

Modeling of Coupled Thermodynamic and Geomechanical Performance of Underground Compressed Air Energy Storage (CAES) in Lined Rock Caverns

Jonny Rutqvist¹, Hyung-Mok Kim², Dong-Woo Ryu², Joong-Ho Synn², Won-Kyong Song²

¹ *Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA 94720 U.S.A.*

² *Korea Institute of Geoscience and Mineral Resources (KIGAM), Daejeon, 305-350 Korea*

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ABSTRACT

We applied coupled nonisothermal, multiphase fluid flow and geomechanical numerical modeling to study the coupled thermodynamic and geomechanical performance of underground compressed air energy storage (CAES) in concrete-lined rock caverns. The paper focuses on CAES in lined caverns at relatively shallow depth (e.g., 100 m depth) in which a typical CAES operational pressure of 5 to 8 MPa is significantly higher than both ambient fluid pressure and *in situ* stress. We simulated a storage operation that included cyclic compression and decompression of air in the cavern, and investigated how pressure, temperature and stress evolve over several months of operation. We analyzed two different lining options, both with a 50 cm thick low permeability concrete lining, but in one case with an internal synthetic seal such as steel or rubber. For our simulated CAES system, the thermodynamic analysis showed that 96.7% of the energy injected during compression could be recovered during subsequent decompression, while 3.3% of the energy was lost by heat conduction to the surrounding media. Our geomechanical analysis showed that tensile effective stresses as high as 8 MPa could develop in the lining as a result of the air pressure exerted on the inner surface of the lining, whereas thermal stresses were relatively smaller and compressive. With the option of an internal synthetic seal, the maximum effective tensile stress was reduced from 8 to 5 MPa, but was still in substantial tension. We performed one simulation in which the tensile tangential stresses resulted in radial cracks and air leakage through the lining. This air leakage, however, was minor (about 0.16% of the air mass loss from one daily compression) in terms of CAES operational efficiency, and did not significantly impact the overall energy balance of the system. However, despite being minor in terms of energy balance, the air leakage resulted in a distinct pressure increase in the surrounding rock that could be quickly detected using pressure monitoring outside the concrete lining.

1 INTRODUCTION

Renewable energy sources (such as solar and wind power) that can reduce or avoid CO₂ emissions are becoming increasingly central to energy planners and others concerned about climate change. Although these renewable energy sources have many attractive attributes, they have an intermittent nature—they cannot steadily provide power, subject as they are to daily cycles and weather conditions. Thus, energy *storage* is critical to making renewable energy more practical.

Along with pumped hydroelectric storage, underground compressed air energy storage (CAES) is considered to be one of the most promising large-scale electric energy storage technologies. Compressed air energy storage (CAES) is an approach by which excess electricity is used to compress air, which is then injected into subsurface caverns (solution-mined cavities in salt deposits, or mines) or porous reservoirs (aquifers or depleted hydrocarbon reservoirs) [1]. When electricity demand exceeds supply, the compressed air is produced from the cavern or reservoir and fed into electricity-generating gas turbines. Because gas turbines typically expend approximately two-thirds of their power for compressing air, compressed air from a CAES reservoir fed into the gas turbine can substitute for one-quarter to one-half of the natural gas needed for a given amount of electricity generated. Depending on how it is calculated, CAES efficiency is typically in the range of 66-82% [1].

Today, two existing commercial CAES plants are in operation: a 290 MW unit built in Huntorf, Germany, in 1978, and a 110 MW unit built in McIntosh, Alabama, USA, in 1991. At both of these sites, solution-mined caverns are used for compressed air storage. In Norton, Ohio, USA, plans are being made to convert an abandoned limestone mine into compressed air energy storage with a capacity of 2,700 MW [1]. In addition, a number of CAES pilot tests have been conducted: one associated with porous reservoir storage in Pittsfield, Illinois, USA [2], another as part of a multiyear reservoir storage project in Sesta, Italy [1]; as well as two pilot tests in rock caverns associated with abandoned mines in Japan [3, 4].

With the rapid growth of installed wind energy capacity in the U.S., there are also projects in various stages of development aimed at aquifer CAES in Iowa, Texas, Oklahoma, and New Mexico [1].

In the case of CAES storage in underground rock caverns, the principal performance requirements include sealing capacity against air leakage, stability, and acceptable surface subsidence [5, 6, 7]. These requirements are subject to geomechanical design parameters, such as cavern geometry and volume, cavern depth, operational pressure of cavern, groundwater table level, as well as other parameters such as rock strength and permeability. One fundamental requirement for preventing air leakage is that ambient hydrostatic water pressure within host rock must balance the pressure of stored air [5]. A water pressure in balance with gas storage pressure is a common practice in design of natural gas storage in unlined caverns; sometimes a so-called water curtain is created by injecting water above the cavern to increase allowable storage pressure [8, 9]. However, balanced ambient pressure may not be an absolute requirement for CAES if the rock mass is sufficiently impermeable. For example, the storage facility at the Norton Mine in Ohio will be located at 670 meters depth, at a hydrostatic pressure of about 6.7 MPa, whereas the CAES operating pressure is planned to range from 6 to 11 MPa [1]. In such a case, the sealing capacity will be provided by the very low permeability of the host rock.

In this paper, we study another alternative, namely CAES in lined rock caverns. Lined rock caverns would be more expensive to mine than salt caverns and naturally occurring reservoirs. However, excavation of new rock caverns provides more possibilities for site selection close to energy sources, such as wind and solar power. Including the transmission line cost from energy source to demand, CAES in excavated caverns could be found to be even more economical. Moreover, lined rock caverns may be located at a relatively shallow depth, significantly reducing construction costs. To the author's knowledge, the only previous study on CAES in lined rock caverns is on one of the Japanese pilot tests mentioned above. It began in the 1990s at a former coal mine, in Hokkaido Prefecture, and the results

have been published in Japanese journals [4]. However, technology for gas storage in lined caverns has been developed over the past 25 years associated with natural gas storage in Sweden, including pilot and demonstration projects, and one commercial operation that started in 2004 [10, 11, 12]. In the case of natural gas storage, a steel lining provides an absolute seal to contain the natural gas within the cavern, and the maximum gas pressure might be in the range of 20 to 25 MPa, which is about 2 to 3 times as high as in a CAES operation. On the other hand, the number of pressure cycles is much higher in the case of a CAES operation: commonly 1 cycle per year or in some cases up to 20 per year are expected for natural gas storage [10], whereas CAES can be operated in daily cycles, i.e., 365 cycles per year. Over a plant life of 50 years, the total number of cycles may approach 20,000, which means that static fatigue in the lining materials is an issue of concern. Moreover, the rapid compression and decompression cycles can result in significant temperature fluctuations, inducing thermal stresses that should be considered when assessing the geomechanical performance of a CAES system.

