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Technical Conference Paper

1965 – 2025

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SMRI Fall 2025 Technical Conference
29-30 September 2025
Wichita, Kansas, United States

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THM-Based Infiltration Assessment for Salt Cavern Design accounting for Macroscopic Fractures

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Abstract

Infiltration fractures are macroscopic separations within the rock salt matrix that allow fluid migration through an otherwise impermeable medium. These fractures can form during gas withdrawal phases in salt caverns as a result of cooling at gas pressure reduction. Accurately modeling the formation and evolution of these fractures - while simultaneously considering thermal, hydraulic, and mechanical (THM) effects - remains a challenging task that often requires simplifications.

In thermo-mechanical (TM) models, hydraulic processes are represented indirectly. Fracture lengths are estimated by assuming that the full cavern gas pressure acts behind the fracture front within the intact rock salt, enabling crack propagation whenever the mechanical stress state drops below a critical threshold. Since rock salt is generally considered impermeable, this assumption is deliberately conservative. However, there is growing interest in modeling approaches that more realistically reflect the pore pressure distribution around caverns and capture localized increases in permeability caused by tensile damage.

Several constitutive frameworks exist to link effective stresses and evolving permeability in salt, including the Stormont criterion, LMS Palaiseau method, TU Clausthal approach, and Minkley's minimum pressure criterion (IfG). Among these, the IUB criterion shows significant promise. This study applies the IUB criterion to identify zones where fluid transport becomes significant. An additional term is introduced to model sharp permeability increases once effective tensile stresses exceed the effective tensile strength of rock salt. This extension allows for the simulation of accelerated fluid infiltration under cooling conditions using the multiphysics finite element software COMSOL. The model captures the effect of thermally induced tensile stresses on permeability evolution near caverns.

For comparison, TM-based models implemented in FLAC3D are used, which do not explicitly couple hydraulic processes during fracture propagation. This enables an assessment of the conservativeness of simplified infiltration fracture models in FLAC3D when estimating storage rates and explores whether THM-coupled simulations provide opportunities to optimize gas storage operations.

Key words: Salt Cavern Design, Infiltration Fractures, THM Simulation, Permeability, Gas Storage

Introduction

In recent years, the operational profile of gas storage caverns in Germany has shifted toward higher flexibility, with increased frequency and intensity of gas withdrawal and injection cycles throughout the year. This development is associated with more pronounced thermodynamic variations, particularly during rapid gas withdrawal, which can lead to significant temperature drops in the cavern atmosphere and the surrounding rock salt.

Such cooling processes induce thermo-mechanical stress changes in the salt formation (Figure 1). When the mechanical pressure at the cavern wall drops below the gas pressure, effective tension emerges. Due to the relatively low tensile strength of rock salt, effective tensile stresses may cause the formation of tensile damage near the cavern wall (see yellow area). This damage, often referred to as infiltration fractures (see Figure 2), can increase the permeability of the rock salt and allow localized fluid transport in an otherwise impermeable medium [1].

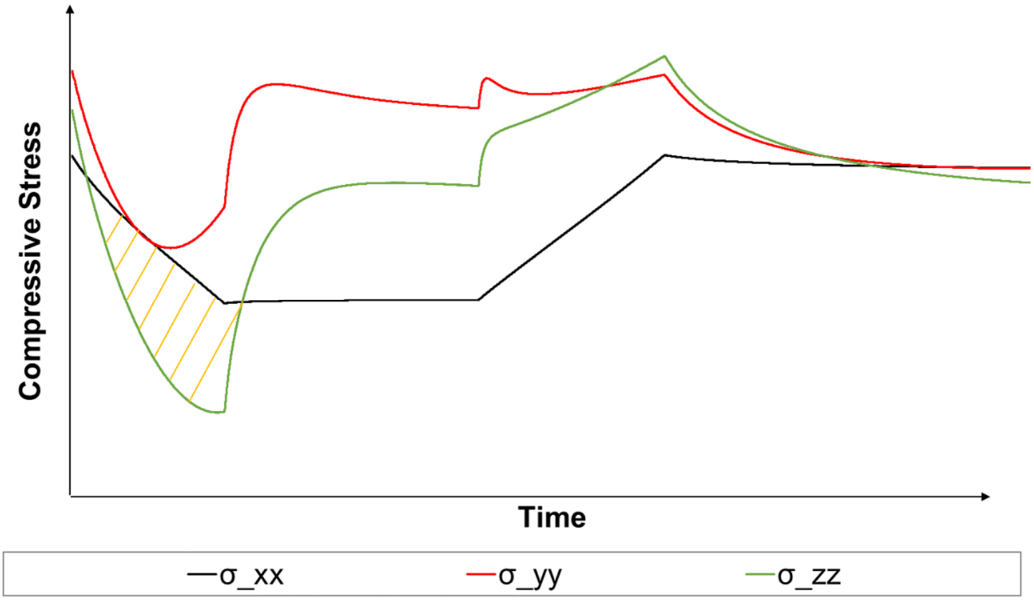

Figure 1: Stress vs. time for a thermo-mechanical calculation of an exemplary storage scenario

