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Natural analogues for containment-providing barriers for a HLW repository in salt

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Abstract In 2005, a German research project was started to develop a novel approach to prove safety for a HLW repository in a salt formation, to refine the safety concept, to identify open scientific issues and to define necessary R&D work. This project aimed at identifying the key information for a HLW repository in salt. One important question is how this information may be best fulfilled by natural analogue studies. This question is answered by starting a review of the required key information needs of the safety case (post-closure phase) in order to assess whether or not these requirements can be supported by natural analogues information. In order to structure the review and to address the key elements of the safety concepts, three types of natural analogues are distinguished: (i) natural analogues for the integrity of the geological barrier, (ii) natural analogues for the integrity of the geotechnical barriers and (iii) natural analogues for release scenarios. For the safety case in salt type (i) and (ii) are of highest importance and are treated in this paper. The assessment documented in this paper on the one hand indicates the high potential benefit of natural analogues for a safety case in salt and on the other hand helps to focus the available human and financial resources for the safety case on the most safety-relevant aspects.

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1 The safety case for a repository for radioactive waste

The assessment of the safety of a repository site for radioactive or hazardous waste requires a comprehensive understanding of the system and qualified numerical tools. The iterative process of evaluating the safety of a repository is known as the "safety case". One major aspect of the safety case is that its safety statement and its robustness rely on multiple lines of evidence. Diverse sources of information are brought together to form a consistent picture of the characteristics and history of a site, from which a reliable prognosis of future evolution can be made (NEA 2004).

A safety case is typically used to support a decision to move to the next stage of the repository programme, but it could also be prepared to help review the current status of a project or for testing the methodology for developing a safety case. A key function of the safety case is to provide a platform for decision making (NEA 2013).

One important source of information used in a safety case is the study of natural analogues, i.e. the investigation of natural, anthropogenic, archaeological or industrial systems which have some definable similarity with one or more components of a radioactive waste repository and its surrounding environment (Miller et al. 2006). According to this definition all natural and man-made analogues are included under the term natural analogues.

The main value of natural analogues studies is to provide information on the complexity of a repository system and on the characteristic of processes over long time scales. In general, the direct use of quantitative information from natural analogues studies in a safety case is limited, since it is very difficult to extract hard numerical data from complex natural systems where initial and boundary conditions cannot be fully defined. Nevertheless, the use of natural analogues complements laboratory and in situ field-scale experimental data and can provide a test of numerical codes used in the safety case. Furthermore, natural analogues are observable and understandable to the lay stakeholder. They are thus an important tool for the building of technical and public confidence.

2 Studies and activities on natural analogues in salt

There is a very comprehensive literature on the use of natural analogues for the safety case with the focus on repositories in clay and fractured crystalline rocks (e.g. Chapman et al. 1984; Miller et al. 1994, 2000). Although there have been activities regarding natural analogues in salt for more than 20 years, only a few published studies address salt-specific aspects (e.g. Knipping 1989; Brenner et al. 1999). In responses to this Noseck et al. (2008) described natural analogues investigations that were specifically related to a HLW repository in salt in Germany (see also Noseck et al. 2015, this issue).

In 2005, a research project was started to develop a novel approach to prove safety for a radioactive waste repository in a salt formation, to refine the safety concept, to identify open scientific issues and to define necessary R&D work (Buhmann et al. 2008). One aspect addressed in this project is an assessment of the applicability of natural analogues to a safety case in salt in the post-closure phase. A first step was a review to define the key information required for the safety case.

