Note:
This is a translation of the ESK statement entitled
“Sicherheitskonzeptionelle Anforderungen an das Barrierensystem eines Endlagers für hoch radioaktive Abfälle und deren Umsetzbarkeit”
In case of discrepancies between the English translation and the German original, the original shall prevail.

E S K

Safety concept requirements for the barrier system of a disposal facility for high-level radioactive waste and their implementability

STATEMENT of the Nuclear Waste Management Commission

CONTENTS

1 Background

According to § 1(3) of the Act on the Search for and Selection of a Site for a Disposal Facility for High-Level Radioactive Waste (Site Selection Act, StandAG) [1], in Germany, rock salt, claystone and crystalline rock[1] are generally considered as potential host rocks for the disposal of high-level radioactive waste. The three host rocks differ in particular in the extent to which low-permeability to impermeable geological layers (geological barrier) contribute to the containment of the radionuclides and thus to the long-term safety of the disposal facility (see § 23(1) [1]). While in disposal systems, the geological barrier is the main barrier in rock salt and claystone, the engineered barriers are the main barriers in crystalline rock.

The safety concept describes the requirements to be met by the components of the disposal system, taking into account the corresponding periods of effectiveness. Based on the safety concept, concrete requirements are derived for the disposal facility site, the disposal concept, the disposal facility design and the assessments to be performed. Different international safety concepts have been developed for the host rocks mentioned above. A comparison of the barrier systems tailored to Germany must take into account that different regulatory framework conditions exist in different countries. If these safety concepts developed abroad are also to be adopted in Germany, the boundary conditions under which a host rock abroad was selected and a concept for a barrier system for this host rock was developed must be taken into account.

Within the framework of the German site selection procedure, different sites with different host rocks and different safety concepts have to be compared with each other. Therefore, it is necessary to discuss the requirements of the barrier systems in general and to explain to what extent the requirements in [1] can in principle be met with the barrier systems described. This is regarded as the basis for further regulatory work, in particular on the proof of containment by safety analyses. However, the actual fulfilment of the requirements can only be demonstrated site-specifically. Further site-specific requirements to be fulfilled for the barrier system could also arise.

2 Consultations

At its 59th meeting on 07.09.2017, the Committee on FINAL DISPOSAL (EL) of the Nuclear Waste Management Commission (ESK) had decided to separate its reflection on the safety concept requirements for the barrier system from the reflections on the procedure for defining the containment-providing rock zone (CRZ) and to set up an ad hoc working group for drafting a statement on the topic “safety concept requirements for the barrier system”. The present document was discussed at the 64th to 67th meeting of the EL Committee on 07.06.2018, 06.09.2018, 18.10.2018 and 05.12.2018 as well as at the 73rd and 74th meeting of the ESK on 24.01.2019 and 21.02.2019 and adopted at the 74th meeting of the ESK on 21.02.2019.

[1] In the following, for the sake of simplicity, the terms “rock salt”, “claystone” and “crystalline rock” are used (see § 1(3) in [1]), irrespective of the fact that all three potential host rocks are usually characterised by a certain variation in their barrier properties based on their mineralogical composition and spatial structure. Accordingly, they have to be assessed on the basis of the local situation.

3 Regulatory requirements for the barrier system

3.1 Barrier requirements in the Site Selection Act

Disposal facility barriers are those components of a disposal system that limit or prevent the migration of radionuclides (see § 2(7) and (8) in [1]). Geological barriers include those rock zones that contribute to the containment or retention of radionuclides. Engineered and geotechnical barriers are engineered units which also limit or prevent the migration of radionuclides (see § 2(8) in [1]). Geotechnical barriers include, for example, drift and shaft seals. Engineered barriers are e.g. waste containers and the waste matrix itself.

Within the barrier system, radioactive and other pollutants shall be concentrated and contained in order to keep them away from the biosphere (see § 26(2) in [1]). The barriers in their interaction must ensure the safe confinement of radionuclides for one million years, i.e. there must be no findings or data that would cast doubt on the preservation of the barrier effect over a period of one million years (see § 23(5) in [1]). For that purpose, knowledge on the manufacturing quality of the engineered and geotechnical barriers and their ageing under disposal conditions at the respective site shall be taken into account (see § 24(2) in [1]).

Areas where, in principle, the best possible site can be found shall be protected against changes that could affect their suitability. To protect the geological barrier, the drilling of boreholes into the geological barrier is limited. In addition, it is required that the boreholes or the measures associated with these boreholes cannot significantly damage rock strata which can provide long-term protection of underlying layers suitable for disposal or which can act as an additional barrier for the disposal facility in the long term (see § 21(2) in [1]). Likewise, influences from previous mining activities that impair the barrier effect must be taken into account. Furthermore, existing old boreholes must demonstrably not impair the barriers of a disposal facility that ensure safe containment in their containment function (see § 22(2) in [1]).

For disposal systems that are essentially based on a geological barrier (i.e. disposal facilities in rock salt and claystone), a CRZ is defined as the part of the rock which (together with the engineered and geotechnical barriers/seals) ensures safe containment of radioactive waste in a disposal facility (see § 2(9) in [1]). For all disposal systems, i.e. also those whose containment capacity is essentially based on engineered and geotechnical barriers, an emplacement zone is defined which also includes the zone of the rock that ensures the functioning and the preservation of the barrier system (see § 2(10) in [1]). The disposal system consists of various components, the coaction of which ensures safe containment of the radioactive waste; these comprise the disposal mine, the barriers and the geological strata surrounding or overlying the disposal mine and the barriers (see § 2(11) in [1]). Since containment for a disposal system essentially based on engineered and geotechnical barriers (i.e. for a disposal facility in crystalline rock) is ensured by these same barriers, safe containment by the geotechnical and engineered barriers over one million years must be demonstrated for this disposal system instead of a demonstration based on low rock permeability (see § 23(4) in [1]). The containment capacity of the engineered and geotechnical barriers is to be determined, taking into account the expected site-specific ageing of the components. The evidence of the quality of the containment by the barrier system shall be robust (see § 24(3) in [1]).

The CRZ is the central element for a disposal system essentially based on a geological barrier. §§ 22 to 24 in [1] lay down site selection criteria and requirements for the CRZ. For disposal systems in which containment is essentially based on engineered and geotechnical barriers, the criteria formulated with reference to the CRZ largely apply as far as possible. For such disposal concepts, the consideration also includes the rock zone that ensures the integrity of the engineered and geotechnical barriers. This is in particular the rock body directly around the emplacement cavities, which protects the containers and the buffer material against external influences.

The barrier effectiveness of a disposal system based on a geological barrier is assessed, among other things, on the basis of the barrier thickness and the degree of enclosure of the emplacement zone (Appendix 2 in [1]). In addition, there is the depth below surface of the CRZ (if definable) as well as the possible impairment of its barrier effect by the proximity to rocks with increased hydraulic potential. The spatial characterisation of the main geological barriers should be reliably possible. Corresponding indicators are the possibility to identify the relevant rock types and their properties, the transferability of these properties (Appendix 3 in [1]) as well as the experiences on the barrier properties and the barrier effectiveness of the rock formations (Annex 6 in [1]). The barrier-effective rocks of a CRZ should have a rock permeability as low as possible and a retention capacity as high as possible with respect to radionuclides relevant over the long term (Appendix 9 in [1]). The material of engineered and geotechnical barriers should behave largely chemically inert towards the existing deep waters and mineral phases of the surrounding rock zone (Appendix 10 in [1]). According to § 22 in [1], geologically active fault zones are also an exclusion criterion if they are present in the rock zones considered for disposal, including a conservative safety distance, and they could impair the disposal system and its barriers.

3.2 Other barrier requirements

On the basis of § 26 in [1], the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) is currently drafting an ordinance on safety requirements for the disposal of high-level radioactive waste. The draft of this ordinance is available to the ESK; it has extracted further requirements for a barrier system from it.

A robust, multi-barrier system is designed to meet the requirements passively and maintenance-free. A distinction is made between “main” and “other” barriers. The main barriers are those on which the containment in the disposal system is essentially based; these are either

a the geological barrier and the geotechnical barriers (in rock salt or claystone), or
b the engineered and geotechnical barriers (in crystalline rock) – if no CRZ can be identified in the crystalline rock

The other barriers are all geological, engineered and geotechnical barriers which, in a disposal system, in addition to and in coaction with the main barriers, limit or prevent the migration of radionuclides. The main and other barriers of the disposal system must be effective together in such a way that the disposal system retains its functionality to a sufficient extent even for deviating evolutions and that releases of radionuclides from radioactive waste are kept to a minimum.