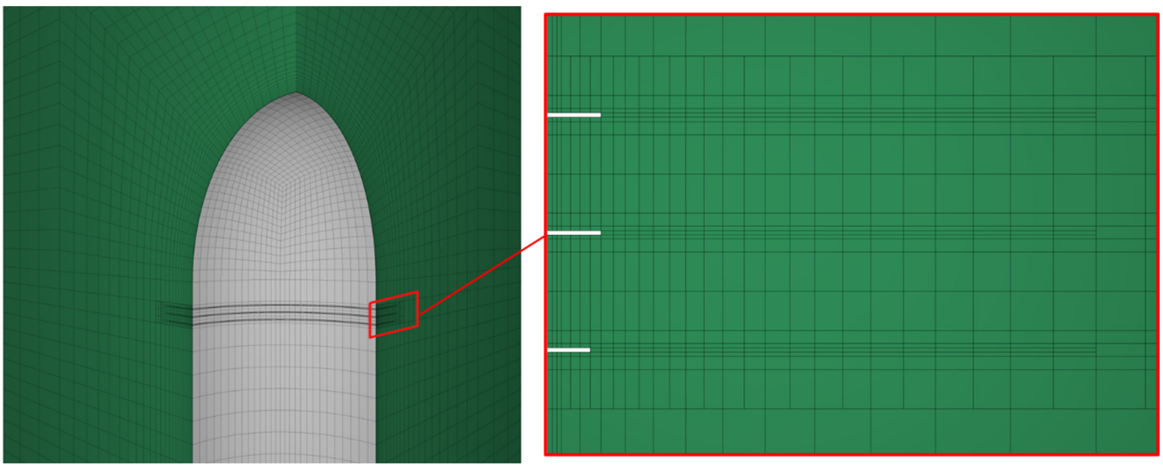

Figure 2: Exemplary illustration of infiltration fractures modelled in FLAC3D

Observations and simplified numerical studies suggest that such processes play a role in the interaction between cavern operation and the surrounding host rock. Still, it has not been possible to verify assumptions made concerning the effects of high storage rates in the field, due to the limited possibilities of exploring the cavern wall and surroundings during its operation. In order to further increase the flexibility of the operating modes, continuous optimization of the numerical models and extensions of the dimensioning concepts are necessary.

Modeling physical interactions around caverns remains a challenge due to the complex coupling between thermal, hydraulic, and mechanical (THM) processes. A common approach is to use thermo-mechanical (TM) models that do not include explicit hydraulic coupling. In such models, fracture propagation is assessed based on the mechanical stress state and material strength assumptions, with the cavern pressure typically assumed to act along the fracture path. The criterion, which defines fracture initiation, is fulfilled as soon as the following equation becomes true:

$$\sigma_t + P_i \geq \beta \quad (1)$$

While σ_t describes the stress components acting normal to the infiltration direction, P_i refers to the cavern gas pressure and β is the effective tensile strength of the rock salt. While computationally efficient, such models treat fluid transport in a simplified manner, neglecting the interaction between pore pressure, permeability evolution, and tensile damage. Instead, a mathematical approach is used to estimate the initiation of damage.

To represent hydraulic effects more explicitly, THM-coupled models have been developed in recent years [2]. Permeability is no longer treated as a constant parameter in numerics, but evolves as a function of effective stress. Several permeability concepts have been proposed to capture this effect in rock salt, including the Stormont criterion [3], LMS Palaiseau approach [4], the TU Clausthal [2] and IfG models [5]. The IUB criterion (illustrated in Figure 3 for an exemplary parameter set) introduces a threshold-based increase in permeability once the effective stresses become tensile, offering a physically motivated mechanism for progressive fluid ingress under tensile conditions [6]. Based on most recent research [7], an additional condition has been implemented into the IUB criterion to account for open pathways due to effective tensile fracturing.

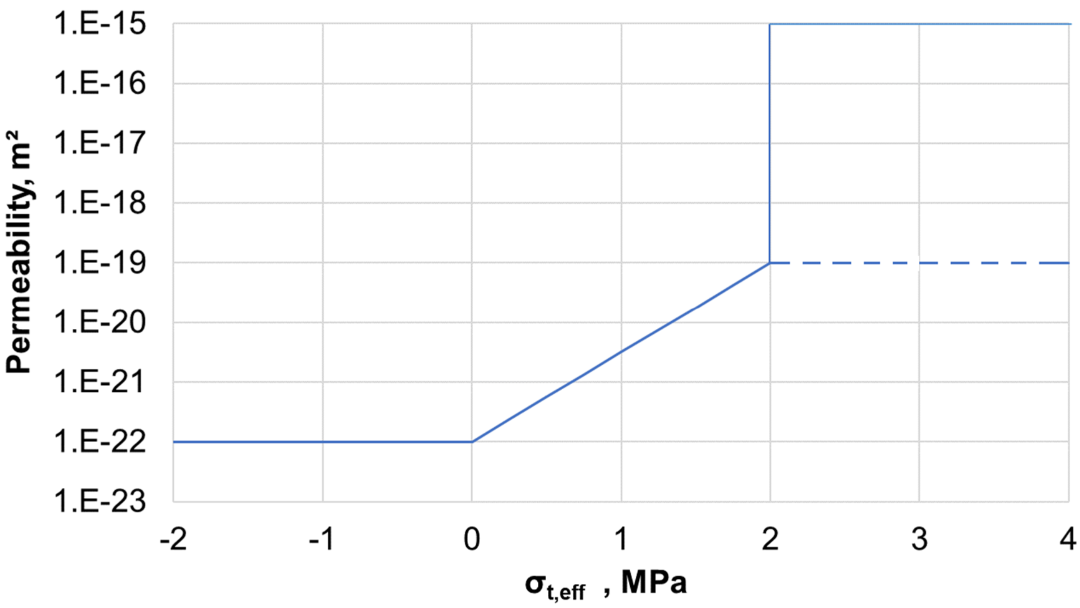

Figure 3: Stress dependent permeability evolution according to the optimized IUB-criterion