3 Safety case requirements

The geological barrier is of utmost importance for the disposal of HLW in salt. The German safety requirements (BMU 2010) specify that the radioactive waste must be contained in a defined rock zone in such a way that it remains in situ and that, at the most, only a small quantity of material may leave this rock zone, referred to as the containment-providing rock zone (CRZ). The required assessment period is one million years. The containment is provided mainly by the geological barrier. Penetration of the geological barrier by repository construction means that an engineered barrier system is required to seal the CRZ. The safety concept envisages a set of shaft and drift seals to fulfill this function (Mönig et al. 2012). The remaining void space in the emplacement areas is backfilled with crushed salt. The requirements for low hydraulic conductivity and longevity of the shaft and drift seals are directly correlated with the compaction behaviour of the crushed salt backfill material (Fig. 1). In the long term, the compacted crushed salt backfill will be characterized by a very low permeability and this takes over the primary containment function of the shaft and drift seals. All barriers described above that have a defined contribution for the containment of the radioactive waste are denoted here as containment-providing barriers (in reality, there are more components within the engineered barrier system, but they are not stressed in the safety concept, e.g. the waste matrix).

According to this concept the decisive elements of the safety concept are the demonstration of the integrity of the geological barrier and the demonstration of the integrity of the geotechnical barriers. The evaluation of releases is focused on those evolutions of the repository system for which the development of a continuous pathway for radionuclides out of the repository cannot be excluded (Buhmann et al. 2008).

4 Review and assessment of natural analogues for a HLW repository in salt

4.1 Introduction

The objective of the review and the assessment of natural analogues studies is to answer the following questions:

- How can natural analogues contribute to identifying and understanding the key features and processes that will operate over relevant timescales within a host rock in salt?
- How can natural analogues contribute to understanding of the long-term behaviour and stability of different components of a repository system in rock salt?
- How can observations from natural analogue systems be used in communication to the stakeholder community (operators, regulators, politicians and the public)?
- What is the current status of knowledge and what knowledge gaps need to be addressed?

These questions are answered by starting a review of the required key information needs of the safety case and an assessment if these requirements can be fulfilled by natural analogues information. The basis for the assessment is a detailed study and documentation of potentially relevant features, events and processes (FEPs) for a potential repository in a domal salt structure in the North German Basin. In this FEP catalogue, all FEPs are linked to the key processes influencing the containment-providing barriers

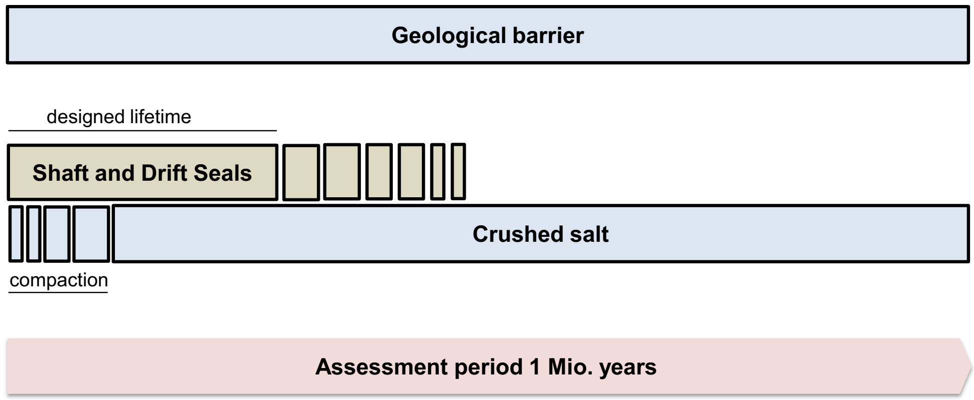

Fig. 1 Functional requirements for the containment-providing barriers (not to scale)

(Buhmann et al. 2010). In order to structure the assessment and to relate it closely to the safety concept, the compiled studies are divided into three types of natural analogues in order to highlight the key elements of the safety demonstration concept:

1. Natural analogues for the integrity of the geological barrier
2. Natural analogues for the integrity of the geotechnical barriers
3. Natural analogues for release scenarios

The first two types of natural analogues are directly referred to the containment-providing barriers and are dealt with in this paper (Sect. 4.2/Table 1; Sect. 4.3/Table 2, respectively).