The exclusion of criticality has to be ensured with the chosen barrier system. It has to be demonstrated that for the operating phase as well as for expected and deviating evolutions during the demonstration period, self-sustaining chain reactions are excluded. As the immediate surrounding of the waste, the barrier system has to make a significant contribution to this requirement.

The barrier system consisting of (the main) geological, geotechnical and engineered barriers must ensure the containment of radioactive waste during the demonstration period. For the individual barriers, their functional capability and the coaction of the barriers in the barrier system are essential. For this purpose, it has to be demonstrated that the barrier system integrally fulfils the requirements of containment and preservation of the containment properties during the demonstration period.

The properties of the barriers must therefore be verifiable. It is to be demonstrated that the relevant properties of the engineered and geotechnical barriers are preserved at least for the period during which these barriers are required for the safe containment of the radioactive waste in accordance with the safety concept. It is also to be demonstrated that it is possible to create and build the required number of barriers, including quality assurance in accordance with the state of the art in science and technology. Construction, emplacement and function of these barriers must have been successfully tested unless their robustness can be demonstrated otherwise. Furthermore, it is to be demonstrated that the properties of the other barriers of the disposal system that are relevant for the preservation of integrity are preserved at least for the period of time required for the safe containment of the radioactive waste in accordance with the safety concept.

The entire barrier system must be designed for robustness. Robustness is defined as the insensitivity of the safety functions of the disposal system and its barriers to internal and external influences and interference as well as the insensitivity of the results of the safety analysis to deviations from the assumptions made. Part of the robustness are also the safety margins in the barrier system. Robustness and preservation of the integrity of the CRZ have to be proven for the demonstration period with regard to the expected evolutions.

4 Task of the barrier system

The barrier system of a disposal facility comprises all engineered, geotechnical and geological barriers. The main barriers must ensure containment of the radionuclides. The barrier system separates the waste from the surrounding geosphere and the part of the geosphere that does not contribute to the containment of the waste. The task of the barrier system is to contain the radionuclides in the disposal facility and to isolate the radioactive waste from the influence of external chemical and physical processes (Figure 4.1).

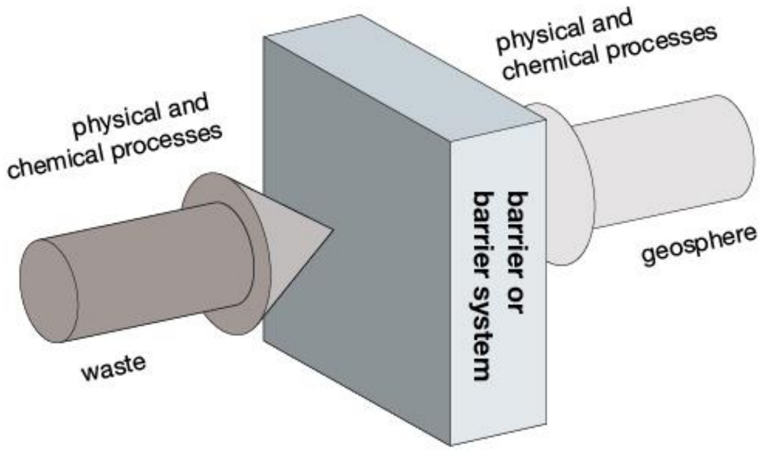

Figure 4.1: Principle of a barrier or barrier system as a separating element between waste and the part of the geosphere that does not contribute to containment.

The effectiveness of individual barriers may change over a period of one million years (see § 1(2) in [1]). The barrier system is to be designed in such a way that the transport of radioactive substances from the disposal facility or the transport of substances that may accelerate their transport to the outside (in particular water or solutions) into the disposal facility is prevented, limited or delayed in the long term.

5 Requirements for the barrier system

In order to implement the objective formulated in Chapter 4, requirements are placed on the barrier system. These can be subdivided into regulatory requirements for the barriers to be fulfilled in accordance with StandAG [1] (see Chapter 3.1) and requirements for the barriers to be considered beyond (see Chapter 3.2):

Requirements to be fulfilled from StandAG [1]:

- **Containment effectiveness:** The barrier system has to prevent the influx of water/solutions to the waste and the migration of radionuclides from the emplacement zone and to slow down processes contributing to the increased migration of radionuclides as long as possible (see § 26(2) in [1]).

- **Durability:** The barrier system must be established as a system being effective in the long term (see § 1(2) in [1]). The radiological protection objectives must be met by retention of the radionuclides over the period required by law. The barriers should mutually support each other in their durability.

- **Compatibility:** The individual barriers must be adjusted to each other and there must be no significant mutual impairment of barrier effectiveness between the barriers due to internal or external processes (e.g. temperature tolerance, Appendix 8 in [1], chemical interactions, Appendix 10 in [1]).

- **Technical feasibility:** The intended barrier system must be technically feasible. Simple implementations are preferable to complex ones if they can achieve the same effect.

- **Retrievability:** The barrier system must allow the possibility of retrieving the waste during the operating phase (see § 26(2) in [1]). The effectiveness of the barrier system must not be impaired by measures taken to ensure retrievability.

- **Enabling recovery:** Adequate provisions must be in place for a potential recovery (see § 26(2) in [1]). Such provisions must not impair the effectiveness of the barrier system.

- **Freedom from maintenance:** After sealing of the disposal facility, further adjustments to the barrier system must no longer be required; it must be able to be effective passively (see § 26(2) in [1]).

In addition, according to the ESK, the following requirements have to be complied with:

- **Criticality exclusion:** The barrier system must ensure that, despite existing waste concentration and long-term processes, a state is never reached that can lead to criticality.

- **Functional effectiveness:** The barrier system has to take effect with the sealing of the disposal facility. This means that in the case of geotechnical barriers, at least one functional element demonstrably assumes a sealing effect at the time of the disposal facility sealing (immediately effective sealing element). Further functional elements can develop their sealing effect later.

- **Verifiability:** It must be possible to verify the natural conditions relevant to long-term safety (e.g. geometries of host rock bodies, fault locations). The compliance of the existing or emplaced barriers with the requirements/specifications must be verifiable covering all of them to the largest possible extent before commissioning of the disposal facility.

- **Robustness:** The barrier system is to be designed such that its safety functions are insensitive to internal and external influences and interference and that the results of the safety analysis are insensitive to deviations from the assumptions made.

The following chapters present exemplary barrier systems for the host rocks crystalline rock (Chapter 6), rock salt (Chapter 7) and claystone (Chapter 8) that are used in disposal facility projects. For crystalline rock, the existing concepts in Sweden and Finland were used as a basis, for rock salt the concept in Germany and for claystone the existing concepts in France and Switzerland. The requirements formulated above are considered on the basis of the safety concepts of the disposal systems in these host rocks on which these barrier systems are based. The extent to which the formulated requirements can principally be fulfilled are examined.

It is not the subject of this discussion paper to show that the barrier systems used here as examples from the international context comply with German regulations. It is only examined whether they can principally be fulfilled. A fundamental review cannot be anticipated with the general considerations made here. It remains reserved for the site selection process including concrete sites and safety concepts. Whether the formulated requirements are actually fulfilled at a selected site is also to be checked taking into account the site-specific investigation results (and the additional requirements for the barrier system that may result).

Nor is the discussion paper intended to assess the extent to which the individual proposed engineered and geotechnical barriers have already been implemented in a tested and approvable manner. This applies in particular to the barrier of the disposal container, which, depending on the barrier system chosen, must fulfil corresponding requirements for long-term containment, retrievability or the possibility of recovery. The ESK confines itself to making a technical assessment.

6 The barrier system in crystalline rock

6.1 Safety concept and barrier system

Unfractured crystalline rocks are rocks with high containment capacity. Based on the geological history of crystalline rocks and their brittle mechanical behaviour in the upper kilometres of the earth's crust, the geological findings (due to surface mapping and mining) as well as the tectonic overprinting of the old crystalline massifs existing in Germany, unfractured rocks are not to be expected in disposal depth and in the necessary extent.

For crystalline rocks with mineralised fissure systems (i.e. fracture systems along which, for example, mineral transformations and new clay mineral formations have taken place), depending on the degree and type of fracture filling, increased containment-providing or retention properties may be conceivable. Although it is likely that fractures have been mineralised due to the geological history of crystalline rocks, providing evidence of existing fractures and mineralisation is only possible to a very limited extent with the available geophysical methods. In addition, it must be expected that new fractures will be formed in the course of the required long demonstration period.

