Problems Related to Temperature-Induced Processes in Long-Term Repositories for Nuclear Waste-17514

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ABSTRACT

Concepts for the final disposal of high level radioactive waste in deep geological formations must consider the heat pulse produced from radioactive decay during operations and in the post-closure phase as an important factor for the integrity of barrier systems. Several safety cases in different countries limit the maximum temperature at the boundary between the technical barrier/canister surface to the host rock/buffer material to 100 C.

Increases in maximum temperature have very diverse effects with respect to the type, intensity and range of the heat pulse. These depend, among other factors, on i) the amount of heat emitted, ii) the type of host rock including site-specific characteristics, iii) the safety and repository concept and further site-specific boundary conditions.

The German Commission on the Disposal of High-level Radioactive Waste (Commission) recommended, for precautionary reasons, that the temperature limit at the outer surface of waste containers should not exceed 100 C. Higher temperatures could only be considered if the maximum physically possible temperatures in the respective host rock have been reliably set as a result of research findings.

INTRODUCTION

According to state-of-the-art research, it may be assumed that the safe storage of heat-generating radioactive waste is possible in deep geological formations in the three types of host rock: clay, crystalline rocks and salt.

Investigations carried out in several countries indicate that the maximum temperature increase at the waste container to host rock (or geotechnical barrier) boundary in clay and crystalline host rocks should not exceed 100°C (limiting temperature) in order to ensure that the barrier effect of the technical barriers and the host rocks is not jeopardised (Dohrmann et al. 2013). In the case of salt rock as host rock, the temperature recommended so far for the outer surface of the emplacement containers is a maximum of 200°C (Mönig et al. 2011). As a precautionary action, the German Commission on the Disposal of High-level Radioactive Waste recommended that the maximum temperature should also in this case be limited 100 degrees Celsius (interface waste container to host rock or geotechnical barrier), until it is possible to scientifically define the maximum physically possible temperatures for each host rock.

This paper summarises and discusses the most important effects of high temperatures on the host rock types and the geotechnical barriers on the basis of a literature study.

RESULTS

Temperature development in a repository for high level radioactive waste in deep geological formations

The peak temperature in a repository for heat-generating radioactive waste in deep geological formations depends, amongst others, on the specific heat generation of the waste and the repository concept (e.g. the number of fuel elements in the waste containers and the distance between these containers). The numerical model calculation of characteristic temperature curves at selected points a salt rock repository is shown in Figure 1. Starting at an initial ambient temperature of around 45 °C (at a depth below surface of about 1000 m), the formation temperature initially rises, because the heat dispersion in salt rock is lower than by advective air flow cooling in the interim surface storage. In the case of the inventory shown in the example, a peak temperature of almost 200 °C is calculated in the centre (point C') of the emplacement area after around 345 years. After that point in time, the temperature decreases with decreasing heat generation by the radioactive decay.

Plots limited to a peak temperature of e.g. 100 °C in the centre of the emplacement area (point C') will basically show the same curve progression. Lower ranges are expected in the clay host rocks and crystalline rock because of their lower thermal conductivity.