The assessment of the natural analogue studies is split into two parts: The first part assesses the status of natural analogues for a safety case in salt. Five classes are chosen for this assessment (see Tables 1, 2).

The second part assesses the communicability of a natural analogue for the safety case in salt. Two classes are chosen here for the assessment (see Tables 1, 2).

In 2010 and 2011 an extensive compilation of potential natural analogues studies for salt were carried out (Tables 1, 2). Table 1 contains an update regarding the behaviour of competent salt formations due to several new studies published in 2012 and 2013. The work presented here was focused on the identification of potential studies or natural analogues and an evaluation if they could be accepted as relevant analogues to support a safety case. Of course, these potential analogues need to be critically evaluated to ensure their appropriateness for a specific site.

In order to assess the situation at a potential site and to compare it to natural analogues studies, the exploration results of the Gorleben salt dome were used as "self-analogue" (see Table 1, column called "Status Site"). No geotechnical barriers are available in the Gorleben salt dome.

4.2 Integrity of the geological barrier

Table 1 summarizes the assessment of all identified natural analogues that are related to the containment-providing properties of the geological barrier. The items 1–11 in Table 1 are discussed in more detail in the following, particularly with reference to the assessments in columns "Status Site", "Status NA" and "Confidence Building".

1. The fact that more than 250 Million years after sedimentation of the evaporites a large number of salt domes exist in the world, e.g. in the Permian North German Basin, provides arguments for the integrity of salt rock, the slow dissolution of salt in the deeper underground and its impermeability and mechanical and structural stability over geological time frames. There are several documentations of salt formations, e.g. for the salt dome Gorleben (Bornemann et al. 2008, see Fig. 2). This fact is a tangible and understandable argument for lay stakeholder and can be used as a general argument for the advantages of the host rock salt.
2. The assessment of neotectonic condition is an important argument for the prognosis of the future evolution of the repository system (uplift or subsidence of the area, expected intensity of earthquakes, occurrence of magmatic events) and is expected to be very important for the discussion with the lay stakeholder. This can be documented for the investigated site, e.g. Köthe et al. (2007), but no further natural analogues can be applied, since the condition cannot be transferred. This aspect cannot be supported by natural analogues.

Table 1 Compilation and assessment of natural analogues (NA) for the geological barrier

Nr.	Aspect/FEP/study	Applicability in safety case (key information)	Status Site	Status NA	Confidence Building
1	Occurrence of salt domes	Long-term stability of salt domes	++	+	oo
2	Neotectonic conditions	Occurrence of earthquakes and magmatic events	++	–	oo
3	Analysis of the salt flow	Uplift rates	++	+	oo
4	Thickness and composition of the cap rock	Subrosion rates	++	+	o
5	Behaviour of competent salt formations	Possible water pathways	+	+	o
6	Br- (and Rb)-distribution in salt formations	Interaction between formation and external solutions	++	++	o
7	Chemical and isotope composition of fluid inclusions	Interaction between formation and external solutions and gases	++	++	o
8	Openings from salt mining	Behaviour of salt at disposal level	●	+	o
9	Basalt intrusions	Behaviour of salt at high temperatures	–	++	oo
10	Basalt intrusions	Sealing of fissures	–	++	o
11	Kryogenic fractures	Occurrences of fractures formed by salt contraction during cooling	-	+	o

"Legend to columns 'Status Site' and 'Status NA'"

++ Natural analogue is identified and documented

\+ Natural analogue is identified and need to be better documented

● Natural analogue is identified (no documentation)

\- Natural analogue is not identified

– Natural analogue is (probably) not identifiable

"Legend to column 'Confidence Building'"

oo Public confidence building: natural analogue is tangible and understandable to the lay stakeholder

o Technical confidence building: natural analogue is an argument to support the understanding of complex behaviour