The IUB criterion is defined for three stress segments (Equation 1). The parameters $\sigma_{t,eff,min}$ and $\sigma_{t,eff,max}$ describe the limits within which a permeability change from primary to secondary permeability takes place and define the transition zone $TS = |\sigma_{t,eff,max} - \sigma_{t,eff,min}|$.

$$\kappa = \begin{cases} \kappa_{pr} & \sigma_{t,eff} \leq \sigma_{t,eff,min} \\ \kappa_{pr} * \exp(\ln(\kappa_{sec}/\kappa_{pr}) * \frac{\sigma_{t,eff} - \sigma_{t,eff,min}}{TS}) & \sigma_{t,eff,min} < \sigma_{t,eff} \leq \sigma_{t,eff,max} \\ \kappa_{fr} & \sigma_{t,eff} > \sigma_{t,eff,max} \end{cases} \quad (2)$$

The primary permeability is specified by κ_{pr}, the secondary permeability by κ_{sec}. The adaption of the criterion for use in cavern operation is the jump in permeability when the upper stress limit is exceeded. In areas where secondary permeability has already been reached, there is a further increase in permeability to a maximum level κ_{fr} as soon as the stress limit is reached, which is interpreted as an equivalent to macroscopic fracturing of the local rock salt matrix. It was already proven in laboratory experiments that macroscopic fractures can develop under cavern-typical stress states [7].

The change in permeability is considered irreversible and healing mechanisms of rock salt are not taken into account.

This innovation makes it possible to identify areas in which the material has undergone effective tensile damage. In addition, the increased infiltration leads to a propagating fluid front, as is to be expected in a fractured matrix. By analyzing cavern models under infiltration, evaluating the fluid propagation due to tensile damage, it is possible to estimate the conservativeness of the infiltration fracture approach in numerical TM-models, which simplify the local hydraulic pore pressure.

Numerical Models

This paper reveals the outcome of the investigation of thermally induced infiltration processes in rock salt using two complementary numerical approaches with identical material properties (Table 1).

In the first part, a TM-coupled three-dimensional cube model with 5 m edges is developed in FLAC3D [8], using the Lubby2 constitutive model to represent the time-dependent creep behavior of salt.

Stresses are initialized in such a way, that the cube undergoes a first displacement in the x- and z-direction. At the same time it is held at zero deformation in the y-direction (see axes in Figure 4), in order to stay comparable with the plane-strain 2D COMSOL model. After the initialization step, stresses in y- and z-direction are -15 MPa (- 2176 psi), in the x-direction stresses are zero.

Afterwards, in a time dependent study, the west side of the cube is subject to a mechanical pressure of 14.5 MPa (- 2103 psi) in the x-direction, simulating a hydraulic pressure (Figure 5, pressure evolution graph and Figure 4, grey surface). As this pressure is close to the implemented initial stress state, a very critical scenario is modelled where analytically evaluated effective stresses emerge quickly as soon as one stress component drops by 0.5 MPa.

It has to be undermined again, that in FLAC3D no hydraulic processes are simulated. The evaluation of the fracture criterion is based on the mechanical stress state, which is being compared to the theoretical gas pressure acting onto the west side.

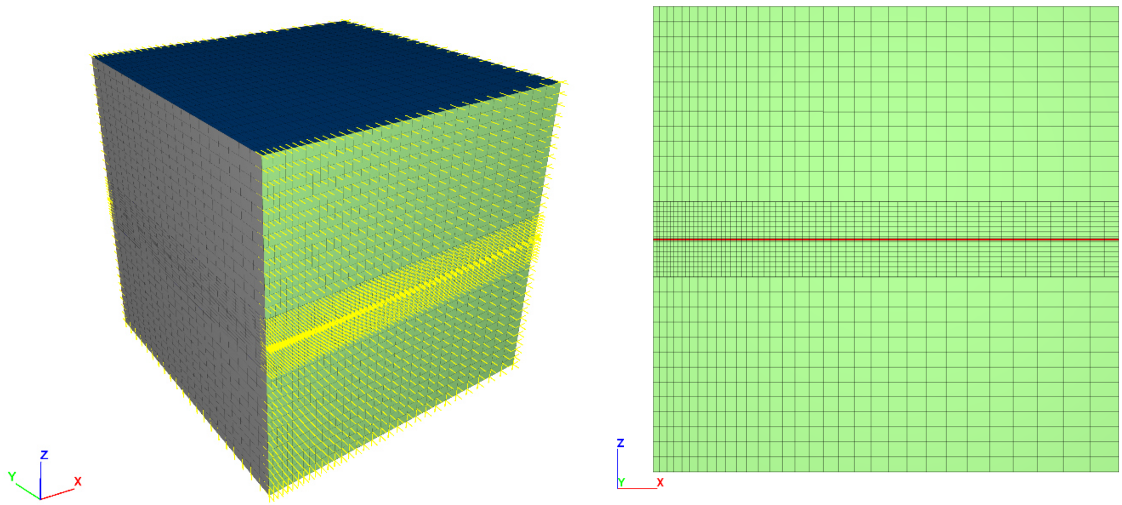

Figure 4: Loading conditions/ Roller bearings (left) and fracture line (right) of 3D cube in FLAC3D

