Integrity of saliferous barriers for heat-generating radioactive waste – natural analogues and geomechanical requirements

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ABSTRACT: We argue for the integrity and tightness of saliferous barriers over geological timescales by considering examples of large-volume gas or fluid intrusions in supercritical phases. These were created by volcanic activity about 20 million years ago and are still trapped in salt deposit today. These natural analogues serve as long-term experiments which show that complete containment of heat-generating nuclear waste in salt rocks is possible. As an alternative to crushed salt as geotechnical barrier, we propose using salt mixtures with melting points in the range of 100°C–200°C and present first experimental results. This approach combines the advantages of immediate complete containment, negligible volume compaction (thus no squeeze-out of contaminants by convergence), and retrievability at any time.

1 INTRODUCTION

In Germany, the dominant approach concerning the disposal of heat-generating radioactive waste is based on isolation by geological barriers and aims to achieve complete containment (Krone et al., 2011). Hence, it is natural to consider salt rocks, claystone formations or sites with multiple salt-claystone barriers as host rock systems (Minkley, 2009).

Undisturbed saliferous rocks are impermeable to fluids and gases. This is supported by natural analogues (Minkley & Knauth, 2013). For example, tertiary volcanism has left local deposits of supercritical CO_2 up to $100{,}000\ m^3$ contained in rock salt until today. In contrast, the overall volume of heat-generating radioactive waste in Germany is $10{,}000\ m^3$ for borehole and $40{,}000\ m^3$ for drift emplacement (VSG a, 2012).

Salt formations can lose their geomechanical integrity and leak tightness if (a) the groundwater pressure or a gas pressure exceeds the minimal stress in the salt formation or if (b) dilational damage occurs. The first process seems to be the most relevant process for the overall barrier integrity (Minkley et al., 2013). The minimal stress may be lowered due to extensional strain conditions, either by subsidence or by thermo-mechanically induced lift-up of the rock mass above the mining horizon or the repository area.

So far, all cases where rock salt barriers lost their integrity, the barriers were rather thin ($\lesssim 100$ m), and confining pressures were low. Such conditions are typical for salt mines in shallow depths (Minkley & Knauth, 2013). If the barrier is sufficiently thick, salt mines are safe from water inflow even under earthquake-like incidents, as can be seen from a dozen rock bursts worldwide with macroseismic epicentral intensities up to VIII-IX (Minkley, 2004). In extreme cases, surface fractures several metres wide and open cracks in the salt rock hanging wall have not led to loss of integrity of the salt-claystone multi-barrier system.

On the one hand, bedded salt provides a simple geological structure and a robust multi-barrier system due to the following reasons: The natural, undisturbed geological layering with watertight insoluble claystone layers above the soluble salt rocks combines the advantages of salt and claystone concepts for the disposal of heat-generating nuclear waste. Salt domes, on the other hand, have a huge basement salt thickness particularly suitable for borehole emplacement.

The conventional containment mechanism relies on the compaction of crushed salt backfill by the convergence of the host rock, with residual porosity over a long time. Novel experimental results show that immediate complete containment as well as retrievability of the waste can be achieved by using eutectic molten salts as backfill material, which are kept liquid by the waste-generated heat. Hence, the waste canisters in borehole emplacement could be easily retrieved. Furthermore, water cannot reach the canisters because of the higher density of the molten salt. When the temperature reaches the freezing point (in the range of $100^{\circ} - 150^{\circ}$C) after hundreds of years, the molten salt solidifies and becomes an impermeable salt mass like the host rock. Since from the outset there would be no residual pore volume, a contamination scenario with transport of harmful material to the biosphere by fluids would be obsolete.

In the following, we will first discuss natural analogues, i.e. examples of high-pressure fluids trapped in salt rocks for geological times, which support the impermeability of rock salt. In Sections 3 and 4, we will outline the requirements for a nuclear waste repository and our proposal for molten salt backfill. In Section 5 we report results from first laboratory experiments on the permeability of recrystallised HITEC salt, and in Section 6 we discuss the geomechanics of molten salt backfill in more detail, before concluding in Section 7.

2 COMPLETE CONTAINMENT IN SALT ROCK: NATURAL ANALOGUES

In the Werra salt deposit, enormous amounts of CO_2 penetrated into the bedded salt formations about 20 Mio years ago by magmatic intrusions during tertiary volcanism and are still stored today. In association with basaltic magmatism, CO_2 (gas or in aqueous solution) rose into the salt deposits, where it transformed some of the primordial salt rocks, in particular the easily soluble carnallitite. After cooling and recrystallisation, the CO_2 was deposited mainly in secondary sylvinite (Giesel et al., 1989). The gas can be stored predominantly on the grain boundaries (mineral-bound CO_2) or in caverns and fractures (free CO_2). Due to the high lithostatic pressure, the gas will generally be in a liquid or supercritical phase (see the phase diagram in Figure 1). Exposure of trapped high-pressure gas by blasting or drilling leads to a phase transition to the gaseous phase associated with volume increases by a factor of the order of 500 (see Figure 2). For gas trapped on grain boundaries, this will fragment the salt rock and pneumatically expel the debris (Salzer, 1989). Similar outbursts, often involving methane as the main component, are known from other salt mines around the world; see e.g. Ehgartner et al. (1998).

As natural analogues, these gas intrusions in the salt and their associated phenomena demonstrate the long-term barrier integrity of salt formations, because highly compressed fluids are preserved over millions of years.

2.1 *Outbursts in the Werra district*

Gas releases induced by blasting or drilling are frequent in the Werra potash district, among them the largest in the world. The first major outburst was triggered on 07 June 1953 in the Menzengraben mine by a remote-controlled blast. No miners were in the mine, but the ejected CO_2 killed three people above ground (Junghans, 1953). The outburst left a cavity of about 100 m long, reaching about 20 m into the hanging wall rock salt. More than a million cubic metres of gas (Duchrow et al., 1988) were ejected and expelled 60,000 t of salt, mainly carnallitite (Junghans, 1955). With lithostatic pressure in a depth of 588 m being 14.4 MPa, the CO_2 must have been in the liquid state (see Figure 1). When pressure drops to atmospheric pressure of 1 bar