In this paper we, apply coupled nonisothermal, multiphase fluid flow and geomechanical numerical modeling to study the coupled thermodynamic and geomechanical performance of underground CAES in concrete-lined rock caverns. We adopt the conceptual design and geometry of a CAES system being considered for a pilot test in Korea. The concept includes a thick concrete lining with the option of internal seals of rubber or welded steel plates. Leakage and energy behavior for this concept was investigated by Kim et al., [13]; here, in this paper, we focus on coupled thermodynamic and geomechanical processes. We present an analysis of a CAES storage operation including daily cyclic compression and decompression of air in the cavern and how pressure, temperature, and stress evolve over months of operation. In particular, we study the stress evolution in the concrete lining and surrounding rock and the potential for inducing fractures that could affect the CAES operation. We also investigate the potential for relying on low-permeability concrete as a primary seal, which may be economical and easier to install and maintain, rather than a more complex design involving steel and

rubber seals. Finally, we analyze the potential impact of cracking and air leakage on system response, including leakage rates and energy loss.

2 PREVIOUS STUDIES OF GAS STORAGE IN LINED ROCK CAVERNS

As mentioned, substantial research and development on gas storage in lined rock caverns has been conducted associated with natural gas storage in Sweden. The main principle of the lined gas storage concept is that the load from the high gas pressure inside the cavern is taken by the surrounding rock mass, while the lining is only there to make the cavern absolutely gas-tight [10]. Another characteristic is that the gas pressure is higher than the *in situ* rock stresses, which implies that the rock mass (in case of a gas leak) would be permeable and cannot hinder gas escape. It is therefore essential that the integrity of the lining be maintained. Furthermore, with the cavern situated at a relatively shallow depth, the rock mass must be strong enough to withstand uplifting forces. The Swedish natural gas storage research and development program includes pilot tests and demonstrations at Grängesberg (construction and evaluation 1988-2003), and at Skallen (construction and evaluation 1999-2002) in Sweden [10, 11, 12]. Moreover, in 2004, the Skallen plant was turned into a commercial operation.

At Grängesberg, three caverns (silos 9 m high and 4.4 m in diameter) constructed in fractured granite at a depth of 50 m were lined with concrete and steel. During a pressure test up to 52 MPa in one of the caverns (Room 2), far above the *in situ* stress and close to the concrete's compressive strength, a maximum radial displacement of 5.65 mm was recorded. Tensile fracturing occurred in the unreinforced concrete behind the steel liner, but the concept was still fully functional, since the concrete was designed for transferring the compressive load to the surrounding rock mass. In a different cavern (Room 3), where

the maximum pressure was increased to about 28 MPa, the concrete lining, which in this cavern was reinforced, remained in very good condition, with only a few, very thin cracks observed [10].

At Skallen, a silo, 52 m high and 36 m in diameter was constructed at a depth of 115 m in granite [11]. Pressure cycles using water and then natural gas up to 20 MPa resulted in a maximum radial displacement of about 5 to 6 mm. The strain in the cavern wall was lower than design values, but strongly affected by the temperature variation within the cavern during cycling of the gas pressure [12]. Finally, in these pressure tests, the steel seal remained completely impermeable.

The only field study of CAES in a lined cavern is one of the aforementioned Japanese underground CAES pilot projects, which began in the 1990s at a former coal mine, in Hokkaido Prefecture [4]. The air is stored in a 57 m long, 6 m diameter tunnel in hard rock at 450 m depth. The tunnel is lined with 0.7 m of concrete and (inside the concrete) with a synthetic (rubber) seal to minimize air leakage. The concrete lining consists of prefabricated reinforced concrete segments with joints in between each segment that during construction were filled with filler material. During pressurization, the joints opened preventing tensile stress from developing in the concrete segments. The results of a leakage test (shut-in test) reported in Yokoyama et al. [4] indicated a daily leakage of 0.2%. Thus, some air loss (below acceptable limits) was observed, despite a depth of 450 m and the use of synthetic (rubber) seal. Moreover, cyclic compression and decompression of the tunnel air were between 4 and 8 MPa, i.e., most probably lower than lithostatic stress, resulting in displacements of up to a few millimeters.

A recent study presented in Kim et al. [13], explored the potential of CAES in lined rock caverns at shallow depth from a leakage and energy-balance perspective, without considering geomechanical changes. The analysis showed that the key parameter for assuring long-term air tightness in such a system was the permeability of both the concrete lining and the surrounding rock. In the absence of a synthetic

seal, a concrete lining with a permeability of less than $1 \times 10^{-18} \text{ m}^2$ would result in an acceptable air-leakage rate of less than 1%, with the operational pressure range between 5 and 8 MPa at a depth of 100 m. The subsequent energy-balance analysis demonstrated that the energy loss for a daily compression and decompression cycle is governed by the air-pressure loss, as well as heat loss by conduction, from the cavern to the concrete lining and surrounding rock. Overall, the study by Kim et al. [13] showed that CAES in shallow rock caverns is feasible from a leakage and energy-efficiency viewpoint, assuming that mechanical stability can be achieved. The study indicated cyclic changes in both pressure and temperature will impact the geomechanical stress and strain evolution. Such coupled thermodynamic and geomechanical changes are the focus of this paper.

3 SETUP OF CAES MODEL SIMULATION AND INITIALIZATION

The coupled thermodynamic and geomechanical numerical simulations of CAES in lined rock caverns were conducted with TOUGH-FLAC [14, 15], a simulator based on the multiphase flow and heat transport simulator TOUGH2 [16] and the geomechanical simulator FLAC^{3D} [17]. The TOUGH-FLAC simulator has been used for modeling of subsurface fluid flow and geomechanical processes related to a wide range of multiphase fluid flow applications [15], but this is the first demonstration of how such a modeling approach can be applied for the analysis of underground CAES.