The west side of the cube is then cooled down by 20 K for half a day (Figure 5, temperature evolution graph and Figure 4, grey surface). The temperature affects the mechanical stress state throughout the thermal expansion coefficient.

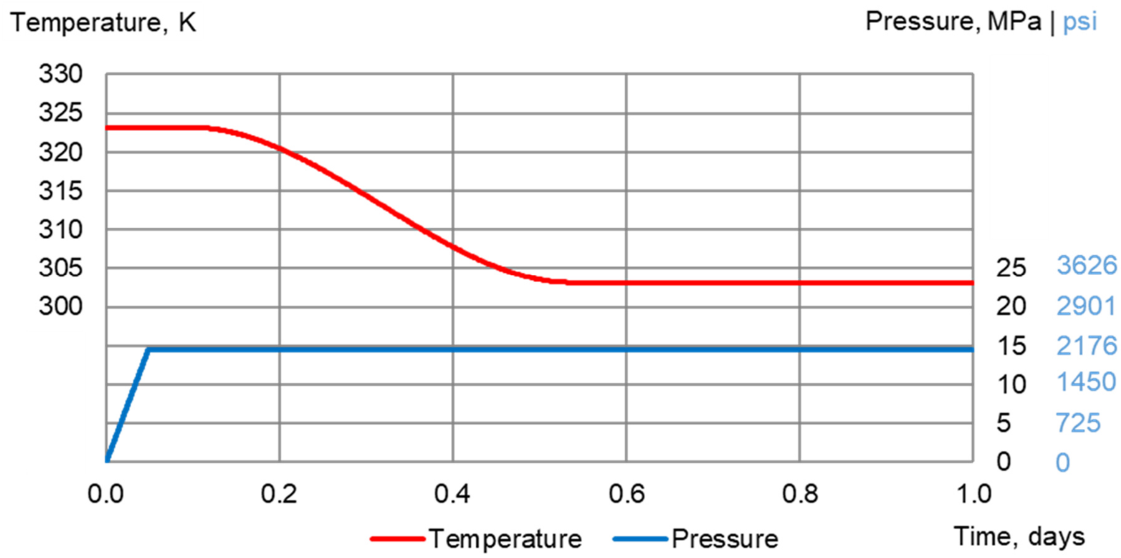

Figure 5: Loading history at west side of cube (at x=0)

Here, the temperature induced fracture propagation is modeled explicitly by defining fracture paths beforehand (Figure 4, red line at right hand side picture). These fracture paths are constantly checked for stresses that are directed orthogonally to the supposed infiltration propagation and as soon as one of these two stresses become more than 2 MPa (290 psi) higher than the induced horizontal pressure, the zone is eliminated and the fracture propagates.

In the second part, a fully THM-coupled cube model is implemented in COMSOL Multiphysics [9]. For calculation efficiency purposes the cube is modelled in 2D, with 5 m edges as in FLAC3D. Boundary conditions and the initial state are modeled as described above, but instead of modeling fractures, the IUB criterion is used to assess permeability changes and fluid propagation driven by effective tensile stresses under cooling conditions.

The infiltration process is simulated using a single-phase Darcy approach, accounting for a storage model based on fluid density and solid porosity. The pore pressure in COMSOL acts as an external isotropic, volumetric load to the inner rock salt matrix. While the fluid density depends on pressure and temperature, the solid porosity is assumed to be constant in this model for simplicity.

As laboratory investigations showed hydraulic fracturing when the injection pressure exceeded the mechanical external loading by about 2 MPa (290 psi) [10], in the THM model a Biot coefficient of 1 is assumed. This way, laboratory experiments are comparable to numerical models investigating permeability changes during mechanical stress reduction. The IUB-criterion depends on the local effective minimum compressive stress and permeability changes are therefore independent to the infiltration direction.

With these modelling assumptions poroelastic effects are being simplified. For the purpose of evaluating the propagation of tensile damage incorporating the hydraulic component into a comparative model, this simplification is justified and appropriate.