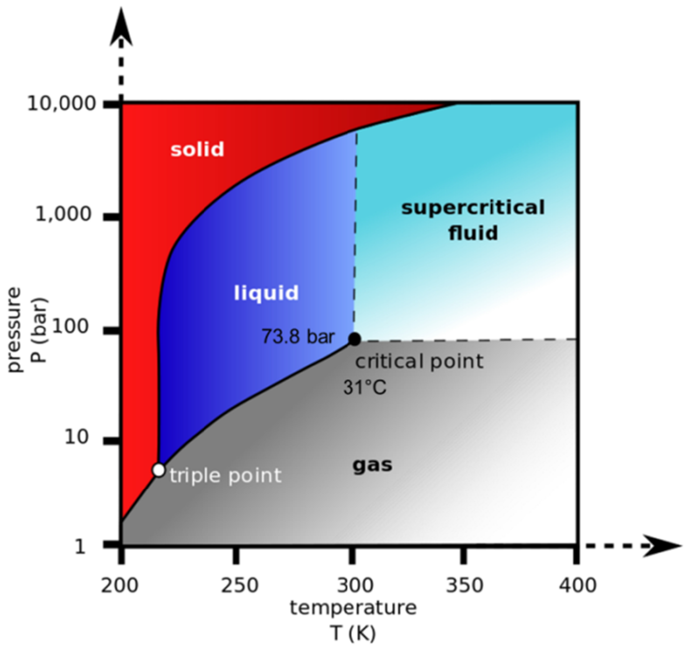

Figure 1: Phase diagram of CO_2

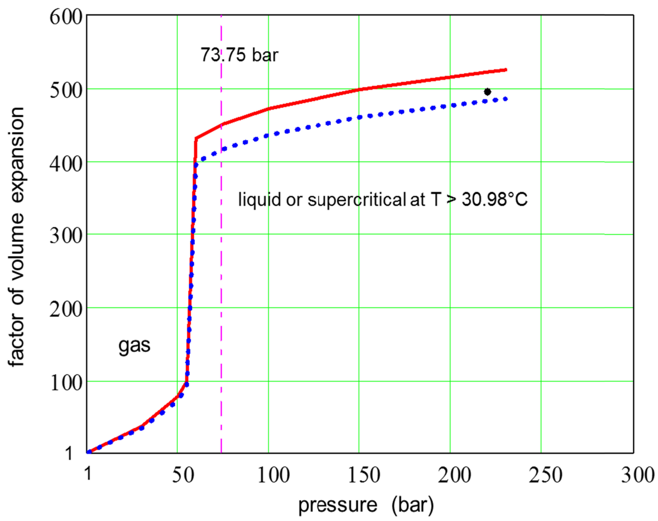

Figure 2: Volume increase after a pressure drop to 1 bar (horizontal axis shows initial pressure). The red (solid) curve is for isothermal expansion at 20°C, the blue (dashed) curve for a temperature drop from 20°C to 0°C. The single black dot is for a temperature drop from 31°C to 0°C. (For comparison: Rioxam HD (Dekamon) expands by a factor of about 780 upon blasting.)

Figure 3: CO2 glacier after an underground gas blow-out in rock salt (CO2 becomes solid below -70°C).

(0.1 MPa), the gas expands by a factor of 495 (see Figure 2). Assuming a mean salt porosity of 10 %, from the expelled material we can estimate a gas volume of $1.4 \cdot 10^6$ m^3.

The world´s largest gas and salt outburst in Sylvinite ejected 110,000 t of salt (Salzer, 1991). Assuming a porosity of 8% (i.e. lower than for carnallitite) in the gas-containing sylvinite, a volume increase by a factor of 500 (see Figure 2) implies a gas volume of 2 million cubic metres.

CO_2 can be ejected without associated expulsion of salt rocks (so-called "blower" or blow-out). On 17 April 1958, an exploration drilling in the Menzengraben mine hit a CO_2 pocket. The gas flowed into the relatively small mine and killed six miners. Since the gas did not leave the mine, the volume can be estimated at about $5 \cdot 10^5$ m^3.

Another CO_2 gas blow-out, again caused by an exploration hole, occurred on 27 to 30 August 2003 in the Unterbreizbach potash mine. With a vertical hole drilled from a lower drift in a depth of about 950 m (situated in the Lower Werra rock salt) the thickness of carnallitite in the hanging wall was to be explored for a subsequent recovery of the carnallitite bulge. The vertical hole had been pierced through the 58 metres of carnallitite and stood four metres in the Middle Werra rock salt when the gas blower was triggered.

Through the exploration hole (diameter of 37 mm), enormous volumes, later estimated at about five million cubic metres, of CO_2 gas flowed into the pit. Due to the supercritical state (22 MPa, 31°C) of the trapped CO_2, this corresponds to a cavity volume of about 10,000 m^3. The cooling of the highly pressurized gas at the exit of the hole formed a CO_2 glacier (30 to 35 m long, 5 to 6 m wide and up to 3 m high) in the rock salt drift, at an ambient temperature of about 30°C (Figure 3).

By far the largest CO_2 outburst occurred on 01 October 2013 in Unterbreizbach (see Figure 4). It was triggered by a blast in the (carnallitite) potash

Figure 4: Outburst cavity in Unterbreizbach

seam Thuringia in a depth of 900 m, which left a protective barrier of only a few meters to a cavern of about 100,000 m^3 in the rock salt hanging wall. This remaining salt barrier could not withstand the fluid pressure (22 MPa, corresponding to lithostatic pressure), and the CO_2 exploded into the pit. The strong expansion distributed the CO_2 in the whole mine in a matter of minutes and killed three miners close to the shaft, about 7 km from the burst point. The blast was so strong that gas and dust were ejected from the Unterbreizbach II shaft in spite of the enormous volume of the connected Unterbreizbach and Merkers mines.

Pressure and temperature conditions (22 MPa, 31°C) again imply an expansion by a factor of 500. Assuming that 20% of the 100,000 m^3 of cavity volume were created by the ejection of rock salt debris, one arrives at a volume of 40 million cubic metres of free CO_2. The additional release of about 2 million cubic metres of mineral-bound CO_2 is negligible in this case.

These examples from potash mining show that rock salt can trap fluids under high pressure for long times.

2.2 *Outburst cavities and tightness*

It is well-known that in abandoned gas storage caverns in salt rock, the brine pressure grows due to the viscoplastic behaviour (convergence) of the surrounding rock salt until it reaches lithostatic pressure. In the roof of high caverns, brine pressure can even exceed lithostatic pressure, leading to pressure-driven fluid percolation (Minkley et al., 2013).