For this study, a 2-D model simulation is conducted for a vertical cross section of the underground CAES system, which is based on a preliminary design for a pilot test in Korea. The numerical grid shown in Figure 1 contains the vital components of the CAES system, including the cavern, rock, concrete lining, and an excavation disturbed zone (EDZ) that could have different material properties from the surrounding undisturbed host rock. As an option, we can also simulate a thin, impermeable synthetic seal at the inner surface of the concrete lining. In our model, the optional inner-surface synthetic seal is so thin

that it has no load bearing capacity, meaning that the air pressure within the cavern is directly transferred as stress normal to the inner surface of the concrete lining.

In the model, we explicitly represent the interior of the air-filled cavern as a medium of high porosity (1.0), high permeability ($1.0 \times 10^{-9} \text{ m}^2$), and mechanical softness ($E = 3.5 \text{ MPa}$, $\nu = 0.3$). The exact values used for the permeability and deformation modulus of the cavern interior are not important as long as the values are much less than the values for the concrete lining and surrounding rock. Using this approach, air can be injected and withdrawn, resulting in changes in air pressure, temperature, and stress exerted from the air pressure on the inner surface of the lining. Thus, we do not have to apply the effect of the air-pressure as a special mechanical boundary condition at the inner surface of the wall. As shown in [Figure 1](#), the air-filled cavern is represented by one row of numerical grid elements that extends from a radius of 2 m to the cavern wall at a radius of 2.5 m in the model. However, in the TOUGH2 coupled thermodynamic, fluid-flow, and heat-transport analysis, the volume of these elements was increased by a factor of 2.78, so that this row of elements adequately represents the entire air-filled cavern volume.

[Table 1](#) presents a set of base-case material properties for our analysis. In this simulation, we assign equivalent elastic properties for concrete, EDZ, and rock mass. The values are within a reasonable range for both concrete and crystalline rock, and are adequate for this generic study. The permeability of the concrete lining is significantly smaller than that of the rock mass, which is also reasonable considering the presence of natural fractures in the rock mass. Using the van Genuchten model [\[18\]](#), we take the water retention and relative permeability curve for water flow from a previous study of water-retention properties around a tunnel in fractured crystalline rock [\[19, 20\]](#), with the gas relative permeability governed by Corey's relative permeability model [\[21\]](#). We use the same retention properties for the concrete lining, which is also within range of laboratory measurements for concrete. However, laboratory

measurement shows that the retention properties of concrete could vary widely, and Kim et al. [13] found that it can have a strong impact on the long-term air leakage through saturation and relative gas-permeability effects. However, for the simulations presented in this paper, we installed the lining at a pre-determined initial saturation, after which it remained almost constant over the course of the simulation time considered.

Finally, the strength properties of the concrete lining are very important for our study. Whereas the compressive strength of concrete is not exceeded in our simulation, the tensile strength for concrete could certainly be exceeded. The concrete lining associated with lined CAES caverns is likely to be reinforced with steel mesh. Such reinforcement, used in the high-pressure natural gas storage caverns discussed above, results in more uniform distribution of fine cracks if the tensile strength is exceeded. Concrete might also be mixed with fibers to increase its tensile strength. However, we will first calculate the stress evolution assuming elastic properties, i.e., lumping effects of steel mesh into our lining properties, to investigate how high tensile stresses could develop. We then consider lower concrete tensile strength in sensitivity cases.

In modeling coupled thermodynamic and geomechanical behavior, it is important to capture the entire construction and operation sequence. We therefore initialized the system by the following steps:

- 1) Initial simulation to achieve steady-state vertical gradients of pressure, temperature and stress in the rock mass as initial conditions before excavation.
- 2) Excavate the cavern and keep it open for 1 week at atmospheric pressure within the open cavern, to allow the cavern to converge mechanically and to achieve new distributions of pressure, temperature and stress in the rock mass.

- 3) Install the concrete linings at a specific initial saturation (e.g., 70%), atmospheric air pressure, and near-zero effective stress, and to keep atmospheric air pressure in the cavern.

In step 1 initial pressure, temperature, and stress gradients are set for a cavern depth of 100 m, with the water table close to the ground surface. Initial temperature was set using a vertical gradient of $0.03^{\circ}\text{C}/\text{m}$ and with a constant temperature of 10°C at the ground surface. At the cavern depth, this corresponds to an initial pressure and temperature of about 1 MPa and 13°C , respectively. After step 2, a pressure sink develops around the excavation, with atmospheric pressure within the excavation and a small inflow of water into the cavern.

Finally, after step 3, we achieve the initial conditions before start of the CAES operation. This includes atmospheric cavern pressure, a concrete lining an initial saturation of 70% and zero stress, a fully saturated surrounding rock mass with excavation induced gradients of pressure, and stress concentrations around the cavern.

After this initialization, we began the simulated CAES operation by injecting and withdrawing air from the cavern for various modeling cases. We simulated daily compression and decompression cycles for a typical CAES operation, with cavern pressure ranging from 5 to 8 MPa. The daily cycles of air compression and withdrawal were simulated by first injecting air at a constant rate for 8 hours, storing it for an additional 4 hours, then producing at a constant rate for 4 hours, and finally waiting for another 8 hours till the start of a new compression cycle. For an air-tight system with negligible air loss through the lining, the injection rate was set to 2.2×10^{-2} kg/s during the 8-hour injection, whereas the mass was withdrawn at a rate of 4.4×10^{-2} kg/s during the 4-hour decompression phase. (The rates of 22×10^{-3} kg/s and 4.4×10^{-2} kg/s are injection rate per unit length of the cavern, whereas half of these rates were applied in the half-symmetric model.) Moreover, during injection, the temperature is kept constant at 21.5°C by

specifying a constant specific enthalpy of air mass. This means that during CAES operation, the air would be cooled during compression to 21.5°C for injection into the cavern.

