key safety case arguments related to feasibility, monitoring, reversibility of waste disposal operations and waste retrievability.

In host rocks with less performance in containment and retardation of radionuclides (e.g. fractured hard rocks) the EBS may provide the most important barriers with regard to long term safety. Even in these cases, the geosphere may contribute to safety by providing isolation of the waste from biosphere, by ensuring a favourable hydrochemical environment and by appropriate hydraulic and mechanical properties to enable the EBS to perform as intended. As examples for disposal strategies in crystalline rocks, SKB and POSIVA made significant progress by defining safety functions, performance targets, and design requirements for all necessary EBS components as a basis for their safety cases (Posiva & SKB 2017).

Due to the close linkage between EBS and safety case, the increase of knowledge on properties of the barriers and the understanding of related processes during the last decades as well as experiences from barrier construction give important input to the performance assessment. A step towards methodological harmonisation and consistency between EBS design and performance/safety assessment as well as transparency and confidence building is the reference to common basic tools – the FEP catalogue and the scenario development (Lommerzheim & Müller-Hoeppe 2022, Simo et al. 2021).

5.2 Optimisation challenges and innovations

A large challenge with regard to the development of an adequate EBS design is the handling of uncertainties with regard to the future evolution of the repository system and the corresponding performance assessment. Therefore, a methodology for EBS design and evaluation has been developed linking the technical approach of EUROCODE with the basic tools for uncertainty handling in the safety case (FEP catalogue and scenario development) (Lommerzheim & Müller-Hoeppe 2022, Simo et al. 2021). The approach of EUROCODE demands the concept of 'ultimate limit states' in combination with the 'partial safety factor method'. For the functional demonstration (performance assessment), different actions (“processes” in the FEP catalogue), the barrier resistances (“features” of components in the FEP catalogue) and the design situations (“scenarios”) have to be determined to define the load cases. For these tasks, the specific evolution in the nearfield and far-field of the barriers has to be analysed by means of the information compiled in the FEP catalogue. The design situations can be derived from the expected scenarios as well as the alternative scenarios. For the numerical functional demonstration of the EBS, hydraulic, hydromechanical, thermal and chemical load cases have to be defined covering the most relevant impacts. The design of the barriers has to be robust for the boundary conditions defined by the expected scenarios. The consequences of the failure of a barrier on the repository system evolution will be analysed in alternative scenarios.

The successful installation of more than 40 seals at the German Asse mine demonstrates the high maturity of the procedure to design and install the geotechnical barriers in salt formations in industrial scale (Engelhardt et al. 2021). The construction material was a site-specific recipe of magnesia concrete. After completion of construction, each barrier was analysed for compliance with the barrier requirements.

For closure of the German Morsleben repository, the recipe for the magnesia concrete has been adapted site-specifically (Mauke 2016). For adequate barrier installation, the limitation of cracks resulting from concrete setting is a challenge (Effner et al. 2021). Furthermore, the functionality of the drift seals in salt formations demands the fixation of the barrier in the contour of the mine excavation to close the contact zone and the EDZ. In halite formations, barrier fixation will be assured by convergence, while hard, rigid anhydrite formations are characterised by the absence of convergence. Therefore, the construction of a barrier in those rocks is a special challenge and need an adaption of the corresponding barrier design. A swelling magnesia shotcrete will be used to close the contour gaps and asphalt sealing elements will instantaneously seal the contact zone and the EDZ.

Different kinds of bentonite are favourite sealing materials for disposal concepts in clay or crystalline rocks. Numerous studies have been carried out to analyse the properties and understand the clay-specific processes such as saturation and swelling. ONDRAF-NIRAS developed an innovative canister concept for disposal in Boom Clay, called “supercontainer” (ONDRAF-NIRAS 2004). This concept is characterised by assembling the waste, the disposal container, a stainless steel overpack, a Portland concrete buffer and a carbon steel overpack. It is the objective of the supercontainer concept to ensure defined boundary conditions for the evaluation of the long-term evolution of the container and thus to increase the accuracy of the prognosis. Key component of the supercontainer is the concrete buffer that has a low hydraulic conductivity and provides a high-pH environment for the thermal phase to limit the container corrosion. Modified supercontainer types (with a bentonite buffer) have also been analysed for disposal concepts in crystalline rock (SKB/POSIVA 2008). Another type of prefabricated barrier components are highly compacted bentonite blocks for the buffer and other engineered barriers that can comply with defined construction material properties (saturation, density, geometry of elements etc.) and corresponding quality assurance requirements.