The safety concept assumed here for a disposal facility for high-level radioactive waste in crystalline rock is based on the principle of concentration and long-term containment of radioactive waste in the disposal container, which is the main barrier here (in contrast to the barrier systems for rock salt and claystone) (see § 23(4) in [1]). Inside a disposal container, the waste forms, e.g. fuel matrix and cladding tubes or glass matrix and stainless steel canister, may also have barrier functions (Figure 6.1). The disposal container is surrounded and protected by a subsequent barrier composed of highly compacted bentonite under rock pressure. The bentonite also serves to protect against mechanical influences and, as a hydrochemical buffer, is intended to limit the transport of water and corrosive groundwater components to the container surface. The bentonite has a high retention capability for any released radionuclides. The barrier host rock has only a subordinate retention function. Crystalline rock, however, offers long-term stable mechanical protection of the inner barriers.

Based on the safety concept, concrete requirements are derived for the disposal facility site, the disposal concept, the disposal facility design and the assessments to be performed.

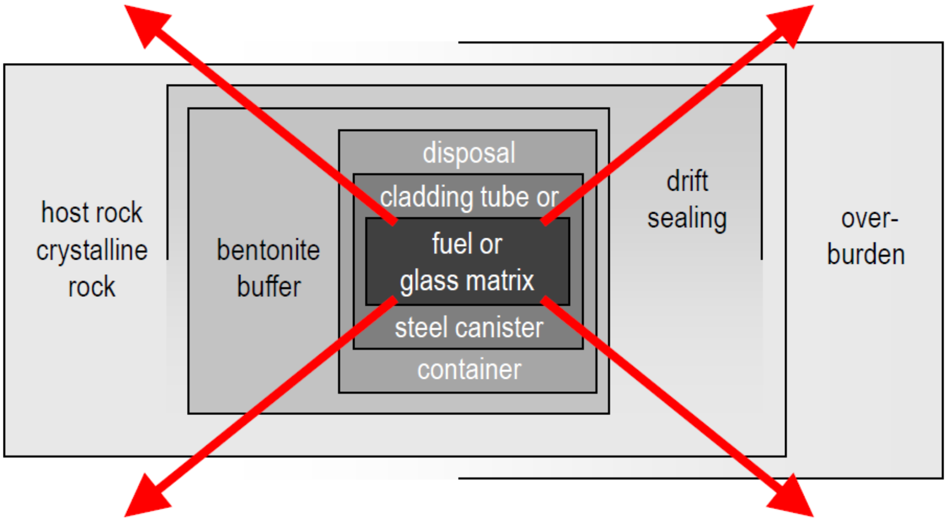

Figure 6.1: Concept of a barrier system in crystalline rock. The red arrows point to different transport paths, some of which do not pass sequentially through all parts of the barrier system or affect parts of the local geological setting (existing or non-existing overburden) that do not contribute to containment.

The essential elements of the safety concept for disposal systems in crystalline rock are based on the following properties of crystalline rock (see Table 3-4 in [2]):

- crystalline rock has good rock-mechanical properties, which allow for excavations with high stability without supporting structures,
- crystalline rock can form extended bodies with large lateral and vertical extent and often good central homogeneity in which emplacement zones can be located flexibly,
- crystalline rock has a medium-range thermal conductivity (compared to other rocks, [3]) and a low coefficient of thermal expansion, which causes only limited thermally induced stresses when emplacing high-level radioactive waste,
- crystalline rock has very low hydraulic permeability and water contents < 0.5 % in unfractured areas,
- crystalline rock is very weakly soluble in water and very resistant to erosion,
- secondary clay minerals with increased sorption capacity can form in the crystalline rock fracture systems.

It has to be taken into account that

- crystalline rock often has weakly alkaline, comparatively low mineralised pore waters and colloidal radionuclide compounds are stabilised and mobilised in solution under such conditions,
- crystalline rock is practically exclusively in a fractured state and the existing interconnected fracture systems can only be detected to a very limited extent.

The main resulting technical and conceptual measures are as follows:

- For emplacement, a weakly fractured rock body is sought which is well predictable with regard to existing fractures and which is located in a tectonically calm environment (minor uplift, low seismicity)
- For the containment of the radionuclides, a disposal container system with a lifetime of approximately one million years (very low corrosion rates) and controllably high production quality is to be provided.
- In order to reduce the effect of water influx through fracture systems, the individual disposal containers are to be enclosed with other barriers of sufficiently insulating and retaining material (bentonite buffer).

Safe containment (or long-term retardation of radionuclide transport) is ensured by a sequence of barriers. The system of staged safety-relevant components consists of several engineered barriers and at least one geotechnical barrier. The natural barrier has a supporting function. The barrier system comprises the following barriers based on the Swedish KBS-3 concept [4]:

- the waste form, consisting for Germany either of spent fuel (fuel pellets, which, with few exceptions, are surrounded by intact fuel rod cladding tubes) or of waste products from reprocessing (glass matrix in tightly welded stainless steel canisters),
- the disposal container as the most important barrier, which is to contain the radionuclides over a long period (in Germany over a period of one million years),
- a bentonite buffer that fills voids in the emplacement boreholes, contributes to the safe containment of the waste packages, minimises the influx of water, creates favourable hydrogeochemical conditions for the slowest possible corrosion of the disposal containers, hinders microbial growth and is intended to retain radionuclides in the long term in the event of incipient loss of tightness of the disposal containers,
- drift sealing (as an abutment for the bentonite and for the hydraulic separation of the backfilled transport and access galleries from non-safety-relevant parts of the disposal facility and accesses to the surface, to limit the flow of fracture waters and for the thermal buffering and sorption of escaping radionuclides), as well as
- the fractured crystalline rock (among others for long-term mechanical protection of the main barriers).

Variants of the KBS-3 concept differ in that the disposal containers are emplaced vertically (KBS-3V concept [4] or horizontally (KBS-3H concept [5]). Finland and Sweden have also proposed slightly different barrier systems for horizontal emplacement with the use of so-called "supercontainers" (copper-coated disposal containers surrounded by bentonite and an outer perforated metal cylinder made of titanium) [5]. Alternatively, concepts have been proposed in which a hard rock abutment is placed above the bentonite buffer (see Chapter 9.1 in [6]). This abutment can be made of crushed excavated material and serves in particular to fix the bentonite buffer in its position. To improve the retrievability and enable recovery, a cast iron liner has also been proposed to line the emplacement section against the host rock (see Chapter 9.2 in [6]). In this concept, the bentonite buffer would be replaced by sand. A "bentonite sealing element" with a thickness of several metres would be provided for between the sand filling and the hard rock abutment. A detailed description of the requirements for the individual barriers of this concept can be found in Chapter 9 in [6].

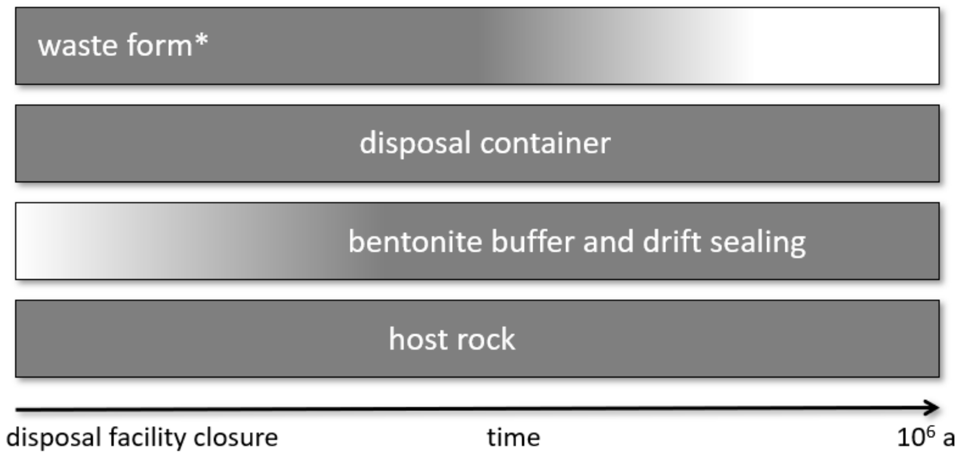

Figure 6.2: Main barriers and their expected basic period of effectiveness in crystalline rock according to the Swedish KBS-3 concept [4]. The graded shading does not indicate the exact working life of the barrier but merely indicates a trend (dark shading means effectiveness).
*(fuel with cladding tube or glass with steel canister)

6.2 Implementability of the requirements

The following section examines the extent to which the barrier system in crystalline rock shown in Figure 6.1 can in principle meet the requirements stated in Chapter 5. Proof that the requirements set out in Chapter 5 are actually met must be provided later within the framework of the required licensing procedure.