4 CASE WITH CONCRETE LINING AS A PRIMARY SEAL

We first present the results for a simulation case considering a concrete lining with a relatively low permeability of $1 \times 10^{-20} \text{ m}^2$ and without an internal synthetic seal. This also represents the case in which an internal synthetic seal has been installed, but is not perfectly impermeable (as a result of some slight permeation through it or through seal construction joints). A similar case was investigated from a leakage and energy perspective in [Kim et al. \[13\]](#) showing a negligible daily air leakage of about 0.03% of the injected air mass.

[Figure 2](#) presents the results of evolution of pressure, temperature, stress, and displacement during a simulation over 100 daily pressure cycles, equal to more than 3 months of continuous operation. We also show in more detail the results of the first few cycles, as well as one cycle at the end of the 100 days simulation (cycle # 100). We first injected air at a constant rate of $2.2 \times 10^{-2} \text{ kg/s}$ and a temperature of 21.5°C to increase the cavern pressure from atmospheric to designed CAES operation pressure. With the assigned injection rate, it takes about 24 hours to build up the cavern pressure to about 5 MPa. During this initial compression, the cavern temperature increases due to the heat of compressed air within the cavern (left column in [Figure 2b](#)). From a thermodynamic perspective and the ideal gas law, compression of air from atmospheric to 8 MPa could result in a temperature increase of several hundred degrees. However, in model simulation, the temperature never exceeds 25°C, because of mixing with the injected air of 21.5°C as well as heat exchange between the cavern air and the lining. The cavern temperature decreases again over the first 250 hours (about 10 days), while the rock temperature increases slightly. After 10 days, the cavern temperature starts to increase again along with the rock-mass temperature. The air pressure in the cavern fluctuates between 5 to 8 MPa over the entire 100-day (and 100-cycle) operation,

but the average pressure remains constant, indicating negligible air leakage from the system. The pressure in the concrete lining (P2 in Figure 2a) increases slowly with time and reaches about 6 MPa by the end of the 100th cycle. This pressure increase has implications for the mechanical behavior of the CAES system, since it leads to changes in the effective stress field. The fluid pressure in the rock (P3 in Figure 2a) does not change significantly because the permeability of rock is much higher than that of the concrete lining and the air leakage is very small. We do not present the evolution of gas saturation in Figure 2, but the simulation results show that the gas saturation in the concrete lining remains constant at 30% (70% water saturation), as it was initially set when installing the lining.

The results of pressure and temperature for the 100th pressure cycle (right column of Figure 2a and 2b) show that there is a significant heat exchange between the cavern air and the concrete lining. During an 8 hour compression the temperature increases by the heat of compression, but there is a significant heat loss to the concrete lining. Between 8 and 12 hours, neither injection nor production takes place, but the cavern temperature decreases due to heat loss, and this temperature decrease causes a slight decrease in cavern pressure. During subsequent production (from 12 to 16 hours), the pressure goes down along with decompression-induced cooling. During this period and until 24 hours, most of the heat lost to the concrete lining is gained back into the cavern.

Figure 2c shows the evolution of maximum and minimum compressive principal stresses. Red lines indicate total stresses, whereas green lines indicate effective stresses. During the first 24-hour pressurization of the cavern (compression phase), the maximum compressive stress increases up to -7 MPa (negative numbers signify compressive stress), whereas minimum compressive stress becomes tensile with a maximum value of 4 MPa. Initially, the effective stress magnitudes are similar to that of total stresses, because of a low magnitude of pore pressure (gas pressure). However, the difference

between total and effective stresses increases with time as air pressure within the concrete lining increases. Moreover, the shear stress (or the difference between maximum and minimum principal stresses) decreases with time. However, most importantly, the minimum compressive principal stress is in tension, and the tension increases in time along with the increase in gas pressure within the lining. At 100 days, for the 100th cycle (right column in Figure 2c), the minimum effective principal stress fluctuates between 5 to 7 MPa. This is a tangential tensile stress that would initiate radial fractures, should the tensile strength of the concrete be less than 7 MPa.

Figure 2d shows that the radial displacement of the cavern is small, not exceed 1 mm for the entire compression from atmospheric to 8 MPa of air pressure. The magnitude of displacement obtained in this calculation is directly related to the pressure change and the modulus of elasticity assumed for the concrete and surrounding rock mass.

Figure 3 presents the distribution of pressure, temperature, volumetric strain, and minimum effective compressive stress after the 8 hour compression—when pressure, temperature, stresses, and strains are the greatest. The positive volumetric strain indicates expansion near the inner surface of the concrete lining. This expansion is a result of extension along the tangential direction and is less than 100 μ strain ($\epsilon_v < 1 \times 10^{-4}$). Maximum tensile effective stress occurs at the inner surface of the concrete lining at the side of the cavern and reaches about 8 MPa. However, the effective tensile stress is relatively uniform across the concrete lining despite a steep pressure gradient, with most pressure changes occurring near the inner surface. This is because thermal compressive stresses tend to reduce the tension near the inner surface of the concrete liner.

5 CASE WITH IMPERMEABLE INTERNAL SYNTHETIC SEAL

Next, we present simulation results for a case assuming a perfect synthetic seal at the inner surface, meaning that there is no leakage between the cavern and the concrete lining. This could be achieved, for example, with welded steel lining, as practiced in the natural gas storage operations mentioned above, or if a perfect seal could be obtained with a rubber seal.

Figure 4 presents the results over the 100 days of operation for this case. The evolutions of temperature and displacement are almost identical to those of the previous case shown in Figure 2, so those results are not repeated in Figure 4. On the other hand, we also now include the stress evolution at P6 and P7, located at the rock wall (near the rock-concrete interface), on the top and side of the cavern. The main difference in this case compared to the previous case without internal synthetic seal is that the fluid pressure within the concrete lining remains constant and equal to the initial pressure. As a result, the minimum effective principal stress does not exceed 5 MPa (tension) over the entire 100 days of simulation time. This shows that an impermeable synthetic seal can help to reduce effective tensile stress and thereby reduce the potential for fracturing in the concrete lining. However, the main function of a synthetic lining would still be to provide an ultimate seal and remain impermeable, even if some fracturing would occur in the concrete lining.