5.3 Past and ongoing (RD&D) projects

Most recent compilations of the results of some former RD&D key projects are given in the Joint EC/NEA Engineered Barrier System Project (EBSSYN) (Bennett 2010), the Long-term Performance of Engineered Barrier System (PEBS) (Schäfers et al. 2014) and the Full-Scale Demonstration of Plugs and Seals (DOPAS) (White et al. 2016a,b) projects.

Ongoing RD&D:

Numerous RD&D projects are ongoing. They are dealing with key issues like technical measures for sealing flow paths at the barriers (contact zone, EDZ) and optimisation of numerical tools for performance assessment. Examples for R&D projects are given below.

- PRECODE (BGE-project (Germany)): Development of injection techniques to improve the EDZ in hard rocks (Herold et al. 2022).
- PIONIER (EURAD project):: Implementation and enhancements of constitutive laws for clay formations and bentonite (Simo et al. 2022).
- BEACON (Euratom research and training programme): Bentonite mechanical evolution; Project includes six work packages and deals with the analysis of results from laboratory tests, in situ tests, model development, verification and validation (Westermark 2022).
- RANGERS (funded by BMWi (Germany)): Methodology for design and performance assessment of geotechnical barriers in a HLW repository in salt formations (Kuhlmann et al. 2022).
- STROEFUN (funded by BMWi (Germany)): Fluidic functional verification for closing structures and fluid-based sealing of the contact zone (Bauermeister & Müller-Hoeppe 2022).

Furthermore, a broad spectrum of RD&D work on EBS resp. on the interaction between EBS and geosphere is ongoing or will be started in international URLs. The corresponding information can be acquired from the corresponding homepages ((e.g. www.grimsel.com, www.mont-terri.ch, https://international.andra.fr/meusehautemarne.andra.fr/, www.euridice.be, https://www.skb.com/research-and-technology/laboratories/the-aspo-hard-rock-laboratory/).

5.4 Lessons learnt

The reports on joint EC/NEA of the previously mentioned and described projects (see Section 5.3) describe the preparation, the installation and the performance of some large-scale in situ tests for components of the EBS in different host rock types and disposal strategies. Furthermore, the results of the long-term tests have been summarised and discussed.

In summary, the most important lessons learnt from past work include the demonstration of feasibility and functionality of different kinds of technical and geotechnical barriers as well as a significant increase of knowledge on key processes and phenomena that interact with the barriers and that are important for the functionality. It is recognised that the EBS is a system of components instead of a series of independent barriers, which works in combination with the host rock and thus offers an acceptable level of safety. Each component of EBS will have its own safety functions, but the performance of the whole system is most important.

EBS design and optimisation is an iterative process starting with the basic safety strategy. Next steps of the process of design and optimisation include:

- Definition of requirements of the disposal system and the EBS (referring to waste-specific and site-specific constraints),
- Understanding of construction material properties and processes that may affect them,
- Adequate modelling and performance assessment of the EBS,
- Demonstration of technical feasibility of EBS components (manufacturing, construction, installation),
- Demonstration that the EBS will provide an acceptable level of safety during operation and after repository closure (performance assessment).

This step-wise approach of EBS design and optimisation is followed by most waste management organisations (WMOs) (along with stepwise repository and safety case development). Simplifications and conservative assumptions during safety assessment modelling are often necessary. While conservatism can be convenient for demonstrating compliance with requirements, it is more useful for optimisation of EBS design to refer to assessment models that are as realistic as possible. Otherwise, conservative assumptions may lead to sub-optimal design decisions and unnecessary costs. Therefore, optimisation of numerical modelling and uncertainty management remain key issues.