Figure 5 sketches the geological situation in the Werra deposit. The Werra rock salt is divided into lower, middle and upper series by the potash seams

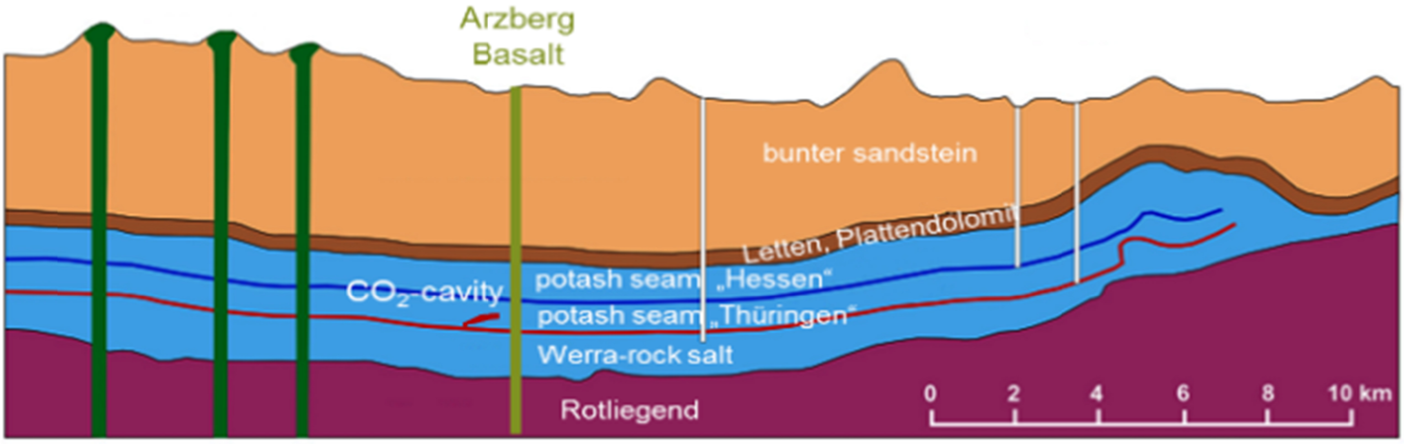

Figure 5: Geological profile of the Werra salt deposit. (Source: K+S AG)

Thuringia and Hesse. The cavity created by the outburst in Unterbreizbach 2013, starting out immediately above the seam Thuringia, has a length of about 180 m and height of 67 m as measured from the roof of the seam (see Figure 6). The cavern is located immediately west of the Arzberg basalt intrusion, which has basalt columns reaching up to the surface. One might thus ask why the CO_2 cavern extends more or less horizontal rather than vertical similar to the basaltic intrusions (see Figure 5).

The horizontal extension can be traced back to the tertiary volcanic processes that created the cavern: High temperatures partially or completely transformed carnallitite into sylvinite, with an accompanying volume reduction by as much as 50%. This created systems of cavities in the hanging wall Werra rock salt.

Figure 7 shows a geomechanical model of this process, simulating the slice-like recovery of potash by longwall mining: The height of a potash seam (red, below yellow band) was decreased by 3.5 m along a length of 100 m. The figure shows the resulting system of cracks above the seam and the generation of elongated horizontal cavities by separation of rock strata in the hanging wall (cf. the cavern shape in Figure 6). A larger volume reduction would correspondingly lead to larger cavities.

Hence, volume reduction by thermal transformation of potash salts generates horizontal caverns in rock salt. In the case of the Unterbreizbach outburst, volcanic CO_2, originating from the same tertiary volcanism that created the cavities, migrated into a cavern of about 10^5 m^3 and stayed trapped there in a supercritical state for about 20 million years.

Even though the CO_2 was trapped under lithostatic pressure in a supercritical phase, no pressure-driven percolation occurred from the cavern roof (Minkley et al., 2013). The cavern height of 67 m implies an excess pressure at the roof of about 0.8 MPa. The hydraulic tensile strength of the salt rock successfully inhibited the percolation into higher strata for geological timescales. As a geological analogue, this clearly demonstrates the isolation potential of salt rocks over millions of years, even for high-pressure fluids.

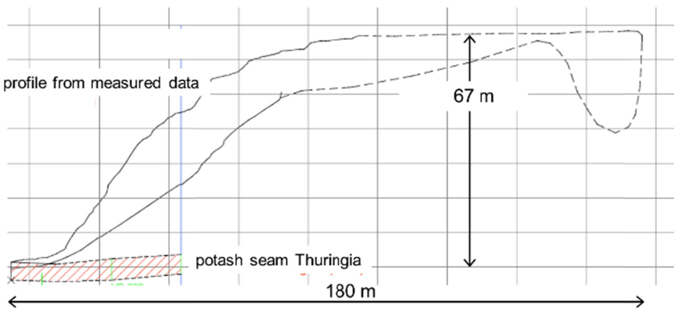

Figure 6: Geometry of the tertiary CO_2 cavern in the middle Werra rock salt above the potash seam Thuringia.

3 REQUIREMENTS FOR NUCLEAR WASTE DISPOSAL

Germany´s heat-generating nuclear waste is solid, comprises about 40,000 m^3 (including containers, VSG a (2012)) and needs to be isolated for about one million years. From the natural analogues discussed in Section 2, which show permanent containment of 10^4 to 10^5 m^3 of supercritical CO_2, one can conclude that a repository in salt rocks is suitable for nuclear waste disposal.

The concept of permanent complete containment in salt formations is based on the viscoplastic behaviour of salt rock, which forms a barrier impermeable

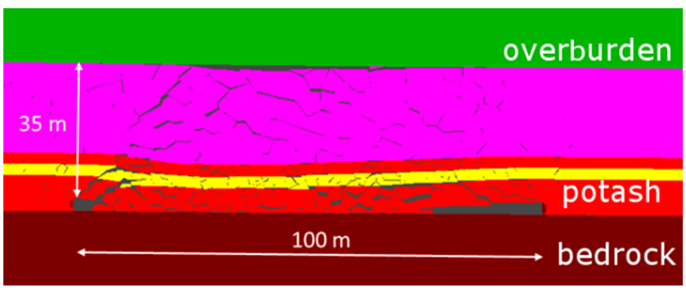

Figure 7: Geomechanical model of disturbances in the hanging wall due to horizontal volume reduction in the potash seam. Note the inclined fracture development.

to fluids up to the lithostatic pressure (minimal stress criterion, Minkley (2009)). Rock salt is a polycrystalline sediment with no connected pore space. In contrast to other rocks, it reacts to slowly acting stresses with creep deformation, without developing fractures or joint systems like crystalline hard rock. Furthermore, the water content is very low (e.g. <0.2% in domal salt, respectively <1% in bedded salt), such that mass transport only occurs as diffusion along the grain boundaries (Hansen, 2014) without advective flow. Hence, the transport rate is orders of magnitude below e.g. diffusion through a fluid-filled pore space in clay (GRS, 2008).

Thus, the geological barrier salt allows, if the geotechnical barriers are similarly tight, a complete containment of nuclear waste, i.e. no emission of contaminants into the biosphere. This is in contrast to a safe containment in other repository options such as claystone or granite with limited release of radionuclides. The long-term geological analogues discussed in Section 2 support this scenario.

It remains to be checked to which extent complete containment is compatible with retrievability, as required by the Federal Ministry of the Environment (BMU, 2010). The BMU stipulates that

- waste containers must be recoverable from the closed and abandoned repository for 500 years, and
- the measures to ensure retrievability must not impair the passive barriers and thus the repository´s long-term safety.

The concepts of reversibility and retrievability while maintaining the passive safety and the robustness of the geological and technical barriers have the potential to play a significant role in public acceptance of geological disposal (OECD/NEA, 2012).