The calculated evolution of stress in the rock near the rock-concrete interface indicates that some tensile stress could occur at the top of the cavern (Figure 4c, stress evolution at P4). The magnitude of tensile stress remains less than 1 MPa, but could in reality result in the opening of existing rock fractures, causing heterogeneous displacement that could impact the mechanical stability of the concrete lining. We have not considered such discrete fracture behavior in this study.

6 ADDITIONAL PARAMETER STUDIES

We performed additional parameter studies of the coupled fluid flow and geomechanical behavior and evaluated the results in terms of the stress and strain evolution in concrete lining and rock. We varied permeability, Poisson's ratio, Biot's effective stress parameter and thermal expansion coefficient of concrete, the deformation modulus of rock mass as well as EDZ, and rock initial stress. The analysis showed that the most important parameters for the maximum tensile effective stress in the concrete lining are the modulus of the rock (and EDZ) and Biot's effective stress parameter. When we reduced the modulus of the rock mass and EDZ by 50%, the effective tensile stress increased from 7 to 9.5 MPa, and radial displacement doubled from 0.7 to 1.4 mm. A reduced Biot's effective stress parameter from 1 to 0.5 resulted in a decrease in effective tensile stress in the concrete lining from 7 to 3.5 MPa. The analysis also showed that thermal expansion of the concrete lining plays a role in reducing the tensile stresses in the concrete lining. For example, during the first few cycles, the maximum temperature increase at P2 in the concrete lining was about 6°C, which results in a thermal (compressive and tangential) stress of about 2.5 MPa. Thus, without thermal expansion, the maximum tensile effective stress increased from 7 to 9.5 MPa.

Finally, we assumed an anisotropic stress field with the vertical stress (σ_z) equal to the weight of the overburden, whereas horizontal stresses (σ_x and σ_y) were assumed to be 2 times the vertical stress ($\sigma_z = \text{depth} \times 9.81 \times 2700$, and $\sigma_x = \sigma_y = 2 \times \sigma_z$). Such a stress field is unfavorable, since it creates tensile stresses near the side wall of the cavern. As a result, a maximum tensile stress of about 3 MPa was obtained. This tensile stress is probably less than the tensile stress of a competent crystalline rock, but could certainly open up existing fractures if any exist at the specific location.

7 RESPONSE TO MECHANICAL FAILURE IN CONCRETE LINING

We investigated the potential impact of permeability changes in concrete linings as a result of straining and potential fracturing. Literature data show that the permeability of concrete is relatively insensitive to changes in compressive stress as long as within an elastic range. For example, [Hosseini et al. \[22\]](#) presented data from [Choinska et al. \[23\]](#) showing how gas permeability of concrete decreases by only about 10% when compressed from stress free conditions to a compressive stress about 50% of peak (failure) compressive stress. When exceeding 50% of peak compressive stress, permeability begins to increase due to increased microfracturing, but the load has to be increased above 80% of peak stress to observe more significant changes in permeability. In our simulations, the maximum compressive stress in the concrete (about 8 MPa) is far from the uniaxial compressive strength of concrete (e.g., 50 MPa). However, our simulations indicated tangential tensile effective stresses as high as 8 MPa at the inner surface of the concrete lining, which is sufficient to initiate radial cracks. Therefore, our analysis of system responses to mechanical failure focuses on the changes that could occur as a result of radial cracking.

Laboratory data show that cracked concrete is several orders of magnitude more permeable than intact (uncracked) concrete [22]. Laboratory results indicated that there is a threshold in the crack-opening displacement (COD) below which there is no significant change in permeability. A threshold COD of about 100 to 200 μm has been observed by [Hosseini et al. \[22\]](#). Thus, although tensile failure occurred and localized opening of a crack opening could be measured, the crack apparently did not have a connected network of pore spaces until COD exceeded 100 to 200 μm . Once the COD exceeded the threshold COD, the permeability increased rapidly by several orders of magnitude [22].

In this study, we used a simple model to simulate permeability changes associated with fracturing in the concrete, capturing the main features described in Hosseini et al. [22] including the permeability evolution as a function of COD. In the modeling, we estimated COD from the calculated strain and then related COD to fracture aperture and finally permeability (Figure 5). We estimated COD from the tangential strain, assuming that when tensile failure occurs, the tangential strain is localized to opening of one fracture intersecting the element:

$$b_m = B \times \varepsilon_\theta \quad (1)$$

where b_m is the mechanical aperture, equivalent to COD, and B is the tangential element width (Figure 5). Using a consistent approximation, we relate this to permeability (k_f) using the cubic law for a fracture flow and aperture according to:

$$k_f = \frac{(f \times b_m)^3}{12B} \quad (2)$$

where f is a factor taking into account the difference between the so-called hydraulic aperture and mechanical (or physical) aperture. Finally, we calculate changes in equivalent permeability resulting from crack opening as being superimposed on the initial (intact) rock permeability according to:

$$k = k_0 + k_f = k_0 + A(\varepsilon_\theta - \varepsilon_\theta^t)^3 \quad (3)$$

where k_0 is the initial (intact) concrete permeability, A is estimated from $A=B^2f^3/12$, and ε_θ^t is a threshold strain related to the COD (or b_m) threshold for onset of permeability changes. Assuming B on the order of 10 cm and f about 0.5, we estimate A to 1×10^{-4} , whereas the threshold strain for a threshold COD of 100 μm can be calculated from Equation (1) as $\varepsilon_\theta^t = 1 \times 10^{-3}$. The resulting permeability versus strain and aperture function is shown in Figure 5. We acknowledge that this is a very simplified approach to modeling very complex processes of fluid-induced crack opening, but we think that it is adequate for modeling the potential impact that cracking and associated air leakage might have on the system in this

type of scoping analysis. Despite the simplification, the main features shown in [Figure 5](#) are consistent with laboratory experimental results, including threshold COD and the several-orders-of-permeability increase upon exceeding the threshold COD as described in [\[22\]](#).