Requirements to be fulfilled from StandAG [1]:

- **Containment effectiveness**: The isolating property of the barrier system is based in the long term in particular on the disposal container, its thickness and corrosion properties. The containment is supported by the bentonite buffer, which minimises water influx, maintains a corrosion-inhibiting geochemical environment and can also delay the transport of most migrating radionuclides in the long term. The host rock (mechanical protection) as well as favourable hydrogeological and hydrogeochemical conditions contribute to the long-term preservation of the containment; corresponding studies (e.g. [6]) suggest that this requirement can be met under certain conditions. In order to ensure containment effectiveness, an appropriate waste container fit for use for one million years still needs to be developed. However, the extent to which containment effectiveness, which is ensured in particular by the container, can be demonstrated for the period of one million years required by the StandAG (see § 1(2) in [1]) is still to be examined. It is therefore currently not possible to determine (neither positively nor negatively) whether the requirement can in principle be met or not.

- **Durability**: The containment is effective in the long term provided that the barriers are not damaged by geological processes (earthquakes, changing geochemical conditions, erosion of the bentonite barrier) during the demonstration period with an impact on safety. The requirement of durability can in principle be met but must be achieved by selecting a suitable site.

- **Compatibility**: Between the individual barriers there are no major driving forces for chemical reactions that negatively influence the disposal system. The bentonite buffer is intended to create corrosion-inhibiting geochemical conditions. The requirement can in principle be met.

- **Technical feasibility**: For the realisation of the various barriers (disposal container bentonite buffer, sealing structures), Swedish experience (e.g. [7]) is already available on the feasibility and can be drawn on if required. Against this background, the requirement of technical feasibility can in principle be met.

- **Retrievability**: The emplacement steps can be reversed with relatively little effort until sealing of the disposal facility. Since the integrity of the disposal containers is to be maintained also beyond the sealing of the disposal facility, it is assumed that the disposal containers can also be retrieved [8]. For improved retrievability, the additional insertion of a cast iron liner was proposed in [6] (thus dispensing with direct surrounding by bentonite). The requirement of retrievability can in principle be met.

- **Enabling recovery**: Integrity of disposal containers with regard to radionuclide release is assumed for a period of 500 years. The requirement can in principle be met.

- **Freedom from maintenance**: The barrier system outlined here is designed to be maintenance-free after sealing of the disposal facility. The requirement can in principle be met.

Additional requirements to be considered:

- **Criticality exclusion**: The barrier system is designed to exclude criticality for the period under consideration. Considering the emplacement of the fuel in small, spatially separated units and the long-term processes occurring in the disposal system, it can be excluded that the state of criticality is reached. The requirement can in principle be met.

- **Functional effectiveness**: With the exception of the bentonite buffer, which will not be saturated at the beginning, and the drift sealing, which also consists of bentonite or alternatively of a bentonite/sand mixture, all barriers and in particular the container are immediately functionally effective (Figure 6.2). It is also assumed for the bentonite buffer that its sealing function will take place in the short term in relation to the period under consideration due to the inflow of fracture water. The requirement to be aimed at regarding the functional effectiveness of the barrier system can in principle be met.

- **Verifiability**: The fracturing of the host rock, which is important for stable geochemical conditions, can only be determined insufficiently. As far as main barriers are concerned, the Swedish work can be referred to, which provides for appropriate quality assurance programmes [4]. Here, too, the reservation applies that the containment effectiveness, in particular of the engineered barrier container, must be verifiable for a period of one million years. Thus, the requirement can in principle only be partially met.

- **Robustness**: The waste matrix and the cladding tube together with the disposal container surrounded by bentonite ensure containment. In the event of failure of the disposal container (i.e. if it does not remain stable over the entire demonstration period), retention can only be provided by the bentonite barrier since the radionuclides can only be retained by the geological barrier to a limited extent. The geological boundary conditions must also provide long-term stable conditions for long-term containment in the disposal container. The barrier system appears robust against a multitude of physical and chemical processes and offers a certain robustness under stable geological boundary conditions and limited fracturing of the host rock (site selection!). However, the extent of the fracturing of the host rock and its future evolution can only be determined and described to a limited extent in the characterisation of the site. Thus, the requirement can in principle only be partially met or its fulfilment can only be proven to a limited extent.

In summary, it can be stated that the requirements from StandAG [1] can in principle be met with the barrier systems considered. However, critical aspects result from the requirement of the StandAG to demonstrate safe containment of the radioactive waste for a period of one million years. In a disposal facility in crystalline rock, the container/bentonite buffer system is the main barrier, which must ensure such containment. How the long-term containment capability of this engineered barrier system can be assessed is currently an open issue. An assessment of the retention capacity of radionuclides in the geological barrier is only possible to a limited extent, since the fissure of the host rock, which has a significant influence on the water circulation around the disposal facility, the possibility of erosion of the bentonite buffer and the local geochemical conditions and long-term migration of radionuclides, can only be captured to a limited extent. The extent to which a concept such as that pursued in Scandinavia can meet the requirements of the StandAG must therefore still be clarified.

The most important task of the host rock is to protect the main barriers against external influences. The safety functions in a disposal facility in crystalline rock are thus almost completely supported by engineered barrier systems, the functionality of which is to a large extent also based on the faultless and defect-free fabrication of the containers, the bentonite blocks and the bentonite barrier as a whole.

Regarding the comparison between the Swedish requirements [9, 10] and the requirements in Germany [1, 2], it should be noted that the demonstration period according to § 1(2) [1] covers one million years, whereas the Swedish requirements provide for a step-wise approach. A quantitative risk analysis is only required for 100,000 years. Proof of the suitability of the Swedish KBS3 concept for the demonstration period of one million years as required in [1] is still pending, but it cannot be ruled out in principle that it can be provided. Alternatively, a specific container concept is to be developed.

7 The barrier system in rock salt

7.1 Safety concept and barrier system

The safety concept for a disposal facility for high-level radioactive waste in rock salt is based on the principle of concentration and long-term containment of radioactive waste in a CRZ. The emplaced waste packages are to be enclosed quickly and as tightly as possible by the salt in combination with engineered and geotechnical barriers. Long-term containment is to be ensured durably by the CRZ, i.e. the geological barrier in combination with the geotechnical barriers, and without any need for maintenance and control. To achieve this, the barrier function of the CRZ should not be impaired by internal or external processes during the demonstration period.

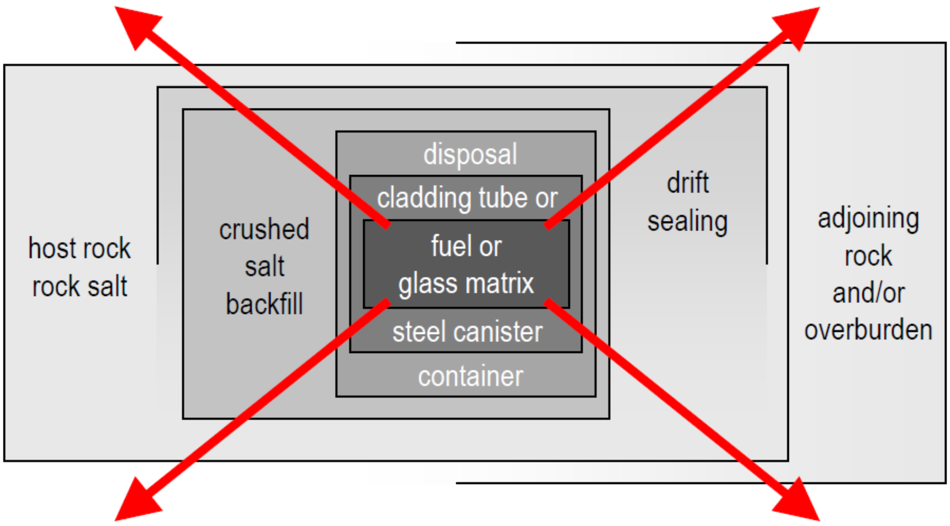

Figure 7.1: Concept of a barrier system in rock salt. The red arrows point to different transport paths, some of which do not pass sequentially through all parts of the barrier system or affect parts of the local geological setting (existing or non-existing overburden) that do not contribute to containment.