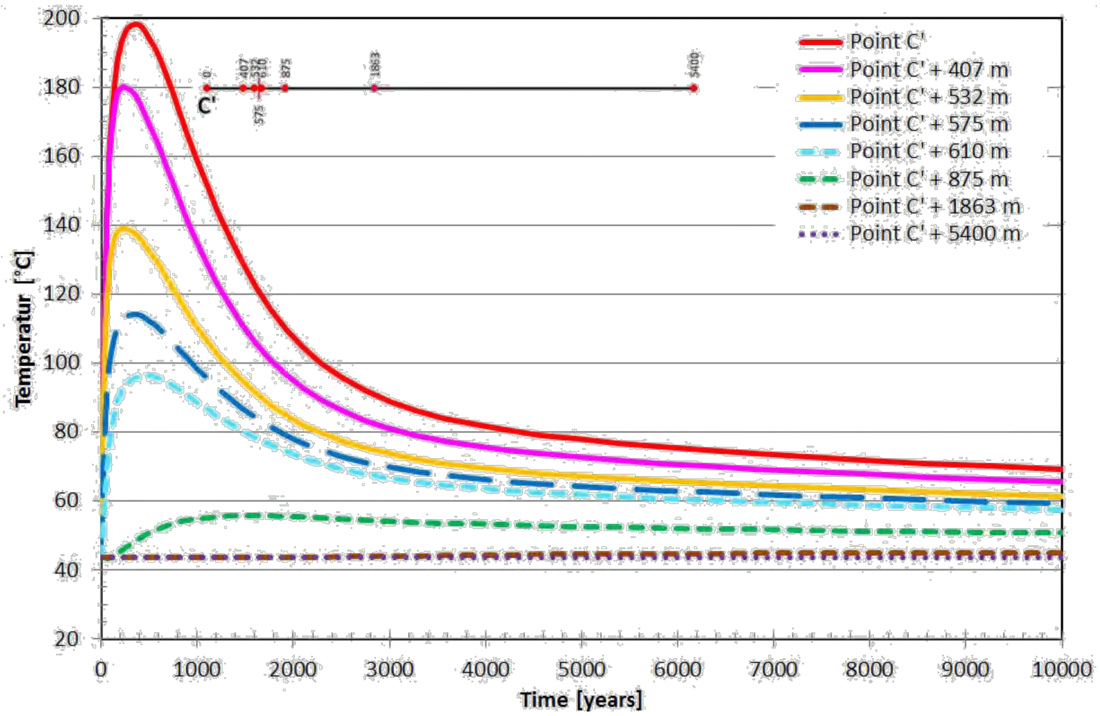

Fig. 1: Numerical modelling: Expected temperature change over time at various distances within an emplacement zone (point C') using salt host rock (from Kock et al. 2012).

Influence of temperature

Beside the consideration of temperature influence on the host rock, a repository concept for a repository in deep geological formations should also take into account the temperature influence on geotechnical barriers and containers, as well as any necessary construction materials such as steel and concrete. The following chapters look at the influence of temperature on selected processes for the host rock types, clay, salt and crystalline rock.

I. Crystalline host rock

Crystalline rocks are formed by magmatic processes and/or rock metamorphosis under the influence of high temperatures and high pressures. These rocks can therefore be heated up well above 100 °C without significant alteration (BGR 2016). The significant factor for limiting the temperature in crystalline rocks is the presence of the necessary geotechnical barrier made of highly compacted bentonite (e.g. Dohrmann et al. 2013).

The Swedish repository concept in crystalline rock limits the maximum temperature on the outside surface of the waste container to 100 °C (SKB 2011). This limit primarily reflects the material properties of the bentonite and the boiling point of water, with the aim of maintaining the integrity of the bentonite barrier during the initial generation of heat after radioactive waste emplacement. If water were to boil in the initially slightly saturated bentonite, this could lead to the undesirable precipitation of salts in the pore spaces within the bentonite, and on the surface of the containers – which in turn could cause corrosion of the containers, and would also diminish the swelling properties of the bentonite (GRS 2005). Additionally, the thermal expansion would increase the pore water pressure. Should the pore water pressure be higher than the hydrostatic and/or lithostatic pressure, this could lead to both, fluid movement and micro-fracturing. These effects must be prevented by restricting the (limiting) temperature to 100 °C. The discussions in the literature disagree on the importance of the illitisation of swelling clay minerals – a well-known process which occurs in sedimentary basins (Sellin and Leupin 2014). Illitisation is the conversion of swelling clay minerals (smectite and/or smectitic layers in illite/smectite interstratified minerals) into illite which is no longer capable of swelling. The degree of illitisation of a claystone is used by the oil industry as a maturation parameter because it reflects the thermal as well as the chemical history. The swelling clay minerals in bentonite barriers ensure the necessary swelling pressure, the sealing, and the high sorption capacity. Illitisation would decrease the effective reaction space of the swelling clay minerals required for this purpose. Although illitisation has often been postulated in repository experiments on bentonites, it has never been unequivocally mineralogically verified (discussion Kaufhold & Dohrmann, 2010). Kaufhold & Dohrmann (2010) also show that illitisation is a process limited by K-availability. Minor illitisation over a period of 1 Ma (conversion of smectite layers, also within interstratified illite/smectite minerals) cannot be excluded. However, the degree of this illitisation will be minor because of the short period of time (1 Ma) compared to geological processes, and the associated limited K-availability. It also depends on the geological history of the claystone ("maturity"). A young claystone which contains only a little illite/smectite and but is therefore rich in smectite, has a greater tendency to illitisation (in the presence of K and at raised T) in contrast to a mature claystone. As a result, bentonites consisting exclusively of smectite, without illite/smectite, show a higher illitisation potential. Real illitisation has never been verified in large-scale experiments (Kaufhold & Dohrmann, 2010). However, the analytical identification of collapsed layers on the basis of 10 Å XRD reflexes, has often been falsely interpreted because it largely involves reversible dehydratation.