For drift emplacement in salt formations, retrievability does not constitute a restriction with regard to complete containment. A re-mining of backfilled drifts and subsequent excavation of the waste containers in rock salt is technically feasible without major changes to the disposal concept.

For borehole emplacement, on the other hand, combining retrievability and complete containment is an unsolved problem so far. Lining the boreholes with steel tubes, as suggested in VSG a (2012), would prevent the rock salt convergence and hence the containment. In addition, some deformation of the boreholes, which are hundreds of metres deep, cannot be excluded and would defy the original retrievability purpose. Filling the annular space of the boreholes with a porous material such as silica sand (VSG c, 2013) would also form permanent fluid pathways to the waste containers.

In the following, we will suggest an alternative geotechnical concept to combine the main advantage of salt, i.e. complete containment, with the requirement of retrievability. The new concept is based on a robust geological and an instantaneous and completely isolating geotechnical barrier.

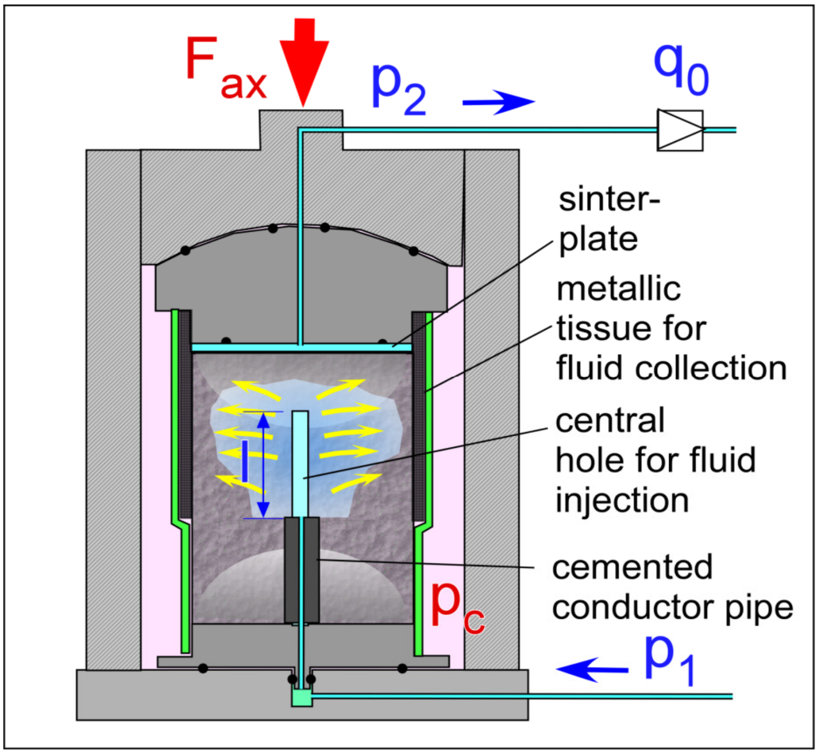

Figure 8: Servohydraulic testing machine and experimental setup for permeability measurements. Flow rates are measured at the top (labelled by q_0).

4 COMPLETE CONTAINMENT IN MOLTEN SALT

So far, the repository concept for disposal in salt is based on the isolation provided by the salt rock as geological barrier and crushed salt backfill as a geotechnical barrier. Over long timescales, convergence of the host, rock driven by the lithostatic pressure, will reduce the porosity of the backfill and completely seal in the waste containers.

As long as this compaction process is not sufficiently progressed, the porous backfill in the shaft and drifts could present an access path for fluids to reach the waste containers, where water or brine could cause corrosion and release of gases. In the worst case scenario, gas pressure and rock convergence could then lead to the emission of radionuclides into the biosphere via the fluid phase.

Hence, a problem of crushed salt backfill is the long compaction time, during which the porosity presents a potential contamination path, so that one cannot reach quick complete containment. Furthermore, our knowledge of the compaction behaviour of crushed salt is limited in the cases of interest, i.e. porosities below 10% and compaction rates slower than 10^{-10} s^{-1} (GRS, 2008).

As an alternative, one might look for non-porous and immediately isolating backfill materials. In combination with the geotechnical seals (dams, shaft plugs), this would allow for immediate complete containment after the closure of the repository. Since there would be no pore space left in the emplacement chambers or boreholes, water or brine could not reach the waste containers. Additionally, a non-porous and hence non-compacting backfill material would prevent the rock convergence from squeezing out contaminated solutions. Hence, the scenario of contamination by fluids, as alluded to above, could be completely avoided!

Such an alternative is the use of molten salts (Minkley, 2012). Liquid salt mixtures are for example proposed as combined fuel and heat exchange fluid in fourth-generation nuclear reactors (thorium reactors, see Merle-Lucotte et al., 2008), and are used as heat exchange and storage medium e.g. in solar thermal power plants (Kearney et al., 2002). In the latter case, commercially available products are usually composed of mixtures of nitrite and/or nitrate salts, with melting temperatures in the range of 120°C to 250°C, and chloride-based formulations have been analysed (Linsinger and Radtke, 2013).

In the repository, the emplacement chambers or boreholes would be filled with molten salt, and for a mixture with sufficiently low melting point, (e.g. HITEC at 142°C), the heat generated by the waste would keep the salt in the liquid phase for centuries. This would also solve the problem of retrievability