The safety concept is developed from the requirements in Chapter 5, taking into account the properties of the host rock rock salt, by deriving the concrete objectives (requirements for the disposal concept) and defining the strategic and planning measures required to achieve these objectives.

The host rock rock salt usually occurs as a large homogeneous formation (steep-bedded and flat-bedded rock salt). The effects of the intervention in this homogeneous area – through the excavation of the mine – can be

minimised by appropriate planning of the emplacement and sealing concept and by taking into account the properties of the salt.
The essential elements of the safety concept for disposal systems in rock salt are based on the properties of rock salt with regard to long-term containment. These are as follows:

- rock salt has a low hydraulic permeability, advective and diffusive transports of radionuclides are negligibly small,
- rock salt exists in large spatial extent and thickness as homogeneous rock,
- rock salt behaves plastically under pressure, i.e. interconnected fracture systems do not occur in the homogeneous areas, cavity convergence leads in the long term to the sealing of mining excavations such as shafts and drifts,
- rock salt has only a low intrinsic moisture content,
- rock salt is characterised by its high temperature compatibility combined with good thermal conductivity, which favours the reduction of thermal stresses,
- rock salt has good rock-mechanical properties, which allow for excavations almost without special supporting structures

It has to be taken into account that

- rock salt is relatively soluble, compared with other host rocks, when water enters from outside, so that dissolution and reprecipitation processes are possible,
- rock salt has only a low retention capability for radionuclides when waste comes into contact with salt solution,

The implementation of the safety concept into a barrier system leads to the derivation of technical and conceptual measures, which vary depending on the emplacement concept. The main technical and conceptual measures are as follows:

- For emplacement, a well explorable rock body in a tectonically calm environment (low large-scale uplift, low salt dome uplift, low seismicity) is sought.
- In disposal facility design, a CRZ is determined that must keep its integrity during the demonstration period and whose barrier function is not to be impaired by internal or external processes.
- The mine openings of the emplacement zones are excavated in salt rock areas with homogeneous

structure and homogeneous properties, especially with regard to their containment properties. The areas shall be free of safety-relevant solution inclusions and have favourable creep properties in order to achieve rapid containment of the waste.

- When planning and designing the backfill and sealing concept, materials are chosen that are compatible with the host rock. In particular, the use of materials with the same properties as the surrounding rock salt, such as crushed salt or salt blocks, is planned.

- The high plasticity of rock salt, in particular at elevated temperatures, leads, on the one hand, to a rapid containment of the emplaced waste and, on the other hand, to a rapid convergence of the cavities and thus to compaction of the crushed salt backfill with a significant reduction in its porosity and permeability. After a transition phase, the crushed salt backfill reaches a containment effectiveness comparable to that of the undisturbed rock salt.

- Day shafts and access galleries are provided with sealing structures (barriers). As far as possible, sealing structures are made of materials with the same properties as the surrounding host rock.

- The moisture that is introduced into the emplacement zones with the waste or the backfill is minimised in order to reduce corrosion of the disposal containers.

- Safety distances to other rock strata (carnallite, main anhydrite, salt dome flanks) and sufficient thickness of the hanging rock strata to protect the CRZ (e.g. sufficient depth) are taken into account.

- Criticality is excluded by appropriate loading and emplacement planning.

Safe containment is ensured by the sequence of barriers. It is a multi-barrier system with safety-relevant components consisting of engineered and natural barriers. The barrier system comprises at least the following barriers:

- the waste form, consisting for Germany either of spent fuel (fuel pellets, which, with few exceptions, are surrounded by intact fuel rod cladding tubes) or of waste products from reprocessing (glass matrix in tightly welded stainless steel canisters),

- the disposal container, which ensures full containment of the radionuclides for the period of time until the drift and shaft seals are effective,

- the crushed salt backfill of the emplacement cavities, which serves to fill the voids and, after its compaction, almost has the containment properties of rock salt, thus effecting full containment of the waste containers on the one hand and hydraulic shielding against external solutions on the other,

- the drift seals, which as early acting barriers hydraulically shield the emplacement zones (especially the emplacement cavities) against external solutions,

- the crushed salt backfill in the other parts of the mine (e.g. transport galleries, infrastructure areas), which serves to reduce voids and, after its compaction, on the one hand contributes to stabilisation and, on the other hand, provides long-term hydraulic shielding against external solutions,

- the shaft seals with their caps, which as early acting barriers hydraulically shield the mine against external solutions,

- the host rock of the CRZ, which due to its long-term containment properties prevents the release of radionuclides through migration and protects the waste against the influx of fluids that promote radionuclide transport (hydraulic shielding),

- the other geological barriers (the parts of the host rock not belonging to the CRZ and, if present, the overburden and adjoining rock), which provide long-term (hydraulic and mechanical) protection of the CRZ.

Figure 7.2 schematically shows how the individual barriers take effect over the demonstration period and complement each other in their effect. The colour intensity for the individual barriers reflects the increase or decrease of their barrier effect after closure of the disposal facility.

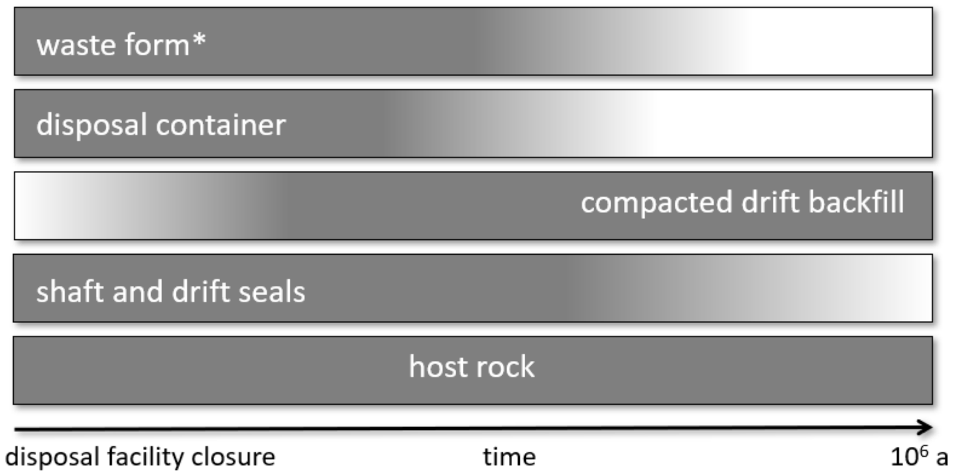

Figure 7.2: Main barriers and their expected individual period of effectiveness in rock salt [11]. The graded shading does not indicate the exact working life of the barrier but merely indicates a trend (dark shading means effectiveness).
*(fuel with cladding tube or glass with steel canister)

7.2 Implementability of the requirements

The following section examines the extent to which the barrier system in rock salt shown in Figure 7.1 can in principle meet the requirements stated in Chapter 5. Proof that the requirements set out in Chapter 5 are actually met must be provided later within the framework of the licensing procedure to be carried out.
Requirements to be fulfilled from StandAG [1]:

- **Containment effectiveness**: The containment effectiveness of the barrier system is ensured throughout the demonstration period by the properties of the CRZ. The geological barrier (rock salt) is effective throughout the demonstration period. The overburden and adjoining rock protect and preserve the CRZ. The engineered barrier components, such as the waste matrix, the waste package and the seals, become effective in different stages for the period of time until the backfill is compacted to such an extent due to the convergence of the host rock that it achieves its containment effectiveness. Its effect lasts until the end of the demonstration period (Figure 7.2). Thus, the requirement can in principle be met if a suitable site is selected.

- **Durability**: After selecting a suitable site and designating a CRZ, the engineered and geotechnical barrier system is designed, considering the evolution of the disposal system to be postulated, in such a way that the durability of the containment and the limitation of influx of external solutions for the entire demonstration period pursuant to § 1(2) [1] can be ensured for the overall system. The requirement can in principle be met if a suitable site is selected.

- **Compatibility**: The individual barriers are designed and coordinated by the choice of material and design in such a way that there is no threat of significant impairment of their barrier effectiveness due to internal and external processes (e.g. temperature development, chemical interaction, corrosion) within their effective period. For example, the geotechnical barrier system is not exposed to major driving forces for chemical reactions if materials that are compatible with the host rock are used for seals and backfilling. The seals must be positioned so that the temperature load on them remains limited. The seal systems also consider the expected corrosion conditions in the choice of material and design. The requirement of compatibility can in principle be met with appropriate planning of the disposal facility and the barrier system.