Large-scale experiments lasting several years are carried out in the Äspö *hard rock laboratory* in Sweden, aiming at creating such thermally-related changes, with temperatures deliberately raised to a significant degree. This is done with the intention of accelerating those processes that can subsequently be extrapolated to long-term effects at lower temperatures. In the 'Alternative Buffer Material' test (ABM), a large-scale test carried out at a maximum temperature of 141 °C and a heating phase of 2 - 3 years, observations were recently made which indicate that boiling may have taken place in the bentonite barrier (Dohrmann & Kaufhold 2016). However, no illitisation of the swelling clay minerals was observed. Boiling is apparently made possible by a pressure loss through fractures in the host rock during the heating phase. The maximum temperature is of major importance in the Scandinavian crystalline rock concept because bentonite forms the last barrier and is then bordered by more or less fractured hard rock (ESK 2015).

II. Clay host rock

Bentonite barriers have also been discussed in the case of clay host rocks. In this case, however, bentonite is considered as an additional option to the sorbing and sealing host rock. On the one hand, the intention is to stabilise the waste containers within the drift emplacement system (Switzerland); discussion here involves the question to what temperature the bentonite may be heated (e.g. 150 °C, BGR 2016), and what the proportion of the "sacrificial layer" may be with respect to the loss of its swelling function. On the other hand, there are plans to use bentonite as a *plug* to interrupt the excavation-damaged-zone (EDZ; in the French repository concept). This concept does not include any temperature stress associated with the surface of the waste containers. In the event that high temperatures should diminish the barrier capacity of the bentonite when used as a sacrificial layer (the Suisse concept), the barrier function of the host rock continues to exist. The consequences of maximum temperature effect on the bentonite at the surface of a hot waste container is thus more prominent in the crystalline host rock concept than in the clay host rock concept.

In contrast to bentonite, claystone is richer in organic matter. Claystone has been consolidated over geological time periods by the pressures and temperatures inflicted on the rock through the subsidence of the sediments. The maturity of the primary organic matter in clay may change as a consequence when the maximum temperature reached by the claystone during the course of its geological history (maximum paleo-temperature) is exceeded. This temperature can be reconstructed by sedimentological and geochemical methods.

It is considered favourable if the maximum paleo-temperature is much higher than the temperature between the boundary of the container surface and the claystone. Should maximum paleo-temperatures be lower than this temperature, thermally-caused changes to the organic matter could occur and result in an unfavourable influence on the dispersion of toxins (e.g. colloidal transport) and/or the formation of gas. However, it should be kept in mind that this consideration (temperature < maximum paleo-temperature = favourable) is based on the assumption of an oxygen-free environment. However, in a geological repository, contact to oxygen will at least occur within the EDZ. Work still needs to be done to demonstrate the consequences for the stability of the organic matter that has already been exposed to high temperatures during its geological history. Experiments looking at this aspect could be carried out for instance in underground rock laboratories under realistic framework conditions.

The repository concepts in Switzerland, France and Belgium substantiate the respective maximum temperatures allowed in these concepts. The maximum paleo-temperature of the Callovo-Oxfordian for instance was 40 °C (Delay et al. 2010). Andra were able to show, on the basis of numerical calculations, that the short-term influence of temperatures of 90 °C should not damage the claystone.

Negative temperature-associated effects on clay/claystone depend, amongst other things, on the clay minerals present and the degree of diagenetic consolidation. Heating tests in the Mont Terri rock laboratory in Switzerland at heating temperatures of 100 °C have not given rise to any visible fracturing in the Opalinus Clay host rock so far, nor to any visible fracturing in the technical barrier made up of bentonite (Wileveau et al. 2008).

The risk of bacterial growth at peak temperatures of up to 100 °C, which could give rise to increased gas formation and the corrosion of containers, has been the subject of discussion. Higher temperatures could "disinfect" the technical barrier and the clay host rock by killing possibly present bacteria (Jobmann et al. 2015). The sustainability of this approach has to be tested experimentally in further experiments.