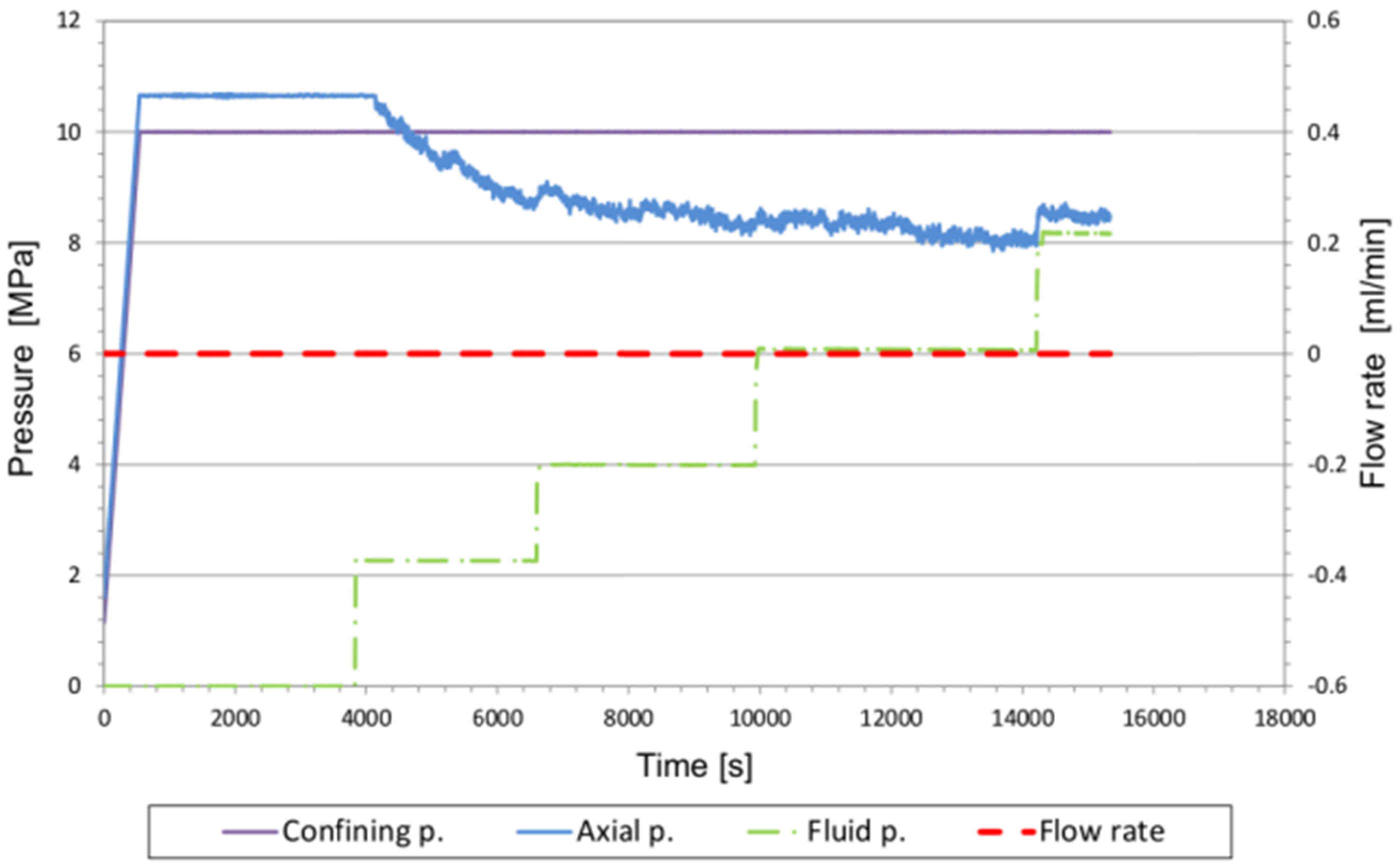

Figure 9. First experimental stage: Pressures and flow rate through the sample versus time. After about 4000 s, the experiment is switched to strain control with constant confining pressure, hence the axial pressure shows small wiggles. The fluid pressure is increased in steps of 2 MPa. No fluid flow could be observed.

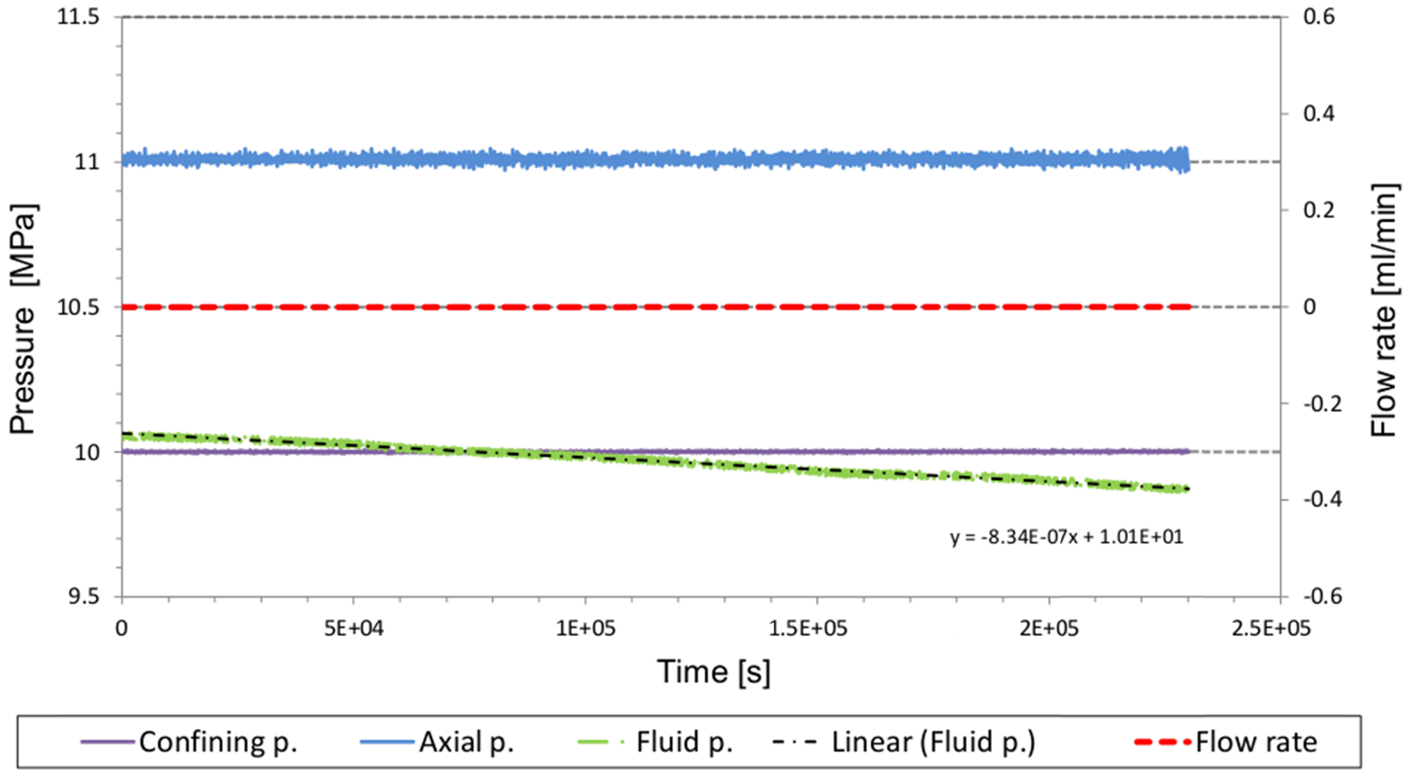

Figure 10. Second experimental stage: Axial and confining pressure are kept constant at 11 and 10 MPa, respectively, with fluid pressure at 10 MPa. Again no fluid flow through the salt is observed. Fluid pressure decreases very slowly, probably due to diffusion into the sample.

for borehole emplacement, while maintaining complete containment.

To test this alternative backfill concept, the IfG has conducted first laboratory analyses.

5 LABORATORY RESULTS: IMPERMEABILITY OF REFROZEN SALTS

The IfG used samples made from HITEC salt, a commercially available product manufactured by Coastal Chemical. Its composition is 53% KNO_3, 40% $NaNO_2$, and 7% $NaNO_3$; the melting point is 142°C. Samples were prepared in a steel pipe closed at one end. The salt mixture was filled into the pipe, heated in a drying oven to a temperature above the melting point and slowly cooled.