3. For the future evolution of a salt dome it is of utmost importance to be able to predict its uplift (stage of diapirism). Other important processes depend on the expected uplift rates, especially subrosion (see item 4, below). Valuable information can be drawn by the analysis of salt flow in the past and remaining salt in the catchment area of the salt dome. An example is the description of development of the salt dome Gorleben by Jaritz (1994) and Zirngast (1991). A comparison with other salt domes provides a deeper understanding of the process and supports the prediction of future uplift rates. This is an aspect that can be also comprehensibly illustrated for the public.
4. An important process is the salt dissolution from the top of the salt surface (subrosion), which might lay open the repository area in very long time scales. During the subrosion process low solubility minerals such as anhydride, gypsum or clayey material become enriched (cap rock). Dating of the recently build cap rock layer is a good argument for the derivation of subrosion rates. Examples for the Gorleben analyses of cap rock layers of salt domes and derived subrosion rates are given in Köthe et al. (2007). As for the uplift rates, a comparison with other salt domes provides a deeper understanding of the process and supports the prediction of future rates.
5. Anhydrite commonly occurs as rock layers in salt formations and shoes a stiff/brittle behaviour when the surrounding rock salt deforms plastically. During a salt dome's uplift the brittle salt formations break into several blocks (for example the anhydrite beds z3GT-z3HA in Fig. 2). If these blocks are hydraulically connected, the resulting structures can provide possible pathways for fluids. If these blocks are isolated, no pathway for fluids exists. This phenomenon is an important aspect for the safety case in a salt dome and should be investigated and documented at other salt formations, especially salt domes. Hammer et al. (2012) investigated the anhydrite in a salt mine in the salt dome Morsleben and documented a