III. Salt host rock

Most of the knowledge concerning salt as a host rock has been acquired in Germany and the USA. This is derived from many years of traditional salt mining in Germany, and the experience gained in final repository projects at the Asse II and Morsleben sites, as well as the exploration activities in the Gorleben mine. The host rock salt previously dominated the research activities on geological repositories in Germany, which looked at steeply inclined salt structures (salt domes). Work on horizontally bedded salt rock in the context of repository research has played a minor role in Germany so far. The thermo-mechanical-hydraulic-coupled processes in these salt formations are now to be evaluated in model calculations undertaken as part of the KOSINA project (concept development for a generic final repository for heat-generating waste in horizontally bedded salt horizons) (DBE-Tec 2015).

Large-scale underground experiments on the temperature behaviour of host rocks have amongst others been carried out in the Asse II site in Germany, and at the WIPP site in the USA (cf. Table 1).

Name	Objective (thermally relevant selection)	UTL
Thermal/structural Interaction (TSI)	Time-dependent behaviour of rock salt under the influence of thermal stress	WIPP
18 W/m2 DHLW Mock-up	Influence of input of thermal energy into the host rock	WIPP
DHLW Overtest	Transfer of thermal energy at raised temperatures: long-term effects of transfer of thermal energy and cavity convergence	WIPP
Heated Axis-symmetric Pillar Experiment	Validity of models and codes predicting the behaviour of rock salt under heat stress	WIPP
Ambient Temperature Room Test	Rock-mechanical data under ambient temperatures relevant to geological repositories	WIPP
Moisture Transport and Release	Movement of natural moisture in host rocks: release of moisture depending on temperature and time	WIPP
Temperature Experiments 1-6 (TW 1-6)	Thermal stability of accessory minerals in rock salt: migration of fluid inclusions in salt under raised temperature conditions: permeability of rock salt in the vicinity of a heated-up borehole	Asse
Brine Migration Test with Co-60 Sources	Migration of fluid inclusions in salt and raised temperature conditions: thermo-mechanical behaviour of rock salt under the influence of thermal stress	Asse
Development of Borehole Seals (DEBORA)	Thermo-mechanical behaviour of rock salt under the influence of thermal stress: thermal behaviour of crushed salt under the influence of thermal stress	Asse
Thermal Simulation Drift Emplacement (TSDE)	Thermo-mechanical behaviour of rock salt interacting with crushed salt backfill	Asse

Table 1: Selected thermal and/or thermal-coupled experiments in salt host rocks (GRS 2016).

Release of water of crystallisation

In Germany, investigations were primarily carried out on salt rocks belonging to the Staßfurt depositional series (Zechstein 2, "Hauptsalz") as a potential strata for waste emplacement, for reasons of its thickness, its general homogeneity, and its low moisture content. The Hauptsalz consists of well over 90 wt.-% rock salt, plus anhydrite and insoluble constituents. The proportion of anhydrite decreases in the stratigraphically younger Hauptsalz strata, being characterised by the presence of polyhalite (GRS 2012). The content of aqueous evaporite solutions in the Hauptsalz of the Staßfurt Series is 0.012 to 0.017 wt.-% (GRS 2012).

At temperatures exceeding their material-specific limiting temperature, hydrate salts (kieserite, polyhalite, carnallite and bischoffite) are liable to decomposition and/or alteration, and the release of water of crystallisation. These hydrate salts are largely found in the potash seams (Kaliflöz) of the Zechstein 2 sequence (GRS 2016, Table 2). It is therefore necessary to ensure adequate safety distances from formations containing hydrate salts, so as to limit the effect of temperature. This means maintaining a limiting temperature in particular for the temperature-sensitive carnallite (< 80 °C).