The solidified salt samples had a density of 2.096 g/cm^3. To analyse the permeability, the samples were placed in a triaxial cell of a servohydraulic testing machine (see Figure 8). Fluid pressure was applied through a pipe-lined borehole (diameter 7 mm, length 25 mm) at the centre of the sample to avoid surface effects, and the flow rate through the sample was measured. As a testing fluid, we used a very low-viscosity oil to which a tracer was added to enhance visibility of fractures and leaks.

Stress conditions have been chosen either as hydrostatic ($\sigma_{\text{ax}} = \sigma_{\text{conf}}$) or extensional ($\sigma_{\text{ax}} < \sigma_{\text{conf}}$), respectively, corresponding to possible in-situ stresses.

In the first experimental stage (see Figure 9), the samples started out in a hydrostatic stress state, with axial and confining pressures being (approximately) equal at 10 MPa. After a consolidation time of about one hour, the testing machine was switched to strain control with slight extensional strain, such that the axial pressure became the minimal principal stress. Then the fluid pressure in the centre of the sample was raised in steps up to the minimal stress (8 MPa) to determine the initial permeability of the recrystallized HITEC salt.

As can be seen in Figure 9, no fluid flow through the sample could be induced. Hence this experiment showed that for pressure differences $p_{\text{fluid}} - \sigma_{\text{min}} \leq 0$, the HITEC sample can be considered hydraulically impermeable.

This result continues to hold for longer times: In the second stage of the laboratory programme, the fluid pressure was kept at 10 MPa for 72 hours, with either confining or axial pressure acting as minimal principal stress, equal to the fluid pressure. Figure 10 shows the results of a test with fluid pressure equal to the confining stress, again with no measurable flow through the sample.

The fluid pressure did decrease slightly during these tests. Assuming tightness of the experimental apparatus, this could be explained by a slow migration into the sample. The pressure system of the experiment has a volume of $V_0 = 20$ cm^3, the test fluid´s bulk modulus is $K = 4$ GPa. Thus the observed rate of pressure decrease, $\dot{p} = 8.3 \cdot 10^{-7}$ MPa·s^{-1}, implies a migration rate of

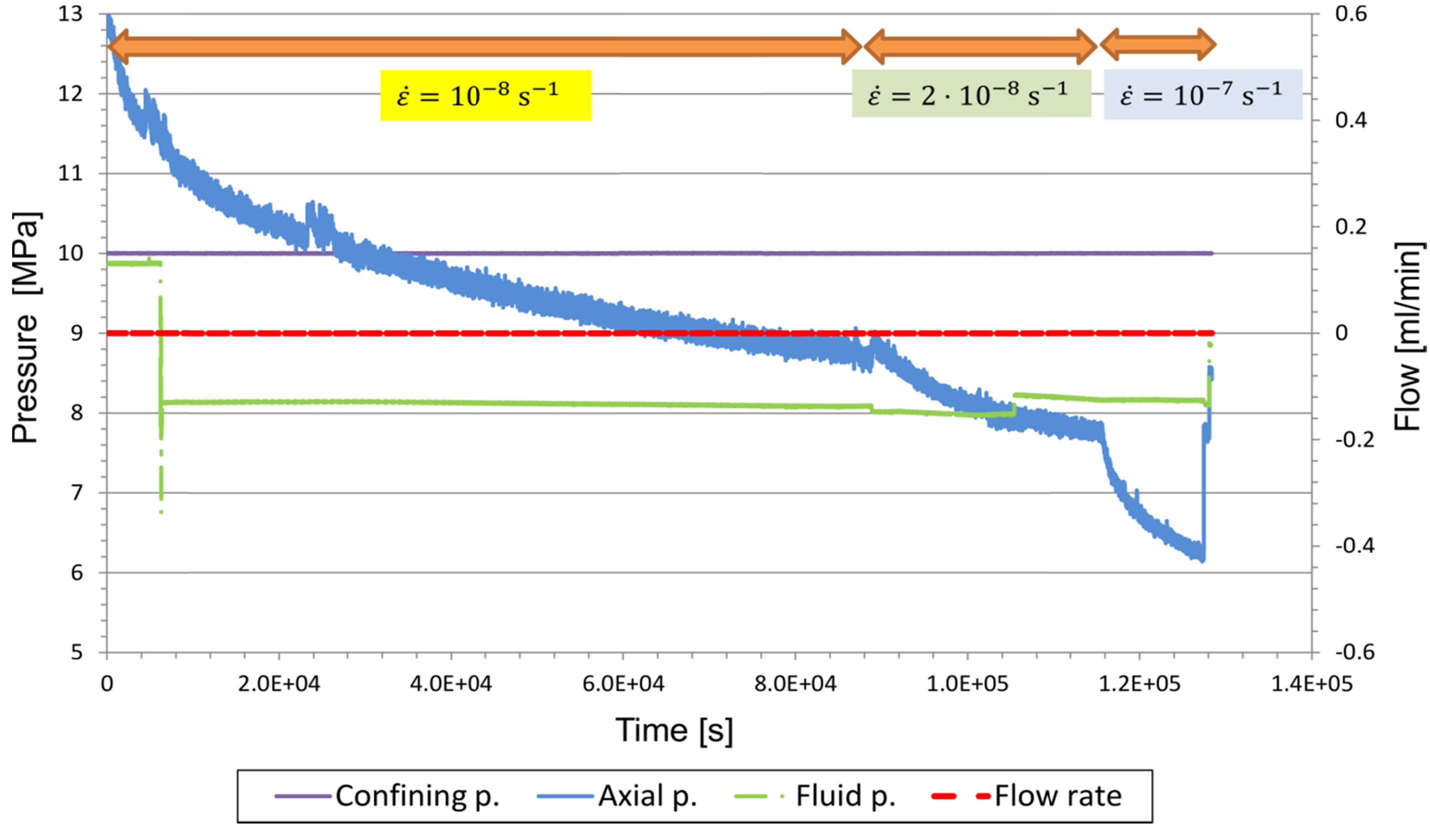

Figure 11. Third experimental stage: The sample is extended at increasing rates, until axial pressure drops sufficiently below fluid pressure for rapid percolation do develop.

$$\dot{V} = \frac{\dot{p}}{K} \cdot V_0 = 4.2 \cdot 10^{-9}\ \frac{\mathrm{cm}^3}{\mathrm{s}}, \quad (1)$$

which in turn leads to a permeability much below the detection threshold at around $\kappa_{\mathrm{min}} \approx 10^{-22}\ \mathrm{m}^2$.