We simulated the CAES operation assigning a tensile strength of 3 MPa to the concrete lining, i.e., assuming that it is unreinforced. The results shown in [Figures 6 and 7](#) show how pressurization of cavern leads to tensile failure and localized permeability increases, and a breakthrough with air leakage out of the cavern. The modeling results showed that tensile failure is first initiated along the outer edge of the lining, near its interface with the rock mass after about 10 hours. The tensile failure of elements propagates inward, toward the inner surface of the lining. However, strains in the lining remain small, because of confinement and the maximum strain of about 2×10^{-4} occurring at the inner surface of the lining. After 24 hours, larger strains are localized at the top of the cavern and at one location at the side of the cavern where the strains increase to a factor of 10, i.e., up to 2×10^{-3} . At this instant, the air pressure quickly propagates through the concrete lining and leads to an increase in pressure within the rock mass outside the lining. At the top of the cavern, the estimated COD approaches 200 μm , which leads to a permeability increase according to model in [Figure 5](#) to about $5.0 \times 10^{-13} \text{ m}^2$, i.e. a seven-orders-of-magnitude increase. However, despite a very abrupt pressure change in the lining and in the surrounding rock mass, there is no significant impact on the pressure evolution within the cavern; the average air pressure within the cavern remains nearly constant during the 10 cycles of simulation. As shown in [Figure 6c](#), the air mass flow through the fracture oscillates along with the pressure cycles between outward (positive) to inward (negative) flows, with the mass rates orders of magnitude less than what is injected and produced from the CAES system.

8 THERMODYNAMIC PERFORMANCE AND GEOMECHANICS

IMPACT

From the simulation results, we can evaluate both the mass and energy balance of the CAES system. For example, for the injected air mass and its temperature (21.5°C), we can calculate the total injected energy from [13] as:

$$E + W = \int_{t_1}^{t_2} (C_{v,air} + R_{air}) T_i m_i dt \quad (4)$$

where E is the internal energy of the injected air, W is the work done on the air in the cavern, $C_{v,air}$ is the specific heat of air at constant volume, R_{air} is the specific gas constant for air $T_i(K)$ is the absolute temperature of injected air, and m_i is the mass injection rate (kg/s). Using Equation (4) with $C_{p,air} = C_{v,air} + R_{air} \approx 1,006 \text{ J/(kg K)}$, injection rate of $2.2 \times 10^{-2} \text{ kg/s}$, at a temperature of 294.65K, for 8 hours (14,400 s), we find that the total injected energy during the compression phase of the 100th cycle is 187.8 MJ. The energy produced during decompression can also be calculated according to Equation (4), but in this case the temperature is not fixed; it varies, depending on the temperature within the cavern. In this study, for the 100th cycle, our simulation results showed that 181.6 MJ was produced during the decompression. This means that air can be produced at a power of 12.6 kW during the 4 hour decompression. Note that these numbers of energy storage and power are per meter of the cavern. For up-scaling to a commercial operation, we need to multiply by the required total cavern length (perhaps involving several long parallel caverns), leading to a desired power output.

The total injected energy of 187.8 MJ and produced energy of 181.6 MJ shows that 96.7% of the injected energy was recovered and 3.3% lost during the 100th cycle. Figure 8 shows how the energy loss evolves over the 100 pressure cycles. The energy loss peaks after about 250 hours (about 10 days) at 3.7% and then monotonically decreases with time to 3.3% at 2400 hours (100 days). Kim et al. [13] found that the

energy loss for this kind of tight (almost impermeable lining) system was caused by heat loss from the cavern to the concrete lining and surrounding rock. Consequently, the energy loss decreases with time, because the thermal gradient and heat loss from the cavern to the surrounding media decreases with time.

Finally, in the case of mechanical failure in concrete linings, we found that the thermodynamic behavior within the CAES system itself was not significantly affected, even though there was some energy loss associated with air leakage through the three simulated cracks through the lining. We can see in Figure 6 that the average pressure in the cavern decreases slightly with time. However, in a field situation, it would be very difficult to quantify the leakage from the fluctuating pressure and temperature evolution. Therefore, if leakage is suspected, a shut-in test would be the most effective way to quantify it. We simulated such a shut-in test for 1 week beginning from the third day, i.e. two days after the cracking occurred (Figure 9). In a field situation, we could imagine that the leakage would first be discovered by pressure monitoring in the rock mass just outside the concrete lining. Indeed, the pressure in point P2 abruptly increases and becomes very similar to the cavern pressure as soon as air breaks through the concrete lining. We may determine the leakage rate using the ideal gas law as:

$$\Delta m = m_1 - m_2 = \frac{V_{cavern}}{R_{air}} \left(\frac{P_1}{T_1} - \frac{P_2}{T_2} \right) \quad (5)$$

where subscripts 1 and 2 indicate initial and later state, respectively. Using accurate readings of temperature and pressure at 100 and 200 hours— $T_1 = 290.32$ K, $T_2 = 288.37$ K, $P_1 = 7.62$ MPa, $P_2 = 7.55$ MPa, with $V_{cavern} = 19.63$ m³ and $R_{air} = 286.9$ J/(kg K)—we calculated that an air mass of 4.47 kg has been lost from the CAES system over 100 hours, leading to a leakage rate of 1.24×10^{-5} kg/s (1.07 kg/day). The total air mass stored during a compression phase was calculated to be 633.6 kg from the injection rate (2.2×10^{-2} kg/s) over 8 hours. Thus,

$1.07/633.6 \times 100 = 0.16\%$ of the injected air mass leaks, which is negligible in terms of the thermodynamic performance of the CAES system. Despite fracturing, heat loss to the surrounding media is still the dominant cause of energy loss, and it is only a few percent, according to [Figure 8](#).

9 CONCLUDING REMARKS AND DISCUSSION

We carried out coupled nonisothermal, multiphase fluid flow and geomechanical numerical modeling to study the coupled thermodynamic and geomechanical performance of underground compressed air energy storage (CAES) in concrete lined rock caverns. Specifically, we focused on the coupled thermodynamic and geomechanical behavior of lined caverns located at relatively shallow depth (e.g., 100 m depth) in which a typical CAES operational pressure of 5 to 8 MPa is significantly higher than both ambient fluid pressure and *in situ* stress. We found that the use of coupled multiphase fluid flow and geomechanical analyses with explicit representation of the air filled cavern was a very useful and practical approach, although we acknowledge that our current analysis is rather simplified regarding system components and uses a rather coarse numerical mesh. Future models of the planned pilot test will be much more refined, including components such as mechanical interfaces between synthetic lining, concrete, and rock, rock fractures, and the drainage zone outside the linings. Nevertheless, we think the present model is adequate for the current scoping analysis of CAES system performance.