Hydrate salt	Chemical formula	Critical temperature [°C]
Kieserite	$Mg[SO_4]\cdot H_2O$	280
Polyhalite	$K_2Ca_2Mg[SO_4]_4\cdot 2H_2O$	230 – 280
Carnallite	$KMgCl_3\cdot 6H_2O$	80 - 170
Bischofite	$MgCl_2\cdot 6H_2O$	155 - 220

Table 2: Critical temperatures of important hydrate salts (modified after GRS 2016)

Gas formation

Heat input caused by high-level radioactive waste may cause the release of fluids in the salt host rock. The release of such fluids could give rise to various processes such as container corrosion, pyrolysis, and the vaporisation of water and hydrocarbons. These processes may lead to gas formation; the associated increase in volume could negatively influence the integrity of the final repository. Other processes resulting in gas formation are thermal sulphate reduction as well as microbial activities (GRS 2016). Further research is required on the availability of fluids and the formation of gas pressure (Hotzel 2010). More research is also required looking at the pressure-induced consequences associated with differential thermal-expansion coefficients of host rocks and fluids, as well as dynamic processes and the self-organisation of processes.

Thermal sulphate reduction

Anhydrite (calcium sulphate) occurs as a natural constituent in rock salt deposits. The sulphate may be affected by thermal-chemical reduction at temperatures exceeding 80 °C. This requires the presence of organic matter (e.g. hydrocarbons) or hydrogen (GRS 2012). Weber et al. (2011) roughly estimate that this process could be associated with volume increase of about 10 %. The effects of thermal sulphate reduction on the integrity of geological repositories have not yet been completely resolve; more research is required (Bracke et al. 2012).

Influence of Microbial processes

Microbial processes can also influence the integrity of and processes in salt host rocks. Bacteria in particular may survive even under extreme conditions. A temperature range of 80 to 110 °C is currently being discussed (Brasser et al. 2014). The associated investigations are being undertaken using natural analogues in particular, such as those considered in a conceptual model at the WIPP site (GRS 2016).

Thermomigration / brine migration

The conditions existing in horizontally bedded salt rock and in steeply inclined salt rock (e.g. in salt domes) differ in various ways, including in the volume of solutions present. Horizontally bedded salt is richer solutions than steeply inclined salt by a factor of 100 (Hansen et al. 2015).

Solutions in salt may occur in intracrystalline form (fluid inclusions), intercrystalline form (on grain boundaries), as well as in the form of chemically bound water and fissure water. The term thermomigration describes the migration of solutions in rock salt under the influence of temperature (GRS 2012). The term "brine migration" is used in the English-language literature in connection with "heater experiments". These tests simulate and investigate the processes arising from the transfer of heat generated by radioactive decay. During transfer of thermal energy, the prevalent temperature gradient results in the migration of solutions in the rock salt, amongst other things (brine migration). Thermomigration is therefore a process which critically depends on the amount of transferred heat. The amount of transferred heat also influences the range of thermal effect in the host rock.

Different heater experiments at various locations (e.g. the WIPP site) are described in a study issued by SANDIA Laboratories (Kuhlmann et al. 2013). However, the results of the tests are not directly comparable with one another because of the different experimental setups. For instance, one of the findings was that initially existing migration paths closed up again in the presence of increasing temperatures because of the expansion of the rock salt. This would temporarily considerably reduce the inflow of solutions; however an increase in permeability again as a result of cooling down could subsequently result in a considerable increase in the inflow of solutions in some cases.

Kuhlmann et al. (2013) suggested a number of additional experiments and further research in order to better understand the processes. The crucial aspect is that the findings concerning the thermomigration process are independent of the experimental set-up and site-specific conditions.

Static percolation

Following up on the work of other authors (e.g. van Bargen and Waff 1986, Birnie 1993, Lewis and Holness 1996), Ghanbarzadeh et al. (2015) contributed to the understanding of the processes involved in the transport of fluids (e.g. hydrocarbons and solutions) into and within salt rocks. On the basis of laboratory experiments and drilling results, the authors concluded that no continuous pore spaces developed as a result of pressure-temperature (PT) caused dissolution processes in unexcavated rock salt under comparatively low pressure and temperature conditions, typically found in salt mines. This result is in accordance with the extremely low permeabilities of rock salt at this depth range as confirmed by experiments (Bredehoeft 1988). However, the authors also reveal that the degree of connection of the solution-filled pore spaces, and therefore the permeability of rock salt, can increase under high temperatures and/or increasing pressures.

Fluid-driven (also pressure-driven) percolation can occur when the pressure in a solution in the rock mass, minus the minimum main stress, exceeds the tensile stress of the rock. This process is different from static percolation. Although the stress state in the rock and the strength of the rock are influenced by temperature, the process is actually temperature-independent. The aforementioned condition for the occurrence of fluid-driven percolation is known as the minimum stress criterion, and is used when verifying long-term safety (BMU 2010, DAEF 2016).