Table 1: Material properties for TM and THM model

Physics	Property	Parameter	Value	
Mechanical	Young's Modulus	E	18 000 | 2.611e6	MPa | psi
	Poisson	v	0.25	-
	Density Rock Salt	ρ_S	2100	kg/m³
Thermal	Thermal Expansion	α_T	4e-5	1/K
	Heat Capacity	c_p	875	J/(kgK)
	Conduction	λ	5.21	J/(mK)
Hydraulic	Biot	α_B	1	-
	Porosity	ε_p	0.1	-
	Permeability	κ	variable	m²

The IUB criterion in COMSOL assumes the following boundaries:

Table 2: Limits of the IUB-criterion for the THM model

Parameter	Value	
$\boldsymbol{\sigma_{t,eff,min}}$	0	MPa | psi
$\boldsymbol{\sigma_{t,eff,max}}$	2 | 290	MPa | psi
$\boldsymbol{\kappa_{pr}}$	1e-21	m²
$\boldsymbol{\kappa_{sec}}$	1e-18	m²
$\boldsymbol{\kappa_{fr}}$	1e-15	m²

By comparing the results of both modeling strategies—one fracture-based and the other permeability-based and coupled—this study aims to evaluate differences in the predicted extent and distribution of highly permeable zones and to assess the influence of model assumptions on the estimation of permeability evolution near gas storage caverns under cooling conditions. The optimization potential of simplified fracture models in TM frameworks can be assessed and the added value of THM simulations for predicting fluid migration during cavern operation can be explored.

Results

The temperature reduction at the west side of the cube leads to propagating thermal front (see Figure 6). After one day, the temperature effect can be detected until 1.5 m (4.9 ft) distances from the wall.

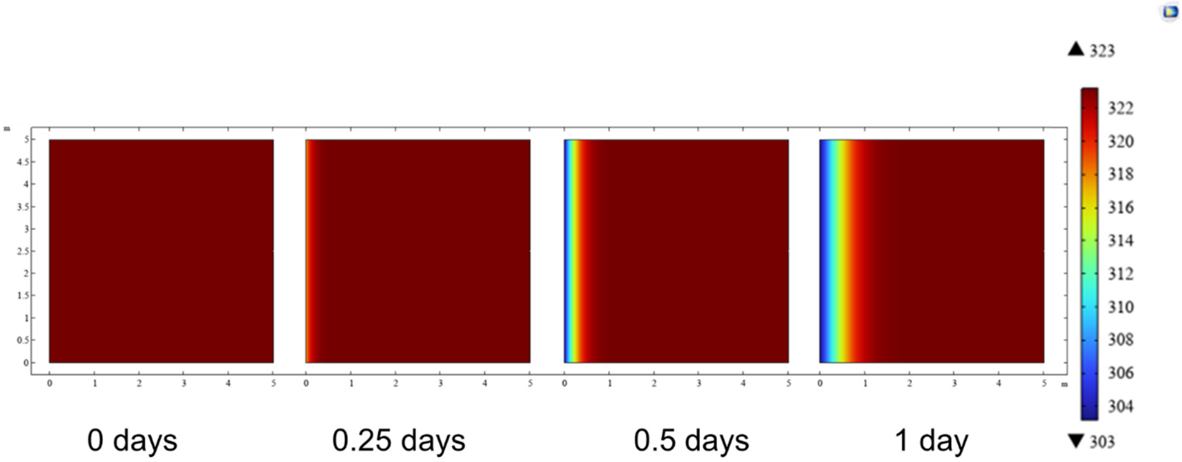

Figure 6: Temperature evolution through cube model in Kelvin

As a consequence of the temperature reduction of 20 K, a macroscopic fracture occurs in the FLAC3D model (Figure 7). The fracture propagates into the rock salt block and reaches a length of 1.5 m (4.9 ft) after one day. The main fracture development occurs during the cooling phase in the first 12 hours (see also Figure 5), afterwards the propagation speed slows down.

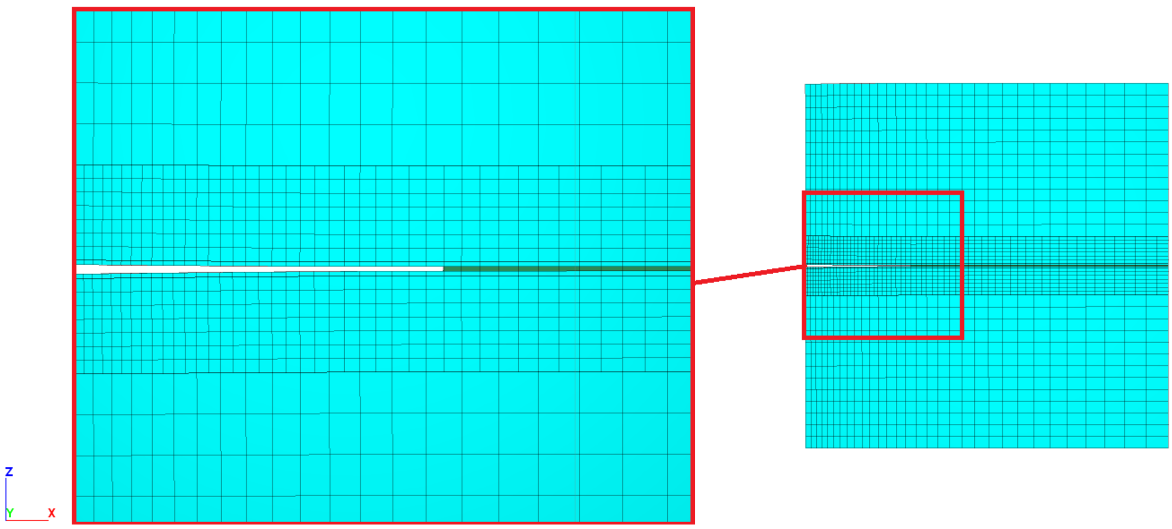

Figure 7: Fracture length after one day (1.5 m | 4.9 ft)