As a result of discussions on safety demonstration methodology, the application of safety function indicators and criteria in the safety case has significantly increased. To increase transparency and traceability, well structured, decision-supporting processes and option evaluations are very useful. Requirement management is an issue especially for advanced projects but should be implemented already in early phases of repository programmes (subject to EURAD WP 12).

With increasing progress of RD&D work on EBS, operational aspects and feasibility assessments and demonstrations became more important as complements to performance and safety assessments as well as for associated RD&D work.

6. Uncertainties

Uncertainty management is a key issue in all steps of the DGR roadmap and in the safety case. It is also very important with regard to confidence building. In the context of a complex safety case, a broad spectrum of uncertainties referring to data, parameter, models, scenarios etc. have to be considered and can be handled by well-established measures. It is well-known that many uncertainties are related to the characterisation of geosphere, the prognosis of future evolution, but also to model definitions that include simplifications and abstractions. All of those uncertainties are also important for EBS design.

Numerous URL impart comprehensive generic knowledge on host-rock specific properties and related processes as well as their interaction with repository specific components. Therefore, plausible assumptions are possible with regard to the future repository evolutions. On this basis, safety strategies and EBS have been developed for different host rock types. The feasibility and functionality of many EBS components have already been analysed in large-scale in situ tests. This includes specific construction materials (e.g. bentonite, concrete) that can be adapted to different hydrochemical environments. Therefore, the barrier constructions are compatible with geosphere and may be stable for the provided functional period. Thus, their properties and their behaviour during repository evolution seem to be well predictable. Nevertheless, some questions are still open or the evolution is not yet fully understood. Some high-level questions and corresponding recommendations for future work have been compiled in the EBSSYN, PEBS and DOPAS projects and are summarised below. As the general understanding of the EBS is already sophisticated, future work prioritizes questions regarding construction procedures including quality assurance.

Thus, based on the results and questions identified in the EBSSYN project (Bennett 2010) the following recommendations for future work on EBS have been given:

- Optimisation of disposal concepts, e.g. by including super containers or pre-fabricated EBS (buffer, components of shaft and drift seals),
- Optimisation of EBS design by referring to requirements management and safety functions,
- Expanding feasibility assessment to all necessary components,
- Consideration of operational experience in EBS optimisation,
- Reduction of simplifications/conservative assumptions in numerical models for EBS design.
- The PEBS report (Schäfers et al. 2014) added recommendations and future perspectives for clay-based barriers:
- Long-time observations (10-20 years) on bentonite performance,
- Impact of temperatures above 100 °C on swelling pressure and strength of the EBS material (bentonite),
- Potential impact of very long saturation times (thousands of years) on EBS performance,
- Further investigations on THMC-processes at material interfaces (e.g. cement-bentonite, cement-host rock) with special focus on porosity determination and the nature of alteration,
- Understanding of the correlations between geophysical parameters and the rock properties,
- Continuation of existing long-term experiments to identify processes potentially relevant for the long-term THM behaviour of the EBS (e.g. thermo-osmosis, double porosity, creep) and to reduce uncertainty in model parameters,
- Calibration of enhanced numerical models developed within the PEBS framework and their application for long-time simulations,
- Investigation of alternative numerical models , e.g. based on the continuum mixture theory,
- Improvement of the predictive capability of geochemical modelling by extensive model testing and supporting data.