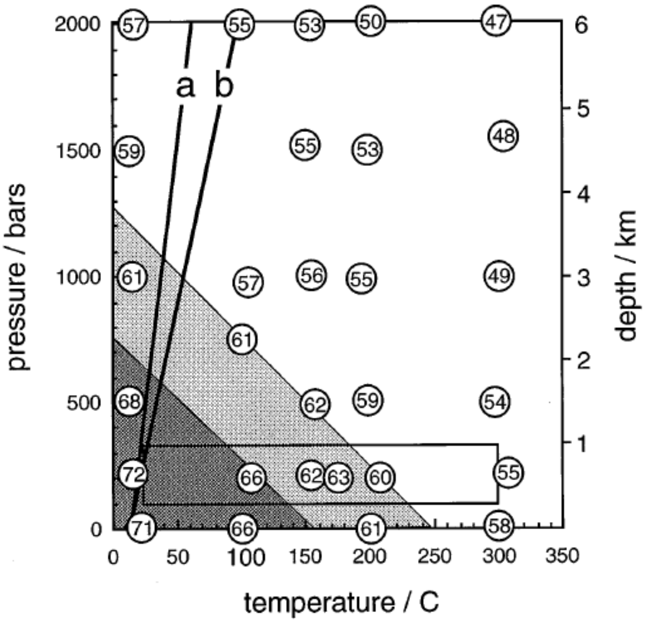

Fig. 2: Extrapolation of laboratory results to the field scale. This shows the zones of possible connection of solution-filled pore spaces in rock salt because of static percolation. The conditions exist in the white zone; the light-grey zone is transitional; and the conditions for connected pore space do not exist in the dark-grey zone. Line a shows the typical geothermal gradient for crystalline rocks; line b for a sedimentary basin. Points with numbers are the temperature and pressure conditions from laboratory tests (from Lewis and Holness 1996).

Thermal expansion

Work on the Preliminary Safety Analysis of Gorleben (VSG) (Kock et al. 2012) revealed that the heat transfer arising from the thermal expansion of salt in the area surrounding an emplacement zone induces additional stresses. These stresses lead to dilatant damage to the fabric on the boundary walls of drifts, and to the development of a zone of increased compressive stresses outside of the dilatant zone. This gives rise to uplift in the overlying rocks, resulting in an uplift of up to 1.3 m at the surface. Because of the volumetric expansion, there is a reduction in minimal main stress at top salt, whilst the minimum stress criterion for fluid-driven percolation is violated up to 150 m below top salt (GRS 2016). These effects of heat transfer must be investigated on a site-specific basis, and form the basis for the long-term safety evaluations.

BGR (1990) already pointed out in 1990 that thermomechanical processes need to be taken into consideration which occur as a result of the expansion of the salt dome because it is heated up by the strongly heat-generating waste. The spread of the temperature in the salt dome, however, takes place slowly according to the results of the model calculations (10,000 years). Contraction processes then take place accordingly when the salt dome cools down again at a later stage.

According to BGR (1991), the thermally-induced volume expansion in the first decades after waste emplacement gives rise to a strong rise in the horizontally-aligned compressive stresses in the repository. This pressure increase is associated with a considerable decrease in stress at around top salt and can thus give rise to tensile stresses which could be associated with a risk of the formation of fractures.

Chimia et al. (2009) revealed on the basis of numerical models that the heat transfer arising from the emplacement of radioactive waste in the Gorleben salt dome would reduce the viscosity, and thus lead to internal deformation within the salt dome.

Creep deformation and compaction:

Salt creep refers to the time-dependent deformation of rock salt which takes place due to the spread of displacements in the crystal lattice and occurs without any fracturing. This process is accelerated by higher temperatures. This also accelerates the stress relocations and the reduction of higher stresses in the rock mass. Cavities are closed up more quickly by the increased convergence. Higher temperatures also lead to faster compaction of the crushed salt backfill, but also have an influence on gas formation. Speeding up these processes leads to faster enclosure of repository containers in a repository (GRS 2010). The temperature therefore has a significant influence on the deformation processes in the repository, and needs to be taken into consideration on a site-specific basis for repository design and for verification.