In Figure 8, the three stress components are shown in a horizontal profile through the fracture after one day of simulation time. The gas-pressure, which is applied as a mechanical load to the west side, is also depicted here, but only for comparison. It does not represent an actual hydraulic pressure inside the matrix. It can be seen, that the vertical stress (σ_{zz}) is responsible for fracture propagation processes as it is less compressive than the stress in the y-direction at the fracture tip (1.5 m or 4.9 ft) and therefore the first to exceed the theoretical effective tensile fracture criterion as soon as further temperature reduction causes a stress reduction 2 MPa (290 psi) below the applied gas pressure.

Infiltration fractures usually develop parallel to the fluid flow, therefore the σ_{xx} component is not evaluated in the fracture criterion and does not cause any propagation of the horizontal fracture in the x-axis. It is evaluated in the center of the zone behind the fracture and is affected by the redistribution of stresses. For this reason, there is no straightforward reaction to the mechanical gas pressure applied at the fracture tip visible.

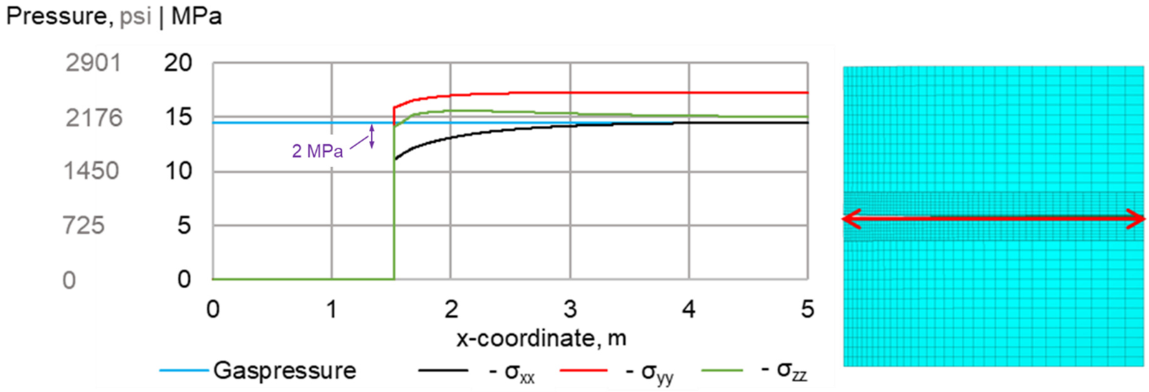

Figure 8: Compressive stresses in horizontal profile after one day of cooling at constant external pressure

In COMSOL, a permeability change indicates occurring damage processes propagating from the west side into the cube. It serves as a comparative parameter, which takes hydraulic processes into account when evaluating the effective tensile stress criterion. As soon as the effective stresses become tensile the permeability increases and finally jumps to its maximum when an effective tensile stress of 2 MPa (290 psi) is reached.

The depicted COMSOL-stresses are effective and subsequently already influenced by the local pore pressure.

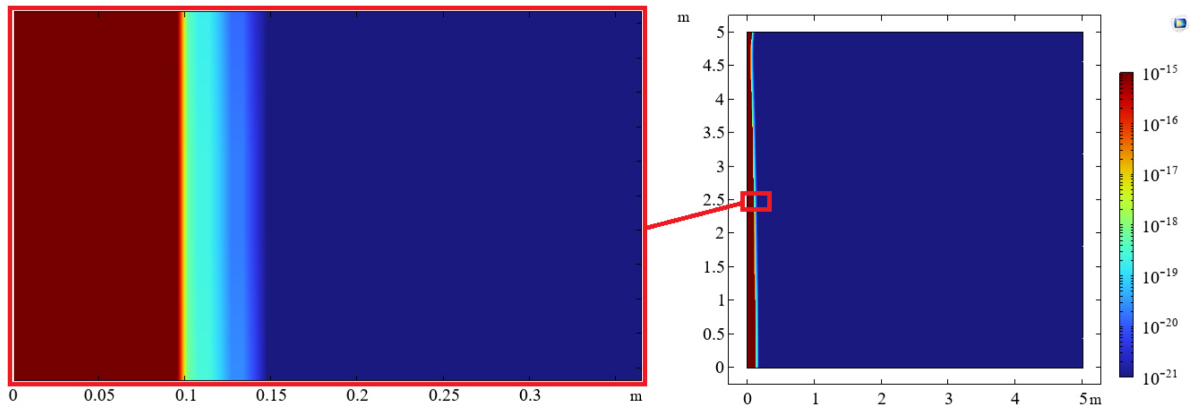

Figure 9: Permeability in m² after one day of cooling at constant hydraulic pressure

After one day the rock salt cube in COMSOL shows a rise in permeability over a total depth of 0.15 m (5.9 inches, Figure 9). The maximum permeability indicating tensile fracturing is reached over a total distance of 0.1 m (3.9 inches). In the zones, where macroscopic fracturing can be assumed and the permeability is 1e-15 m², pore pressure can flow almost freely and therefore propagates along this area to its full value. When the permeability becomes smaller at a higher distance to the wall, the fluid pressure reduces as well, until becoming zero behind the secondary permeable region.