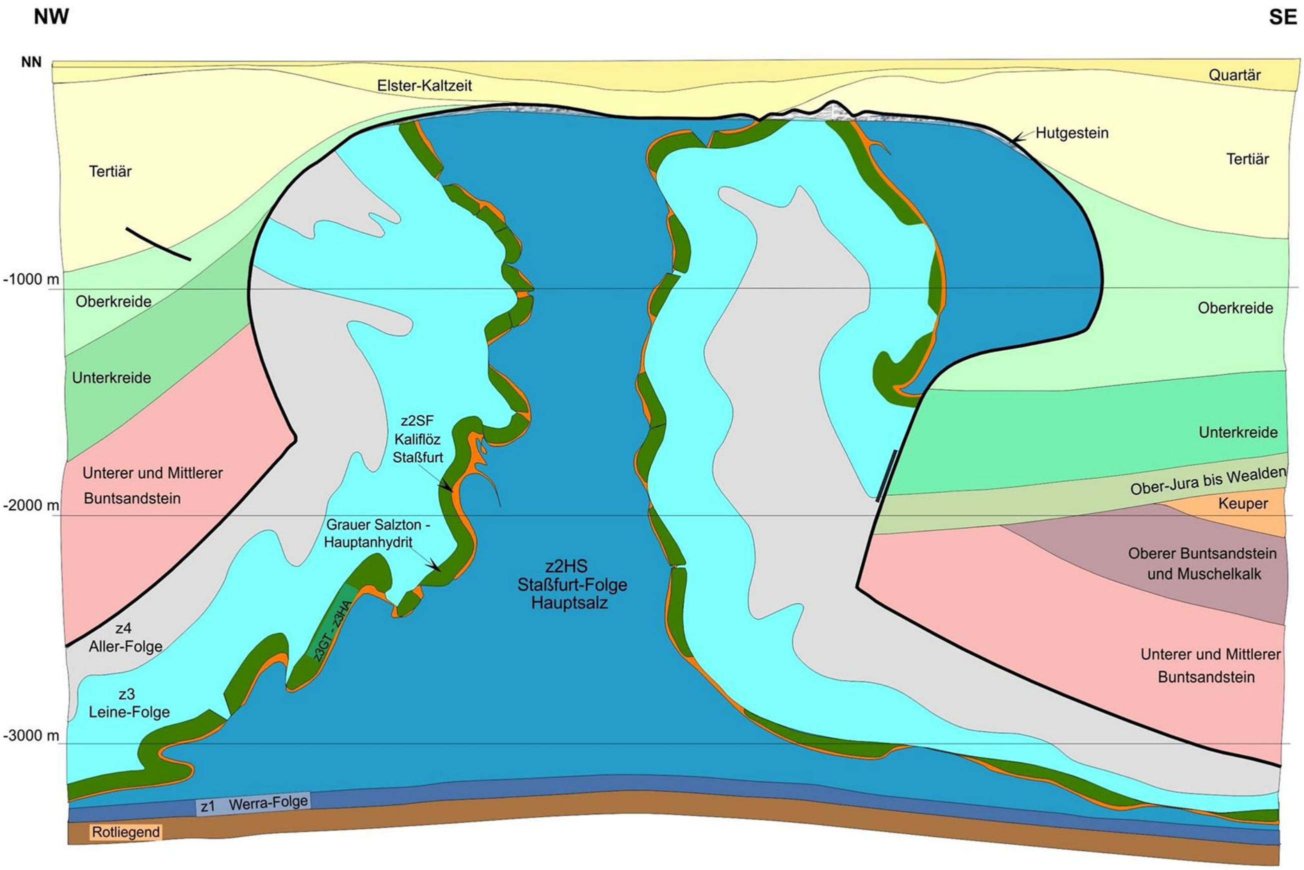

Fig. 2 Simplified geological cross section of the Gorleben salt dome, *z2HS* Staßfurt Series (main rock salt), *z3GT-z3HA* Leine Series (anhydrite beds, salt clay and carbonaceous layers) [based on Bornemann (1991), adjusted in Buhmann et al. (2008)]

wide spectrum of boudinage structures (Fig. 3). In addition, the rheological behaviour of composite samples of a single anhydrite layer embedded in rock salt matrix deformed in laboratory experiments was investigated (Zulauf et al. 2009, 2010, 2011). The results of these investigations support the assumption that boudinage of anhydrite in salt domes with a geological development (tectonic regime etc.) representative for the Northern German Basin is a common feature in domal salt structures.

6.–7. Concerning the integrity of the salt dome, arguments demonstrating that external fluids from adjacent or overlying strata did not migrate into the inner of the salt dome are of great importance. It is a strong argument that no fluid pathways existed in the formation. Natural analogues studies like profiles of content and isotope signatures of gases in fluid inclusions can be used to support such conclusions. For the salt formations in the Permian North German Basin several detailed studies are available, e.g. Herrmann and van Borstel (1991a, b), Siemann and Ellendorf (2001), Potter et al. (2004). A second aspect to support this argument is the interpretation of bromides distribution in the evaporites. If the characteristic bromide profile of the evaporation phase is preserved, it can be followed that there was no interaction with fluids after sedimentation (e.g. Schulze 1960; Braitsch 1963a, b; Becker 2008). In general, the understanding of such interpretations requires an advanced knowledge of geochemistry and is more appropriate for the discussion of experts.

8. The mechanical behaviour (especially deformation processes) of salt in several hundreds of meters depth could be analysed by investigations of existing and former salt mines. Despite the vast activities of the salt mining and gas storage industry only a few studies indicate, how far natural analogues can support the understanding of such mechanical processes (e.g. Brenner et al. 1999).