In the final stage, confining stress and fluid pressure were kept constant at $\sigma_{\mathrm{conf}} = 10$ MPa and $p_{\mathrm{fluid}} = 8$ MPa, while the axial pressure was decreased by a strain-controlled extension. The extension rate started out at $\dot{\epsilon} = 10^{-8}\ \mathrm{s}^{-1}$, was later increased to $2 \cdot 10^{-8}\ \mathrm{s}^{-1}$ and finally to $10^{-7}\ \mathrm{s}^{-1}$. Results are shown in Figure 11. Due to the extension, the axial stress falls first below the confining pressure, becoming the minimal principal stress, and then below the fluid pressure. Once this pressure difference, $\Delta p = p_{\mathrm{fluid}} - \sigma_{\mathrm{min}}$, reaches a critical value, which in this case was about 2 MPa (at time $t = 128000$ s), a rapid fluid-pressure driven percolation develops. As expected, this fracture occurs in the direction of maximal and perpendicular to the minimal principal stress, i.e. horizontal (due to the extensional strain).

As can be seen in Figure 12, the fluid leakage is concentrated to a single spot in the centre of the sample. Hence, the pressure difference did plausibly open up a single, rather concentrated channel. Presumably, this is at least partially due to the very fine-grained structure of the HITEC sample, which differs from naturally occurring rock salt. At the fluid breakthrough, the maximum measured permeability corresponds to an average value of around $\kappa = 10^{-18}\ \mathrm{m}^2$.

Figure 13 summarises the laboratory results of measured permeabilities of rock salt and HITEC as a function of $\Delta p = p_{\mathrm{fluid}} - \sigma_{\mathrm{min}}$, the difference between fluid pressure and minimal principal stress. Even in the laboratory, HITEC is impermeable for $\Delta p = 0$, as predicted by fluid percolation models. Similar behaviour is displayed by natural rock salt under in-situ conditions as a characteristically impermeable medium (Minkley et al., 2013).

6 GEOMECHANICAL MODELS OF BOREHOLE EMPLACEMENT

Due to their huge footwall barrier of thousands of metres, salt domes are well-suited for waste emplacement in vertical boreholes. Disposal in higher depth offers the advantage of higher convergence rates and consequently faster containment. However, so far there is no convincing scheme that combines this advantage with the requirement of retrievability.

The Gorleben salt dome has been analysed in the preliminary safety analysis (Vorläufige Sicherheitsanalyse Gorleben, VSG b, 2012). The analysis included thermomechanical simulations of borehole emplacement of BSK-3 waste containers in boreholes of 300 m depth, with a spacing of 50 m, starting from the 870 m level. The computation performed by the IfG used the visco-elasto-plastic constitutive model for salt rocks and an adhesive friction model for contact surfaces and discontinuities in the salt rock (Minkley & Mühlbauer, 2007).

Figure 12. HITEC sample after percolation test, with the fluid indicated by the tracer and bubble. The leakage is localised to a small spot.

The left panel of Figure 14 shows the temperature distribution 30 years after emplacement. The temperature around the waste reaches up to 200°C in the central boreholes and about 170°C in the outer ones. Hence, a backfill with HITEC salt or similar salt mixtures (see e.g. Linsinger & Radtke, 2013) would be in the liquid phase. Temperatures above the melting point will be maintained for centuries, such that the waste could be readily retrieved. Over time, the molten salt would develop lithostatic pressure, acting isotropically on the waste containers.

After backfilling, the boreholes would need to be sealed with a tight plug to prevent borehole convergence. The IfG has successfully tested a gastight borehole seal using a Sorel cement plug of diameter 1.3 m in a salt mine (Popp et al., 2012). The MgO concrete plug tested by the IfG has shown excellent load-bearing and hydraulic properties, forming an impermeable seal at least up to lithostatic stress.

Even after longer times, when the backfill salt has solidified, the waste containers could be retrieved by opening the seals and reheating the backfill, e.g. after installation of electrical heaters in vertical boreholes. The containers could then be pulled out of the liquid salt.

Due to the instantaneous complete containment of the waste containers, first in the molten and later the recrystallized backfill salt, this scheme prevents any water from the overburden from reaching the waste. Even if this would happen, there is no mechanism

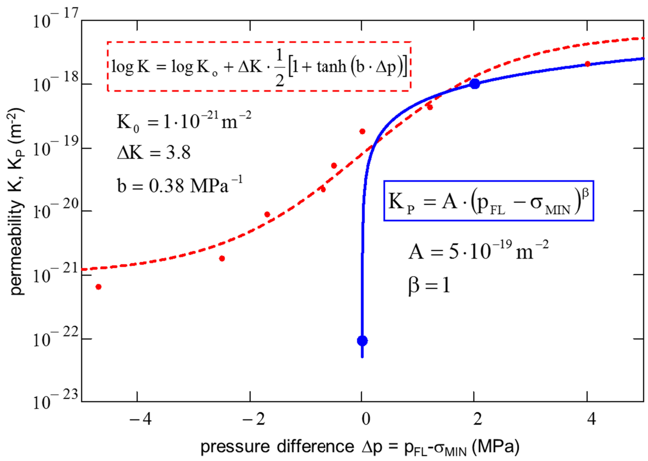

Figure 13: Permeability of rock salt (red, dashed) and HITEC (blue, solid). The power-law behaviour is predicted by fluid percolation models.

that would squeeze out contaminated brine, since there is no backfill compaction except for a volume decrease of about 4% at recrystallisation.

Besides the backfill molten, respectively recrystallized, salt, as a geotechnical barrier, complete containment is ensured by the geological saliferous barrier of the salt dome. The waste-generated heat in the emplacement field leads to a thermal expansion of the rock salt which lifts up the top of the dome by several metres. Some decades after emplacement, the resulting extensional strain will temporarily lower the minimal principal stress at the salt surface below the ground water pressure. In other words, the minimal stress criterion is violated, and the violation region can extend more than a hundred metres into the salt dome, even deeper along contact surfaces between different rock salt strata (see right panel of Figure 14). Hence, fluid pressure driven percolation, i.e. a migration of water or brine into the salt rock along grain boundaries, will start at the salt surface. However, the salt dome is sufficiently large, such that this violation of barrier integrity did not reach the waste disposal level in any of the considered simulations.

To demonstrate the robustness of the salt barrier against the thermal impact, the thermal power of the waste containers was increased exemplarily by a factor of 1.5. This raised the maximal temperature from 200°C to about 280°C, the salt surface lift-up increased, and the violation of the minimal stress criterion extended further into the salt by about 125 m. Even in this extreme case with unrealistically high thermal load an intact salt barrier of several hundred metres remained, so that the geological saliferous barrier system is rather robust.