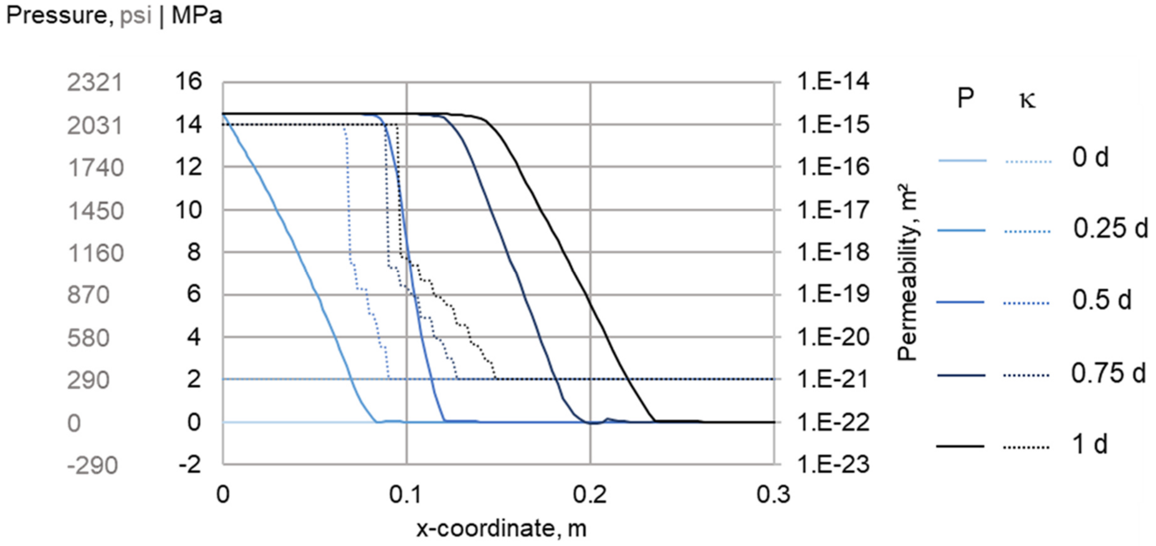

Figure 10: Pressure and permeability development in a horizontal profile at 2.5 m height (8.2 ft)

The gas pressure infiltrates into the rock mass even behind the secondary permeable front. This becomes especially clear when looking at the pressure after 0.25 days. While the permeability has not changed up to this point, gas already infiltrated up to 8 mm (0.3 inches) behind the wall but at a constant decrease of pressure. With an increase of permeability due to effective tensile stresses above the tensile strength after over 0.25 days, the induced fluid pressure propagates deeper into the cube.

Effective stresses are tensile around the infiltrated area due to pore pressure and cooling effects. When the pore pressure drops as a consequence to a permeability decrease at an x-coordinate of ~ 0.15 m (5.9 inches), a strong increase in compressive stresses can be seen, as well (Figure 11). Cooling effects lead to reduced stresses over the first meter of distance to the west side.

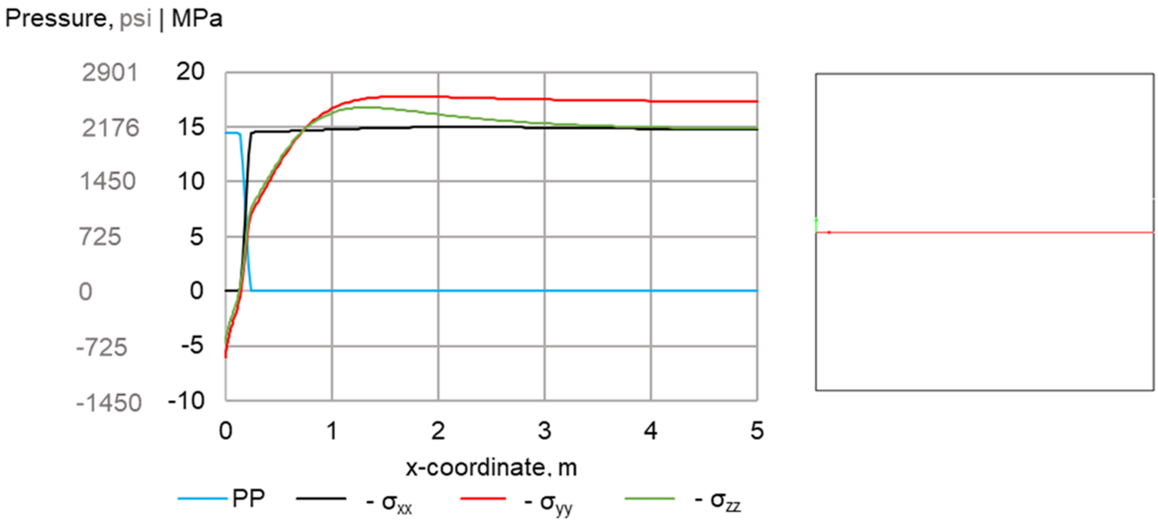

Figure 11: Compressive stresses in horizontal profile after one day of cooling at constant hydraulic pressure

It can be seen, that the implementation of the IUB-criterion and a subsequent THM coupled simulation of the permeability development during cyclic storage leads to smaller regions affected by tensile damage than the approach accounting for macroscopic fractures in TM analyses.