- **Technical feasibility**: For the realisation of the engineered and geotechnical barriers (disposal containers, backfilling technology, sealing structures), experience is already available for the technical implementation, in particular for sealing structures and backfilling technology. In large-scale experiments, the technical feasibility of the barriers and the fulfilment of the requirements placed on them could in principle be demonstrated (e.g. [12]). Thus, extensive experience can be drawn upon for both geological and engineered barriers. The requirement of technical feasibility can in principle be met with appropriate disposal facility planning.

- **Retrievability**: So far, there have been concept plans for retrievability [11]. These show that the emplacement steps can in principle be reversed, involving effort and expense, until sealing of the facility since all the equipment is still available for emplacement. The concept planning suggests that the requirement can in principle be met.

- **Enabling recovery**: For the recovery of the waste within a period of up to 500 years, an appropriate waste container is to be developed. The requirement of enabling recovery can in principle be met.

- **Freedom from maintenance**: The barrier system is designed to be maintenance-free in the long term. The requirement can in principle be met.

Additional requirements to be considered:

- **Criticality exclusion**: The barrier system is designed to exclude criticality for the period under consideration. The emplacement concept must provide for the emplacement of the spent fuel in small, spatially separated units and to keep the concentration of the fissile material in the waste low, so that criticality can also be excluded in the long-term processes. The requirement can in principle be met with appropriate disposal facility planning.

- **Functional effectiveness**: At the beginning of the post-operational phase, when the backfill has not yet reached sufficient barrier effectiveness, the barriers rock salt, container and sealing structures have a sealing effect. In the post-closure phase, the backfill unfolds its full barrier effectiveness and ensures long-term containment in combination with the rock salt barrier. The functional effectiveness of the barrier system is ensured by the sum of the effectiveness of the individual barriers at all times (Figure 7.2). The requirement can in principle be met if a suitable site is selected and with appropriate disposal facility planning.

- **Verifiability**: The geometry of the rock salt body can well be measured from above ground and examined for the required dimensions (volume of the salt body). Only a limited statement can be made about the internal structure of a salt body from above ground. For this reason, underground investigations are necessary to verify the conformity of the host rock properties (e.g. its dimensions, homogeneity, tightness). These can be used to identify homogeneous areas and facies changes. In order to verify the properties of the engineered and geotechnical barriers, experience is available from large-scale experiments as to how the specifications of the individual barriers can be safely achieved. The durability of the barrier effectiveness within the duration of effect cannot be verified directly. However, it can be deduced well-founded from the properties of the individual barriers and the barrier system. The requirement can in principle be met with appropriate disposal facility planning.

- **Robustness**: The engineered and geotechnical components of the barrier system are designed according to relevant technical rules, taking conservative assumptions into account, and thus robustness is included in planning. For the host rock salt, it can be assumed that the CRZ occupies only part of the host rock, which in turn can be enclosed by overburden and adjoining rock. The host rock beyond the CRZ as well as the overburden and adjoining rock can provide additional robustness in protecting the CRZ. If a suitable site is selected and with appropriate disposal facility planning as well as by favourable host rock properties, the barrier system can be designed such that containment can be ensured also in the case of extreme evolutions of the disposal system with its physical and chemical processes. In particular, the respective barriers made of different materials with overlapping effects and periods of effectiveness

(Figure 7.2) contribute significantly to the robustness of the system. Thus, the requirement can in principle be met.

In summary, it can be stated that all requirements from [1] as well as the additional requirements considered can in principle be met with the considered barrier system in rock salt if a suitable site is selected and with appropriate disposal facility planning. The long-term effectiveness of the barrier system can be ensured by the selection of components that become effective in different stages, whose effects and duration of effects are coordinated with each other. Thus, the delayed effect of the drift backfill is compensated by early acting barriers (containers, drift and shaft seals) in the transition phase.

8 The barrier system in claystone

8.1 Safety concept and barrier system

Clay-rich rocks are pursued in several countries (Belgium, France, Switzerland) as a host rock option for the disposal of high-level radioactive waste due to their high containment capacity. The term "clay-rich" means that the rock consists to a significant extent of swellable clay minerals. In particular, geological boundary conditions are advantageous where the rock has been deformed as little as possible in its geological history (lateral extrapolability of the lithological conditions) and heated (preservation of the swelling capacity of the clay minerals). Due to the geomechanical properties of claystone (strength, stiffness), an increasing size of the excavation-damaged zones, in which the properties of claystone are demonstrably downgraded, is to be expected with increasing depth when excavating underground cavities [13]. However, claystone options that are considered for disposal show that structures in the rock created by tectonic movements can be sealed again due to the swelling capacity of the clay minerals [14].

As with crystalline rock and rock salt, the safety concept of a disposal facility for high-level radioactive waste in a clay-rich host rock is based on the principle of concentration and long-term containment of the radioactive waste. In the disposal container, the waste form (i.e. fuel matrix with cladding tubes or glass matrix with stainless steel canisters) is relevant as a barrier with regard to long-term evolution (Figure 8.1). The disposal container is protected by the barriers of the bentonite drift backfilling and the host rock. The barrier claystone has a paramount function due to its extent, sealing (due to its very low hydraulic conductivity and swelling capacity) and retention properties (long-term immobilisation by sorption of most migrating radionuclides on the surfaces of the clay minerals in the drift backfilling and in the host rock). As with the rock salt barrier system, the claystone host rock is the main barrier. As with a disposal facility in rock salt, a CRZ is also determined for a disposal facility in claystone, which may, however, also include other clay-rich rock layers above and below the host rock.

There are differences between the current French and Swiss barrier systems for a disposal facility in claystone: The French concept is based on horizontal, approx. 40 m long emplacement boreholes with a diameter of approx. 70 cm, the cavity of which is first secured by a pressed-in iron liner and into which the disposal container is then inserted [15]. The individual disposal containers have a maximum length of 1.6 m. The Swiss concept is based on a tunnel lining using shotcrete or prefabricated cement elements (tunnel lining segments), which secure a horizontal emplacement drift with a diameter of 3 m, into which a disposal container is placed along the central axis on a pedestal made of compacted bentonite blocks and the drift is then backfilled with bentonite granulate [16]. While according to the French concept only stainless steel canisters with highly radioactive glasses are emplaced, the Swiss concept is aimed at the emplacement of spent fuel and high-level radioactive glasses, whereby the Swiss disposal container has a diameter of 1 m and is approx. 5 m long. With 40 m, the emplacement drifts in the French concept are considerably shorter than the Swiss ones (300 to 1,000 m long [16]), in which the individual disposal containers are also separated from each other by horizontal sections backfilled with bentonite granulate only.

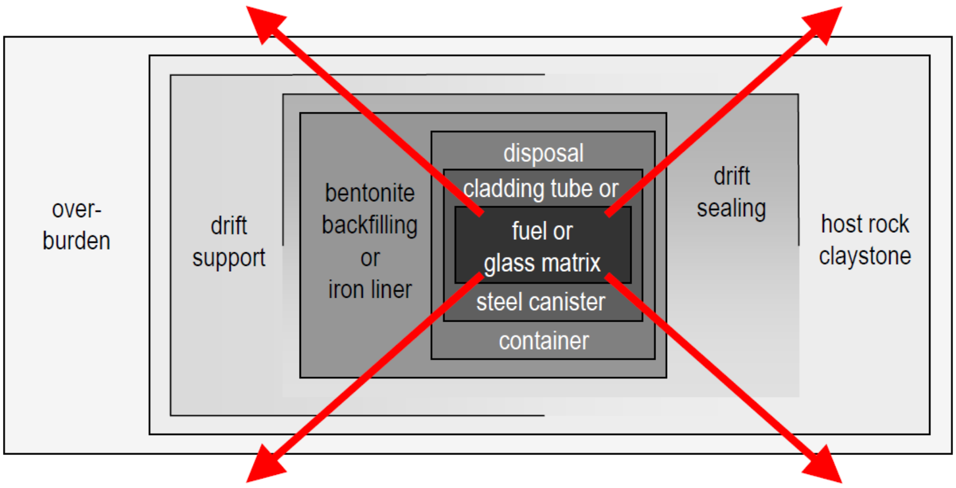

Figure 8.1: Concept of a barrier system in claystone. The red arrows point to different transport paths, some of which do not pass sequentially through all parts of the barrier system or affect parts of the local geological setting (existing or non-existing overburden) that do not contribute to containment.