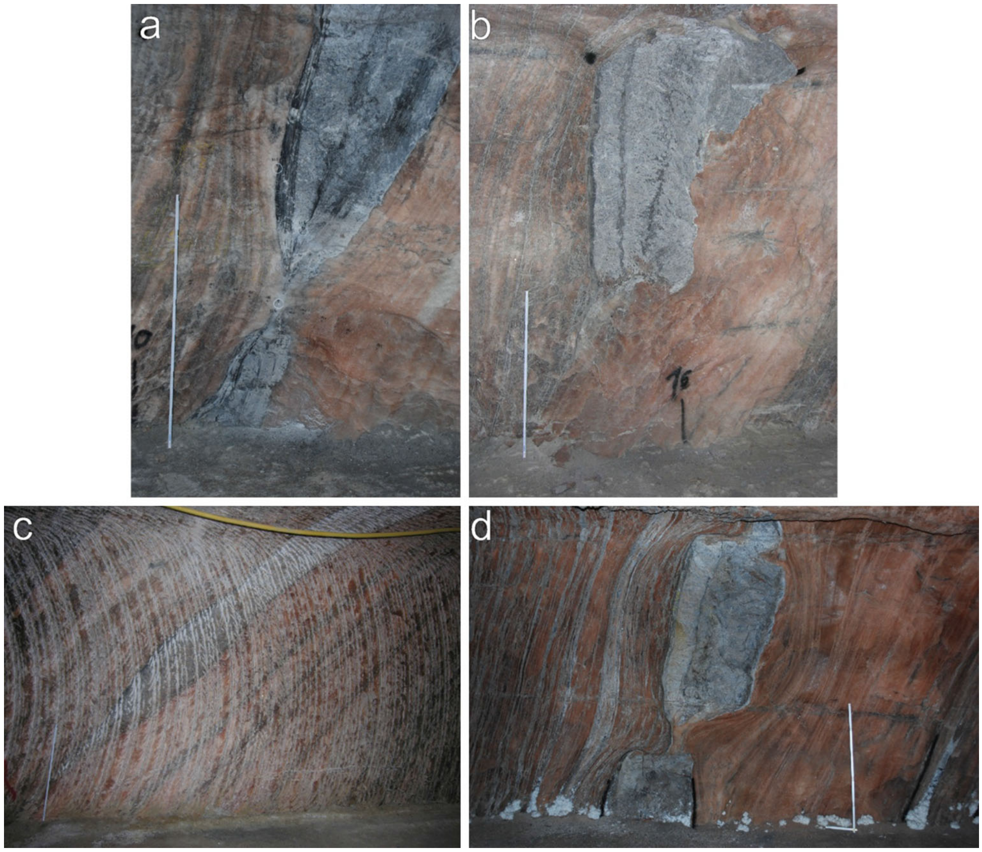

Fig. 3 Boudin structures in the mine Morsleben (Hammer et al. 2012)

9.–10. Due to the heat production of HLW, the thermal stability of salt rocks and minerals is an important aspect. Here, the geologic analogue of salt penetrated by volcanic dikes can be used to demonstrate that transient high-temperature processes have a very limited influence on the salt structure (Knipping 1989).

11. Natural analogues can also help in controversial discussions. For example, in the discussion on the origin of joints (up to 600 m depth) in the salt dome Bokeloh near Hannover, Germany, Bauer (1991) suggests that the low temperatures in past glacial periods could be one reason for the evolution of these joints. Other reason, e.g. a tectonic origin, are also plausible. Here, investigations of other domal salt structures are required to increase understanding of such joint-forming processes (Hammer et al. 2012).

4.3 Integrity of the geotechnical barriers

Table 2 summarizes the assessment of all identified natural analogues that are related to the containment-providing properties of the geotechnical barriers. The items 1–7 in Table 2 are discussed in more detail in the following, particularly with reference to the assessments in columns "Status Site", "Status NA" and "Confidence Building".

1. The excavation of the repository infrastructure with drifts and boreholes changes the favourable properties of the rock salt amongst others by an increase of permeability in the excavation disturbed zone (EDZ) around the voids. Natural analogues giving evidence that healing, i.e. decrease of the permeability back to that of the undisturbed rock salt occurs are of great importance for the safety case and support the numerical models describing the time dependent decrease of permeability in the EDZ around the seal structures. As an

Table 2 Compilation and assessment of natural analogues (NA) for geotechnical barriers