The causes are multifold: Fracture opening and the resulting mechanical stress concentrations around the fracture tip affect their development and the surrounding stress state. In the FLAC3D model, it is conservatively assumed that the whole model is fully saturated by the current gas pressure. Effective stresses are calculated analytically on that basis and the hydraulic component does not affect the stress state in the model directly.

In COMSOL, the pore pressure leads to a change in the local stress state, which affects further pore pressure development through permeability changes and hence the transient stress development around the infiltration zone. The permeability front shows a rapid drop in pore pressure and, consequently, an increase in compressive stresses behind the damaged zone. This leads to a reduced tendency in COMSOL to propagating damage in the form of an increase in permeability.

Discussion

The comparison between the TM fracture model accounting for discrete mechanical fractures and the THM model capturing local hydraulic pore pressure shows differences in the spatial extent of infiltration-related tensile damage. In the TM approach, infiltration fractures develop based on mechanical failure criteria, assuming that the full cavern gas pressure acts behind the fracture within the intact salt. This leads to longer fracture lengths, also due to the geometric concentration of stresses behind the fracture tip.

In the THM model, permeability changes are induced by the IUB criterion, which links effective tensile stress to a local increase in permeability. Rather than explicitly resolving fractures, the model captures a gradual transition from intact to permeable rock, reflecting the progressive development of damage and pore connectivity. Here, the fluid pressure increases locally depending on the permeability.

These differing modeling strategies result in a larger extent of infiltration fractures in the TM model compared to the zone of permeability rise in the THM model. The assumptions in the TM model represent a conservative upper-bound estimate, while the THM approach yields a more gradual, stress-dependent permeability evolution. It can be expected that the actual behavior of rock salt under thermo-hydro-mechanical loading lies between both representations: tensile stresses can indeed open discrete separation planes and increase gas entry, but pore pressure likely propagates slowly over large distances and does not act by its full amount everywhere onto the rock salt solid matrix.

From an operational perspective, these insights may support more differentiated evaluations of cavern integrity. Cavern models simulating THM coupled processes during cyclic storage can predict permeability changes around the facility and help to understand increased infiltration due to damage mechanisms.

Figure 12 provides an impression of how permeability can evolve after several storage cycles in an exemplary simulation model when effective tensile stresses create open pathways within the rock salt. In the vicinity of a cavern, a system of separation planes within the matrix resulting in high permeabilities can be expected. The distance of the primary, infiltration-free state from the cavern wall has to be assessed on an individual basis.

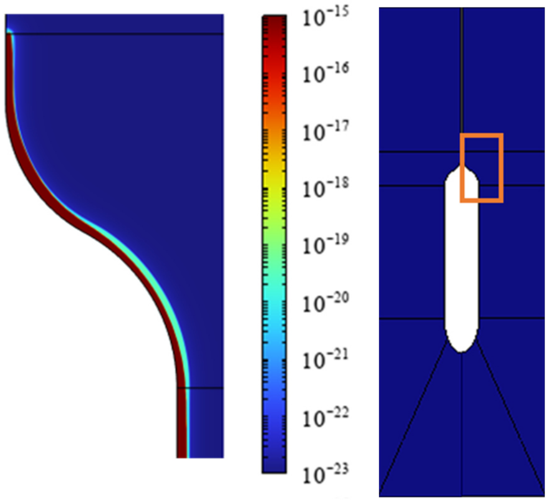

Figure 12: Roof-detail of exemplary cavern model incorporating pore pressure and permeability changes due to cooling of the storage medium

For industry, the obtained results imply that the real extent of thermally fractured zones around storage caverns and hence permeability increased regions is likely smaller than previously assumed. This insight is crucial for operators: if permeability increases remain confined to a narrow zone at the cavern wall, withdrawal and injection rates could be safely increased, improving storage performance and economic efficiency without compromising long-term stability. Further research is necessary to confirm the phenomena for different boundary conditions.

Outlook

Dedicated parameter studies can reveal whether the hydraulic damage front remains limited to a few meters also in long-term studies and whether faster storage rates with higher thermal gradients are possible without increasing the permeability in greater depths. Future studies could focus on

i. the influence of varying storage scenarios
ii. bedded salt effects
iii. the meaning of faults
iv. coupling between fracture mechanics and THM-processes.

They could capture the effect of the mentioned conditions on effective tensile fracturing around caverns during cyclic storage.

Models accounting for elaborated fracture mechanics while coupling THM-conditions can capture both the thermo-mechanical initiation and propagation of fractures and the subsequent evolution of pore pressure and permeability. They can help to improve the understanding of how thermally induced tensile stresses influence fluid migration into salt formations. Moreover, they could reveal possible optimization potential due to conservative modelling techniques.

For an optimization of the storage rates and a more realistic estimation of permeability increases around the caverns, further laboratory and insitu experiments investigating hydraulic processes at temperature cycling are of great interest.

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