The essential elements of the safety concept for disposal systems in claystone are based on the properties of claystone (see Table 3-3 in [2]). Due to sedimentation and diagenesis processes, however, the properties of claystone can vary considerably and must therefore be assessed site-specifically. Under favourable conditions, the following properties may be present which are important for the long-term containment of radionuclides:

- extended lateral homogeneity in marine claystone,
- low hydraulic permeability and groundwater flow velocity (diffusion-dominated mass transport, stable hydrodynamic regime),
- low porosity and very small pore sizes,
- plastic behaviour and self-sealing of previously formed fractures,
- high rock-internal grain surface with slightly negative charge and therefore good sorption properties for most relevant radionuclides dissolved in pore water,

- reducing properties of the pore water in claystone, which keeps corrosion rates low and promotes radionuclide retention.

It has to be taken into account that

- claystones show an often vertically limited and laterally variable thickness,

- the lateral homogeneity of non-marine claystones is often limited and the content of swellable clay minerals in it may be variable (higher demands on exploration),

- with increasing burial depth or rising temperatures, claystones lose their plasticity and react increasingly brittle to deformation, pore water is released at higher temperatures and the swelling capacity decreases (p. 32 in [2]),

- claystones have a low thermal conductivity,

- clay minerals are not stable at high pH values (reactions with cement structures),

- claystones (also when overconsolidated) have limited strength and stiffness and are therefore demanding from an engineering point of view.

Based on the safety concept, concrete requirements are derived for the disposal facility site, the disposal concept, the disposal facility design and the assessments to be performed. Essential elements of the safety concept for a disposal system in claystone are based on the long-term retention properties of claystone, its sealing behaviour and its low hydraulic conductivity. If a suitable site is available, these elements of the safety concept can include

- the large mineral surface in the rock due to the high proportion of clay minerals, on which there is a large sorption capacity of positively charged radionuclides due to the slightly negative mineral surface charge,

- the high impermeability of claystone, which leads to low hydraulic conductivity and thus strongly inhibits the advection of fluid within the rock or virtually restricts mass transport to diffusion and thus limits long-term corrosion of the disposal containers,

- the good lateral predictability of marine clay-rich layers in the subsurface by means of seismic investigations and, based on this, the reduction of uncertainties in the lateral migration potential of radionuclides within the host rock,

- the plastic behaviour of claystone (with limited overburden), which in the geological past has led to the closure of formed fractures (corresponding evidence is known from the Mont Terri rock laboratory and has to be provided site-specifically) and will seal newly formed fractures in the event of future seismic impacts due to the swelling capacity of the present clay minerals,

- the limited strength and stiffness that lead to excavation-damaged zones when excavating underground structures along the drifts and require considerable structural safety measures at great depths (additional barrier “drift support”, Figure 8.1), and in areas of strong erosion near the surface can also lead to the formation of decompaction zones with increased hydraulic conductivity,

- the sensitivity of the rocks to high temperatures (water loss of clay minerals) and high pH values (instability of clay minerals at pH > 10).

The main resulting technical and conceptual measures are as follows:

- For emplacement, a marine-deposited rock with a clay mineral content as high as possible and a limited thermal impact in the geological past is searched for that is located in an environment with the least possible tectonic disturbance. Large vertical and lateral homogeneity, a large thickness and possibly clay-rich rocks above and below are an advantage.

- To limit the corrosion of disposal containers and for containment of radionuclides, a rock with the lowest possible hydraulic conductivity is to be preferred.

- Due to low geomechanical strength, claystones are to be preferred, which based on their geological past and additional mineral components such as quartz and/or calcite have a certain level of consolidation (increased strength). Tunnel excavation methods are to be used that cause only minimal damage to the rock.

Safe containment (or long-term retention of radionuclides) must also be ensured for this host rock by means of a multiple barrier system (Figure 8.1). The system of staged safety-relevant components consists of several engineered barriers, at least one geotechnical barrier and one natural barrier. It may include the following barriers (given as examples):

- the waste form, consisting for Germany either of spent fuel (fuel pellets, which, with few exceptions, are surrounded by intact fuel rod cladding tubes) or of waste products from reprocessing (glass matrix in tightly welded stainless steel canisters),

- the disposal container (full containment of radionuclides for a period as long as possible; in Switzerland, full containment for at least 1,000 years is required [18]),

- bentonite backfilling (only in the Swiss concept: bentonite blocks and granular bentonite, which fill the voids in the emplacement drifts, after a saturation period ensure full containment of the disposal containers and hydraulic separation between the containers, minimise the access of water to these and thus their corrosion, create favourable geochemical conditions for a minimal corrosion of the disposal container, exert a swelling pressure on the rock contour after saturation depending on the deformation that occurs and retain radionuclides migrating from leaking disposal containers in the long term),

- drift support using iron liner (only in the French concept) or cement-based interior fitting (only in the Swiss concept, stabilisation of the drift geometry against the lithostatic pressure to ensure controlled emplacement of the disposal containers and to ensure retrievability), as well as

- the host rock (long-term mechanical protection of the internal barriers and erosion protection for the disposal facility, sorption of radionuclides migrating from the disposal container after loss of its integrity and not adsorbed by the bentonite barrier, preservation of the geochemically favourable environment to minimise corrosion rates).

As an alternative, the Swiss concept also mentions the possibility of completely replacing bentonite by backfilling the tunnels with cement mortar [17]. In this case, the geochemical gradients between backfill and host rock would be increased, but the geochemical conditions would still cause only low corrosion rates for the disposal container. With such a cement mortar backfilling, the emplacement drifts would also be stabilised in the long term. The corrosion rates at the surface of the disposal container would continue to be low due to the high pH values, whereas the geochemical gradients between backfill and host rock would be significantly higher and the hydraulic permeability along the emplacement drift orders of magnitude higher than in the adjacent host rock.

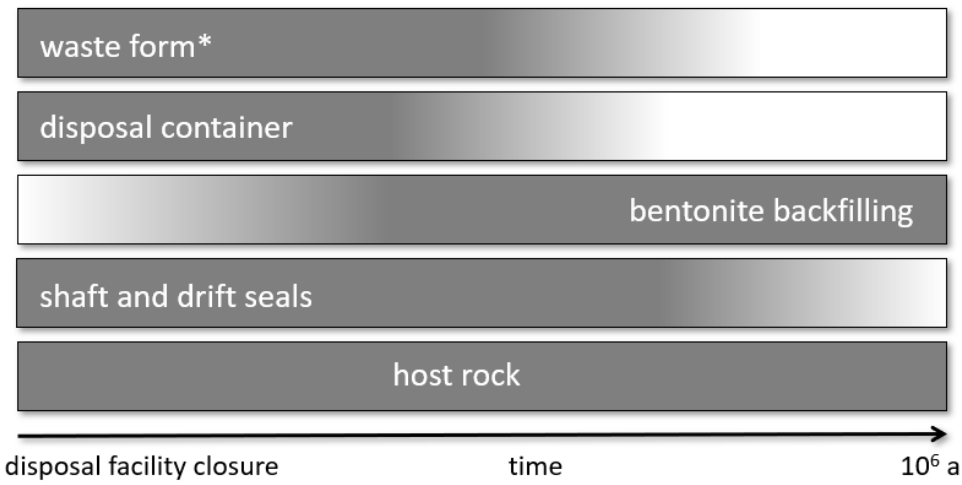

Figure 8.2: Main barriers and their expected individual period of effectiveness in claystone (Swiss concept). The graded shading does not indicate the exact working life of the barrier but merely indicates a trend (dark shading means effectiveness).
*(fuel with cladding tube or glass with steel canister)

8.2 Implementability of the requirements

The following section examines the extent to which the barrier system in claystone described above and shown in Figure 8.1 can in principle meet the requirements stated in Chapter 5. Proof that the requirements set out in Chapter 5 are actually met must be provided later within the framework of the licensing procedure to be carried out.