Nr.	Aspect/FEP/study	Applicability in safety case (key information)	Status NA	Confidence Building
1	Investigations of bulkhead drift	Reduction of the permeability of an EDZ around drift sealing	+	o
2	Basalt intrusions	Long-term behaviour of basaltic gravel	++	oo
3	Chemical and mineralogical composition of natural clays	Impact of high temperatures on clay minerals	++	o
4	Properties of natural salt clays in salt	Long-term behaviour of clays as sealing material	+	o
5	Corrosion of historical concrete buildings	Long-term behaviour of cementitious materials	++	o
6	Bentonites in saline environment	Long-term behaviour of bentonite as sealing material	+	o
7	Compacted backfill material from old drifts in salt mines	Compaction of crushed salt over long time scales	●	o

"Legend to column 'Status NA'"

++ Natural analogue is identified and documented

+ Natural analogue is identified and need to be better documented

● Natural analogue is identified (no documentation)

"Legend to column 'Confidence Building'"

oo Public confidence building: Natural analogue is tangible and understandable to the lay stakeholder

o Technical confidence building: Natural analogue is an argument to support the understanding of complex behaviour

example for short-term processes the permeability reduction of the EDZ in rock salt can be observed in old drifts (Bechthold et al. 2004; Wieczorek et al. 2001).

2.–6. A very important field where natural analogues can provide valuable information is the long-term stability of the materials used in a repository (waste forms, waste packaging, buffers, backfills and seals). Natural analogues can provide information on the long-term behaviour of these (or homologues) materials complementarily to laboratory investigations. In the salt concept, different cementitious and bentonite are used in the seal structures. Several studies are available (Jull and Lees 1990; Roy and Langton 1982; 1983 and Pellegrini et al. 1999). For basaltic gravel (one option for filling parts of the shaft column) the results of Knipping (1989) can be used to get valuable information for its long-term behaviour in salt.

7. As explained earlier the compaction of crushed salt plays a decisive role in the safety concept (Fig. 1). This process is important for time scale that cannot be covered with laboratory experiments. Therefore, it is very important to find natural analogues that confirm the understanding gained from these experiments. One option is the investigation of old backfilled mines. A first analysis of possible activities was carried out in Brenner et al. (1999), but more effort is necessary to document natural analogues for this important aspect for a safety case in salt.

5 Conclusions

The use of natural analogues is one important element in alternative lines of reasoning to complement the results of the safety assessment in the safety case (IAEA 2012). Their key role is to be complementary to laboratory studies and modelling exercises and to increase the understanding of complex long-term processes (see also Reijonen et al. 2015, this issue). In some cases, natural analogues may be more accessible, more convincing and of more interest to the public than the results of complex mathematical models. In order to use this potential benefit of natural analogues, a review of the key information required for a safety case has been carried out for a generic repository in rock salt. The basis for this review and assessment is a comprehensive FEP catalogue for salt. In order to structure the assessment and to relate it closely to the safety concept, the compiled studies are related to the integrity of the geological barrier and to the integrity of the geotechnical barriers. The results of the assessment are summarized in Tables 1 and 2 (see Sect. 4.2, 4.3).

This kind of review and assessment of natural analogues described here provide some important information:

- Overview on available natural analogues
- Statement of their importance for the post-closure safety case

- Initiation of discussion on the use of natural analogues for a specific safety case
- Identification of R&D needs

The integrity of the geological barrier is of special importance in the case of deep disposal in salt, since it is assumed to guarantee the containment of the waste for the whole assessment period of one million years. The review showed that for its integrity a lot of well described natural analogues are available. Further potential natural analogues are identified but need to be better documented. For some important aspects, future R&D work could be identified. A good example of the ongoing work is the investigation of the behaviour of anhydrite in different salt structures, e.g. in the former salt mine Morsleben.

Despite the vast experience in salt mining and gas storage in Germany, the situation is worse when discussing the use of natural analogues for demonstrating the integrity of geotechnical barriers. There are only a few publications on how to use this knowledge. This is especially true for the compaction of crushed salt, a key process for the German safety concept.

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