For our simulated CAES system, the thermodynamic analysis showed that 96.7% of the energy injected during compression could be recovered during subsequent decompression, while 3.3% of the energy was lost by heat conduction to the surrounding media. Our geomechanical analysis showed that tensile effective stresses as high as 8 MPa could develop in the linings as a result of the air pressure exerted on the inner surface of the linings, whereas thermal stress were relatively smaller and compressive. We simulated one case in which the tensile tangential stresses result in radial cracks and air leakage though

the lining. The simulation showed that such air leakage could be quickly detected using pressure monitoring outside the concrete lining. However, in terms of CAES operation, the air leakage was minor (about 0.16% of the air mass injected during one daily compression) and did not significantly impact the overall energy balance of the system.

Air leakage could certainly be completely prevented by using internal steel lining, as has been practiced in natural gas storage. However, for CAES systems, the costs of complex lining systems will be an issue for a commercial-scale system that would involve much larger storage volumes. Moreover, requirements for air tightness may be less stringent when dealing with storage of air rather than (explosive) natural gas. For technically and economically successful CAES, simplified lining systems are preferable, which is one of the reasons why we investigated the option of using a tight concrete lining as a primary seal. Our analysis indicated minor leakage, although some localized fracturing occurred. Moreover, the concrete reinforced with steel meshes has been used in lined natural gas storage facilities not only to prevent the formation of larger localized fractures, but also to promote the formations of many smaller and more evenly distributed fractures. In fact, with a uniform distribution of radial cracks around the periphery of the lining and uniform tangential strain, the modeling indicated that the crack opening displacement of each fine fracture could be less than the threshold for abrupt permeability increase. In such cases, the radial symmetric geometry of the lining provides mechanical confinements and suppresses the opening of radial cracks. These are some of the issues and processes that can be best studied through pilot tests, such as the one planned to be conducted in Korea.

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List of Figure Captions

Figure 1. (a) Preliminary design of a cross section of a CAES cavern with concrete lining and (b) model grid and boundary conditions.

Figure 2. Results of coupled thermodynamic and geomechanical simulation for CAES in a lined cavern with a tight concrete lining as a primary seal. The results are presented for the first week of operation (left column), for 100 days (100 pressure cycles) of operation (mid column), and for the 100th pressure cycle (right column). See Figure 1 for the exact locations from P1 to P5. σ_1 and σ_3 are total maximum and minimum principal stresses, respectively, and prime indicates effective stress.

Figure 3. Calculated distribution of thermodynamic and geomechanical responses after 8 hours compression during the 100th pressure cycle for a CAES system with a tight concrete lining as a primary seal.

Figure 4. Results of coupled thermodynamic and geomechanical simulation for CAES in a lined cavern with impermeable synthetic seal. The results are presented for the first week of operation (left column), for 100 days (100 pressure cycles) of operation (mid column), and for the 100th pressure cycle (right column). See Figure 1 for the exact locations from P1 to P7. σ_1 and σ_3 are total maximum and minimum principal stresses, respectively, and prime indicates effective stress.

Figure 5. Element strain (and implicit crack opening displacement) versus element permeability model for simulating permeability changes caused by cracking of concrete.

Figure 6. Calculated evolution of (a) pressure, (b) gas saturation, and (c) leakage rate through a tensile crack in concrete linings during 10 pressure cycles, using the element strain versus permeability function shown in Figure 5 and assuming a concrete tensile strength of 3 MPa.

Figure 7. Calculated distribution of (a) gas saturation and (b) pressure after 10 pressure cycles.

Figure 8. Calculated evolution of daily energy loss as percentage of daily injected energy for the case of tight concrete linings as a primary seal.

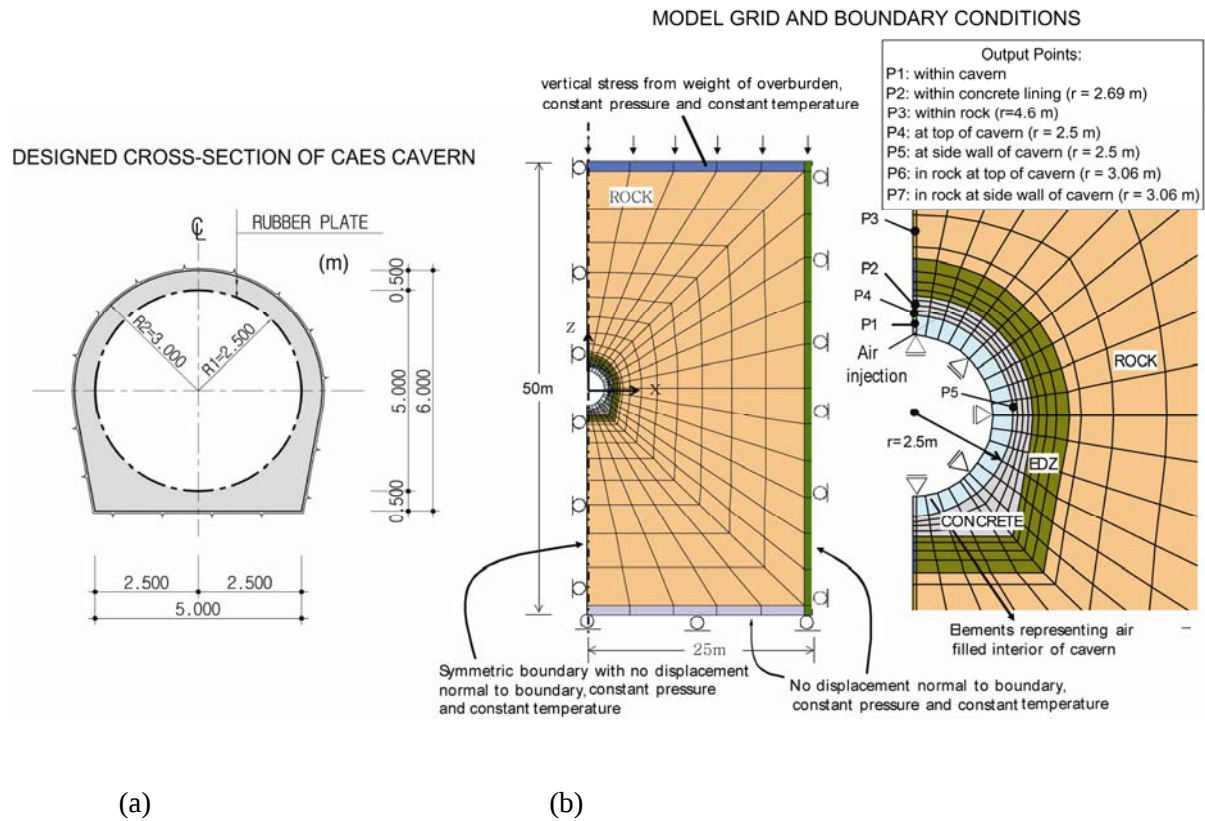
Figure 9. Calculated evolution of cavern pressure and temperature during simulated shut-in test for the case of air leakage through the cracks in the concrete lining.