Requirements to be fulfilled from StandAG [1]:

- **Containment effectiveness**: In the medium term, the isolating property of the barrier system is based on design, thickness and corrosion properties of the disposal container (in the Swiss concept, the tightness of the containers must be ensured of for at least 1,000 years [18]; in the Belgian concept, the disposal container is proposed as a supercontainer made of cement [19]). The host rock (and in the case of the Swiss concept also the bentonite backfilling) favours long-term preservation of a corrosion-inhibiting geochemical environment. The transport of most radionuclides is also delayed or prevented in the long term by the host rock (and the bentonite filling). Measures are to be taken to prevent hydraulic by-passes due to excavation-damaged zones around emplacement drifts and increased porosity of the lining (if present). Assuming the effectiveness of these measures, the requirement can in principle be met.

- **Durability**: This requirement can in principle be met if a suitable site is selected and with appropriate disposal facility planning, since containment effectiveness of the CRZ is in principle maintained during geological processes (e.g. earthquakes). Water pathways would be sealed again at the location of water influx by the swelling capacity of the rock. The durability of the barrier of the host rock (including the formation of a deep decompression zone) must be achieved in particular by the depth and selection of the site in a tectonically undisturbed area (minor uplift, low erosion). Thus, the requirement can in principle be met.

- **Compatibility**: The redox conditions as well as the binding of water by bentonite and host rock support low corrosion rates for the metal installations. It can therefore be assumed that gas production and gas transport reach equilibrium, which does not cause any safety-relevant mechanical damage to the host rock. The bentonite filling has a heat-insulating effect so that the inner parts of this backfilling could be damaged by the decay heat [20]. The bentonite backfilling and the host rock show a sharp pH gradient compared to the cement-based drift support, which can lead to local destabilisation of clay minerals (pH plume). Due to the volumetric limitations of the effects to be expected (limited availability of pore water and flow paths), this requirement can in principle be met.

- **Technical feasibility**: For disposal containers made of steel, it can be assumed from the experience with this material and its processing that flawless seals are technically producible. So far, there is no experience on pressing-in of the iron liners in the French barrier system. Both with this concept and with emplacement drift support structures using cement-based material and possibly an inner support liner, the detailed implementation of a complete backfilling is still technically unclear. Backfilling of a drift with bentonite granulate in the Swiss concept has already been demonstrated in the Mont Terri rock laboratory. Excavation of appropriately dimensioned tunnel systems and installation of support structures was demonstrated in the Bure rock laboratory. Against this background, a technical implementation seems feasible and the requirement can in principle be met.

- **Retrievability**: The emplacement steps can be reversed until sealing of the disposal facility. For better retrievability, Andra [15] has provided for the additional insertion of an iron liner, which is pressed into the rock, flush with the inner excavation surface. Accordingly, the current French concept does not include a bentonite barrier. Thus, the requirement for retrievability can in principle be met.

- **Enabling recovery**: Up to a period of 500 years (according to § 1(4) in [1]), integrity of the disposal containers can be assumed, especially if, according to the Swiss concept, it must be absolutely tight for more than 1,000 years (and corrosion experiments tend to indicate that the containers will only fail after approx. 10,000 years) [21]. The bentonite backfilling (in the Swiss concept) could be removed using mining techniques despite saturation. According to the French concept with iron liner, the latter would have to be designed accordingly in order to be able to ensure retrieval of the horizontally emplaced disposal containers. The requirement can in principle be met.

- **Freedom from maintenance**: The barrier systems proposed in France and Switzerland are based on the assumption of freedom from maintenance after sealing of the disposal facility. Thus, the requirement can in principle be met.

Additional requirements to be considered:

- **Criticality exclusion**: The barrier system is designed to exclude criticality for the period under consideration. The emplacement concept must provide for the emplacement of the spent fuel in small, spatially separated units and to keep the concentration of the fissile material in the waste low, so that criticality can also be excluded in the long-term processes. The requirement can in principle be met with appropriate disposal facility planning.

- **Functional effectiveness**: With the exception of the bentonite backfilling (Swiss concept) in the emplacement drifts not yet saturated at the beginning, all barriers are immediately functionally effective (Figure 8.2). For a bentonite filling, it is assumed that its saturation will take place in the medium term due to ground moisture migrating into it. In the Swiss concept, the drift support must ensure the stability of the drifts over this period; in the case of the French concept, the drift geometry is ensured by the iron liner. Thus, the requirement can in principle be met.

- **Verifiability**: In the case of favourable site conditions (marine claystones), the geometry of the host rock body can be well determined by seismic exploration and the properties of the host rock can be well laterally extrapolated due to the marine depositional history. A large number of experimental results covering periods of up to several decades are available to verify conformity of the individual barriers. At the Mont Terri rock laboratory it was shown that bentonite backfill will swell to a homogeneous mass when water is added. Experience with long-term corrosion rates (disposal container, iron liner) and ageing of the cement lining is available that covers a period of 100 years. Thus, the requirement can in principle be met.

- **Robustness**: Due to the waste form (fuel matrix / cladding tube or glass matrix / stainless steel canister, Figure 8.1) on the one hand and the disposal container on the other, a robust containment is ensured during the first part of the demonstration period. The retaining properties of the bentonite backfill (Swiss concept) are enhanced by the sorption properties of the host rock (and if necessary the entire CRZ, i.e. including the clay-rich rocks below and above it). The barriers show strongly overlapping periods of effectiveness (Figure 8.2). In both the Swiss and French concepts, heat input from waste can adversely affect the host rock. In both concepts, the excavation-damaged zones along the underground structures can be detrimental to long-term safety. The effects of this on long-term safety are therefore to be shown and minimised in terms of the robustness of the system. The robustness requirement can in principle be met.

In summary, it can be stated that, in the case of favourable site conditions and appropriate disposal facility planning, the requirements from [1] and the additional requirements considered can in principle be met with a barrier system in claystone. Critical aspects include the reduced functionality of the bentonite barrier at the beginning of the post-closure phase (delayed saturation) and the possible transport along the drift support and the excavation-damaged zones (increased by the difficulty of complete backfilling between drift support and rock wall). At increased depths, the removal of the drift support and, as proposed in Switzerland, the use of intermediate seals (establishing direct contact between bentonite backfilling and host rock) have not yet been conclusively resolved [22]. However, a number of successful experiments have already been carried out for the technical implementation [23]. The inner part of the thermally insulating bentonite barrier could be partially damaged due to decay heat [20], whereas the pH gradient between drift support on the one hand and bentonite/host rock on the other should, based on current knowledge, only cause locally limited changes in the host rock [22].

9 Conclusions

The objective of a barrier system and the requirements for it were formulated on the basis of the Site Selection Act of 5 May 2017 [1] and additional requirements considered. The review as to whether the requirements can in principle be met for existing concepts of barrier systems in the host rocks crystalline rock (with reference to existing concepts in Sweden and Finland), rock salt (with reference to concepts in Germany) and claystone (with reference to concepts in France and Switzerland) shows that the barrier systems can in principle meet all the legal requirements [1] in the case of favourable site conditions and appropriate disposal facility planning. Most of the additional requirements considered can be met for crystalline rock, whereas all can in principle be met for rock salt and claystone. Individual barriers (e.g. the disposal container in the rock salt or claystone concept that can be recovered after 500 years and, in particular, the disposal container in the crystalline rock concept that is stable for one million years) still have to be developed. Whether the requirements are actually met depends above all on the selection of a suitable disposal facility site and the associated appropriate disposal facility planning as well as on the successful development of the relevant technical systems for disposal. The ESK has found no requirements for a barrier system in the host rocks under discussion in Germany that cannot be met in principle.

All host rocks provided for in the Act (rock salt, claystone and crystalline rock, see § 1(3) in [1]) show advantages and disadvantages in their properties when selected to host a disposal facility. It is the task of a barrier system to compensate in particular the disadvantages by suitable barriers or barrier sequences. The review of the formulated requirements shows critical aspects and requirements for the individual barriers in the respective host rocks, which in principle could only be partially met. By combining different barriers in barrier systems, it may be possible to largely meet all the requirements contained in the Site Selection Act [1] and additionally considered in Chapter 5 and thus to compensate unfavourable properties of the host rock on the one hand and processes triggered due to the host rock and site selection on the other hand without potentially critical aspects in the long term.

Direct adoption of existing concepts, such as those developed abroad, needs to be carefully examined site-specifically and on the basis of German legal requirements and waste inventories. Due to site-specific geological and hydrogeological conditions at potential sites on the one hand and the German legal framework on the other, appropriate modifications to the individual concepts for barrier systems may be necessary in order to adapt them optimally to the site-specific situation and long-term evolution. Such adaptations can be assessed on the basis of the requirements formulated here.

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