The final report of the DOPAS project (White et al. 2016b) addresses remaining issues associated with plug/seal design and the next steps in industrialisation of plug/seal installation and gave the following key recommendations for future work:

- Use of the DOPAS design basis development methods, including the corresponding workflow, to adopt system engineering approaches for other elements of the EBS.
- Implementation of requirements management systems to develop comprehensive design bases in formalised hierarchies and to assure effective and efficient processes.
- Revision of reference designs for plugs and seals, and verification of compliance with the design basis.
- Clarification on the requirements of the rock adjacent to plugs and seals to support the siting of the structures.
- Adaption of the plug/seal slot excavation techniques to the site-specific conditions at repository sites.
- Evaluation of the requirements on bentonite homogeneity and greater understanding of homogenisation processes for bentonite seals.
- For self-compacting concrete: optimisation of delivery and logistical issues as part of the industrialisation of plugging and sealing.
- For shotcrete: improved recipes and delivery/installation methods (e.g. reducing rebound to ensure a more homogeneous product).

- Development of strategies for monitoring of plugs and seals based on relevant and mea-surable parameters, and linked to the needs of the safety case.
- Industrialisation the plug/seal implementation, including development and documentation of construction processes and quality control programmes.

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 EBS.

The main goal of EURAD Work Package (WP) 13 is to establish the ‘School of Radioactive Waste Management (RWM)’.

OECD-NEA published several key documents regarding the importance of the EBS in the safety case as a result of the EBSSYN project (Summary in Bennett 2010). Furthermore, the relevance of EBS in the context of safety strategy, safety case and safety assessment has been described in the NEA report on the “Nature and Purposes of the Safety Cases for Geological Repositories” (NEA 2013). Additionally, OECD-NEA implemented the “Integration Group for the Safety Case (IGSC)” as a main technical advisory body to the “Radioactive Waste Management Committee (RWMC)” on the deep geological disposal of long-lived and high-level radioactive waste to foster full integration of all aspects of the safety case. Because EBS and safety cases are closely connected, the relevance of EBS is also discussed in this group, with an increasing focus on feasibility issues, operation and requirements management. The task of the IGSC is to assist member countries to develop effective safety cases supported by a robust scientific-technical basis. Furthermore, the group provides a platform for international dialogues between safety experts to address strategic and policy aspects of repository development. The IGSC is supported by four subgroups carrying out tasks on specific topics, e.g. Clay Club, Salt Club, Crystalline Club and the Expert Group on Operational Safety (EGOS). Work of IGSC is closely linked to IAEA and EC groups.

IAEA is another international guiding authority that publishes several Safety Guides and TECDOC addressing the functions of EBS during the different phases of DGR system evolution and for the safety cases, e.g. IAEA 2011, 2012, 2016.

Information on implementing in situ tests, a corresponding monitoring and RD&D programmes can be acquired from the webpages of those WMOs that operate URLs and publish their results online (e.g. www.grimsel.com, www.mont-terri.ch, https://international.andra.fr/meusehautemarne.andra.fr/, www.euridice.be, https://www.skb.com/research-and-technology/laboratories/the-aspo-hard-rock-laboratory/)..

With regard to education and on-the-job training of students and young colleagues, many WMOs have implemented adequate programmes that are often linked with lectures at universities. Furthermore, training courses are commonly offered at underground research laboratories (e.g. Grimsel URL, Mont Terri URL, Bure URL, ÄSPÖ URL, see links above).

The DECOVALEX project is an international research and model comparison collaboration, initiated in 1992, for advancing the understanding and modelling of coupled THMC processes in geological systems. Prediction of these coupled effects is an essential part of the performance and safety assessment of geologic disposal systems for radioactive waste and SNF, and also for a range of sub-surface engineering activities. The project has been conducted by research teams supported by a large number of WMOs and regulatory authorities. Research teams work collaboratively on selected modelling cases, followed by comparative assessment of model results. This work has yielded in-depth knowledge of coupled THM and THMC processes associated with nuclear waste repositories and wider geo-engineering applications, as well as the suitability of numerical simulation models for quantitative analysis. Information on running RD&D work and results is given at https://decovalex.org/.

Training
www.grimsel.com, *www.mont-terri.ch*, *https://international.andra.fr/meusehautemarne.andra.fr/*, *www.euridice.be*, *www.skb.com/research-and-technology/laboratories/the-aspo-hard-rock-laboratory*

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