Temperature-dependency of material parameters:

The mechanical behaviour of rock salt is temperature-dependent and is affected by various parameters to a varying extent:

The viscosity (time-dependent creep behaviour) has a strong temperature influence (Cristescu, N.D., Hunsche, U., 1998). Creep rates rise with increasing temperatures. This dependence is implemented in material laws for the simulation of the salt behaviour. A significant decrease in average failures with increasing temperature is described in BGR (2012). In these experiments, the failures reached at a test temperature of 180 °C are around 50 % lower than tests at room temperature. Breaking strain is also significantly dependent on temperature. In many samples it is several times higher at 180 °C than in tests at room temperature.

The modulus of elasticity is less dependent on temperature, however. The modulus of elasticity describes the static elasticity, and decreases slightly with increasing temperature. This results in an increase in elastic deformation. However, according to BGR (2012) its influence is of only minor importance.

The material parameters and their temperature dependencies need to be determined on a site-specific basis for the verifications. Many test series have already been carried out at room temperature, but the tests carried out at higher temperatures are less extensive. Further investigation and research is required.

DISCUSSION

The expert reports prepared by BGR (2016) and GRS (2016) on behalf of the Commission on the "Storage of high-level radioactive waste", concluded that temperature-relevant processes have a gradual effect on the host rocks, and that it was therefore not possible to define a clear limiting temperature below which these processes will stop. There is an international understanding, however, that a limiting temperature for claystones and bentonites (used as geotechnical barriers in crystalline rocks) should not exceed 100 °C. The exception to the rule is the "bentonite sacrificial layer" approach of the Swiss claystone repository concept with about 50 % of the bentonite volume directly coating the waste container. However, the concept prevents the host rock to be heated above 100 °C.

With respect to salt host rock the reports of BGR (2016) and GRS (2016) show that according to today's state of research, an emplacement temperature of 200 °C in salt rock is feasible in terms of technical safety in combination with the previously analysed repository concepts. The results are largely based on different in-situ tests, e.g. in Asse, and primarily from investigations carried out at the Gorleben site. This holds exclusively for steeply inclining salt in salt domes, since there has not been done research in this regard on horizontally bedded salt so far.

However, with the input of these amounts of thermal energy (at temperatures up to 200 °C), static percolation processes in addition to other processes, such as fluid-driven percolation, could also play a role for a geological repository in salt host rocks (Lewis and Holness 2015 as well as Ghanbarzadeh et al. 2015). Minkley and Brückner (2016) attempted to verify the comments made by Ghanbarzadeh et al. (2015) by carrying out tests in a natural rock salt sample and came to the conclusion that there is no identifiable increase in permeability with increasing temperature. Because of the differences in the experimental setup, e.g. changing the through-flow medium from brine to nitrogen, there are limits to how far the results of the studies may be compared with each other. A broader experimental basis is required to generate verifiable results. DAEF (2016) also considers more research to be required on this topic.

With respect to gas formation, thermal sulphate reduction, microbial influences, and thermomigration processes described for salt host rock, there is a clear need for more research to be carried out to improve process understanding, the relevance and extent of these processes, as well as potential interactions, with respect to the integrity of barrier properties.

The final report of Commission on the "Storage of High-level Radioactive Waste" final report (Commission on the Storage of High-level Radioactive Waste 2016) recommends the disposal of high-level-radioactive waste in deep geological formations with the necessary precautions for retrievability during the operating phase and recoverability for at least 500 years (see also the safety specifications in BMU 2010). Retrievability under the high emplacement temperatures acting during the operational phase in a mine however, would require extreme technical effort, especially with regard to the cooling systems which would be necessary, and because of the expected high convergence rates. Moreover, retrievability under these conditions has not yet been tested technically.

OUTLOOK

Thermally-influenced processes taking place in host rocks and geotechnical barriers are the subject of intense research efforts.

With respect to the emplacement temperatures for salt host rocks in particular, many processes are also subject to critical debate; many processes have not yet been fully investigated, and the need for more research has been identified.

The German Commission on the Disposal of High-level Radioactive Waste therefore recommended, for precautionary reasons, that the temperature limit at the outer surface of waste containers should not exceed 100° C. Higher temperatures should only be recommended if the maximum physically possible temperatures in the respective host rock have been reliably set as a result of research findings.

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