The thermomechanical effects on the barrier integrity peak a few decades after emplacement. After that, salt creep will reduce the region where the minimal stress criterion is violated, although the heat influx continues to lift the salt dome. After one hundred years, the anthropogenically induced violations

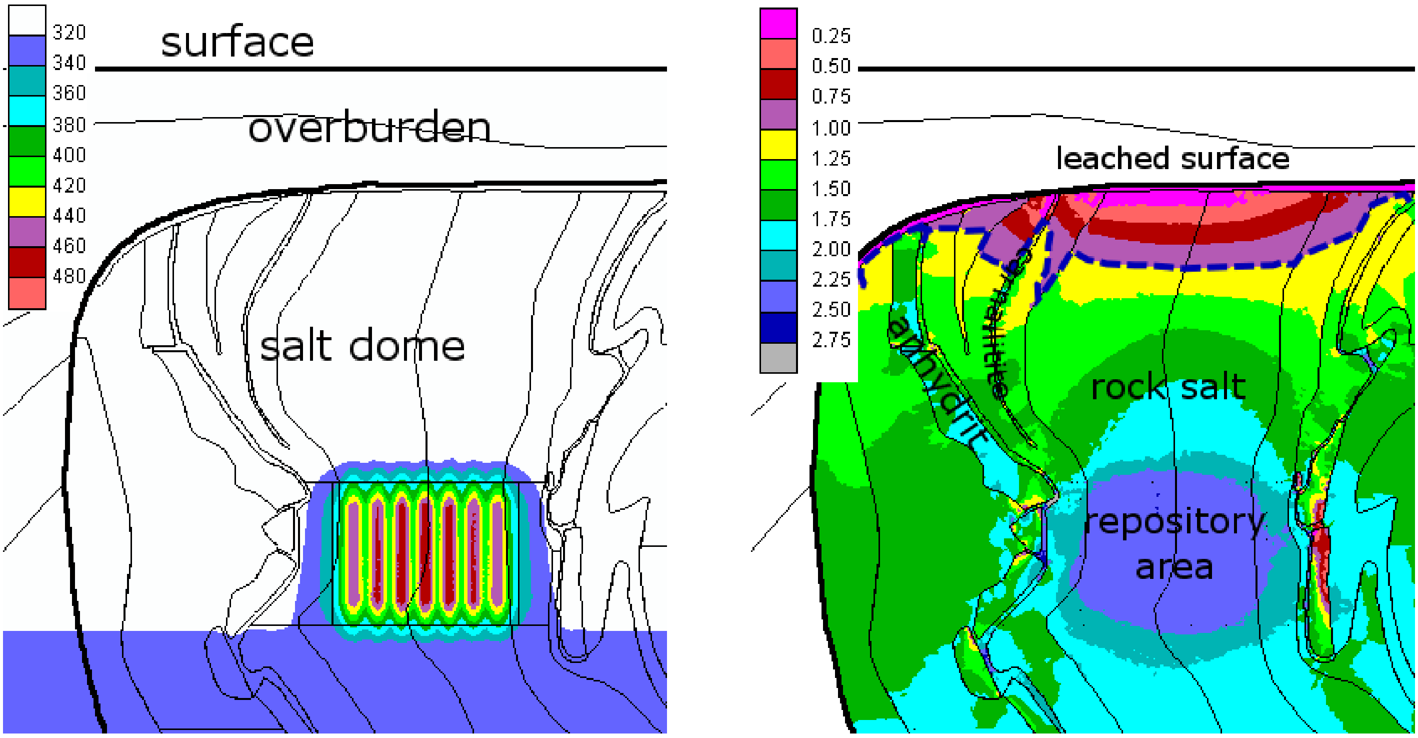

Figure 14: Model of borehole emplacement in the Gorleben salt dome 30 years after emplacement. The figures span 1400 m× 1400 m each. *Left panel*: Temperature in K, *right panel*: ratio of minimal principal stress to groundwater pressure (minimal stress criterion). The criterion is violated for values smaller than one, i.e. purple, red and pink (above blue dashed line).

of barrier integrity have basically stopped, and the salt dome behaviour is again dominated by the geological situation, under which salt has demonstrated its long-term integrity and isolation capacity (see Section 2).

7 SUMMARY AND CONCLUSIONS

Natural analogues known from salt and potash mining show that gases such as CO_2 are trapped in salt rocks in gaseous, liquid and supercritical form over geological timescales. For example, CO_2 which migrated into the Werra salt deposit during tertiary volcanism was contained in cavities of volumes up to 100,000 m^3 for about 20 million years. Due to the viscoplastic behaviour of the host rock, the pressure in these fluids was equal to the lithostatic (overburden) pressure.

The German supply of heat-generating nuclear waste comprises about 40,000 m^3 (including containers) and is, in contrast to supercritical CO_2-fluids, in a solid state, i.e. less mobile. Because it is a very limited volume, it could be, in principle, deposited in a single salt cavern. However, to reduce the thermomechanical load of the surrounding salt rock barrier the waste containers are distributed over a larger area (drift emplacement) or volume (borehole emplacement). In particular, this reduces the perturbed regions at the top of the salt deposit where the minimal principal stress is lower than the acting ground water pressure (i.e. the violation of the minimal stress criterion initiating pressure-driven percolation).

However, in salt domes we prefer the borehole concept, because the waste is emplaced at greater depth which favours the tight inclusion due to the salt visco-plastic behaviour. To meet the requirement of retrievability, we propose a novel backfill material, i.e. the use of (eutectic) salt mixtures with low melting points, rather than the usual crushed salt with high initial porosity. Salt mixtures with melting points in the region of 100°C to 200°C are used as heat-exchange fluids in various industrial applications, e.g. for solarthermal power plants. Similar mixtures have been proposed as combined fuel and heat exchange fluid in fourth-generation nuclear reactors. In the repository, the heat generated by the nuclear waste would keep the backfill in a liquid state for centuries before it slowly recrystallises.

Laboratory investigations at the IfG have shown that recrystallised HITEC salt is impermeable to fluids similar to natural rock salt loses its integrity only for fluid pressures above the minimal principal stress.

This backfill concept with molten salt for repositories for heat-generating nuclear waste has several distinct advantages:

- Immediate and complete containment of the waste containers in the molten salt,
- no water or brine access to the containers due to the higher density of the backfill,
- no squeeze-out of contaminated solutions by creep convergence,

- only slight volume reduction upon recrystallisation,
- and retrievability at any time.

The thermomechanical disturbance of the salt barrier could be further reduced by dispersing the waste-generated heat, using the molten salt as heat exchange fluid. As an additional benefit, one could envisage the generation of energy, somewhat similar to a geothermal power plant or a radiothermal generator. In this case, the efficiency could be increased by concentrating the waste in a smaller volume. On the other hand, the integrity of the geological and geotechnical barriers has to be ensured even if the heat dispersal is stopped prematurely.

We think the use of low-melting salt mixture backfill as a geotechnical barrier warrants – and needs – further modelling, laboratory and in-situ studies. This includes the calculation of the spatial and temporal evolution of the temperature field in the emplacement area, the analysis of the geochemical long-term stability of the molten salts in contact with the host rock and the demonstration of the feasibility of the technical concept.

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