Tables

Table 1. Material properties used as a base case for modeling of CAES in a lined rock cavern

Property	Material		
	Rock mass	EDZ	Concrete lining
Young's modulus, E (GPa)	35	35	35
Poisson's ratio, ν (-)	0.3	0.3	0.3
Thermal expansion coefficient ($^{\circ}\text{C}^{-1}$)	1×10^{-5}	1×10^{-5}	1×10^{-5}
Effective porosity, ϕ (-)	0.01	0.01	0.1
Permeability, k , (m^2)	1×10^{-17}	1×10^{-17}	1×10^{-20}
Residual gas saturation (-)	0.0	0.0	0.0
Residual liquid saturation (-)	0.01	0.01	0.01
van Genuchten, P_0 (MPa)	1.47	1.47	1.47
Van Genuchten, m (-)	0.595	0.595	0.595
Thermal conductivity λ (J/s/m $^{\circ}\text{K}$)	3	3	3
Specific heat (J/kg $^{\circ}\text{K}$)	900	900	900

Figures



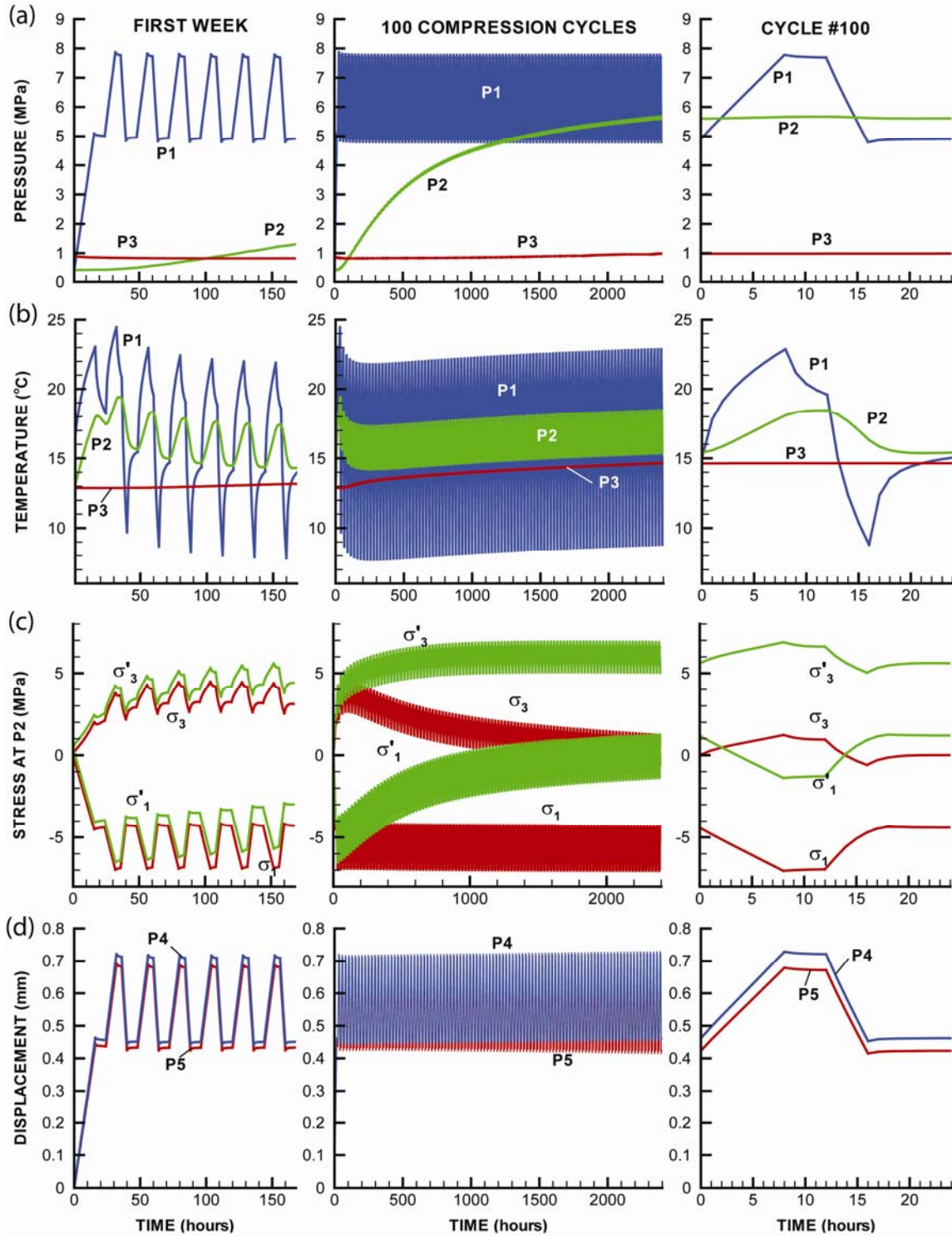


Figure 2. Results of coupled thermodynamic and geomechanical simulation for CAES in a lined cavern with a tight concrete lining as a primary seal. The results are presented for the first week of operation (left column), for 100 days (100 pressure cycles) of operation (mid column), and for the 100th pressure cycle (right column). See Figure 1 for the exact locations from P1 to P5. σ_1 and σ_3 are total maximum and minimum principal stresses, respectively, and prime indicates effective stress.

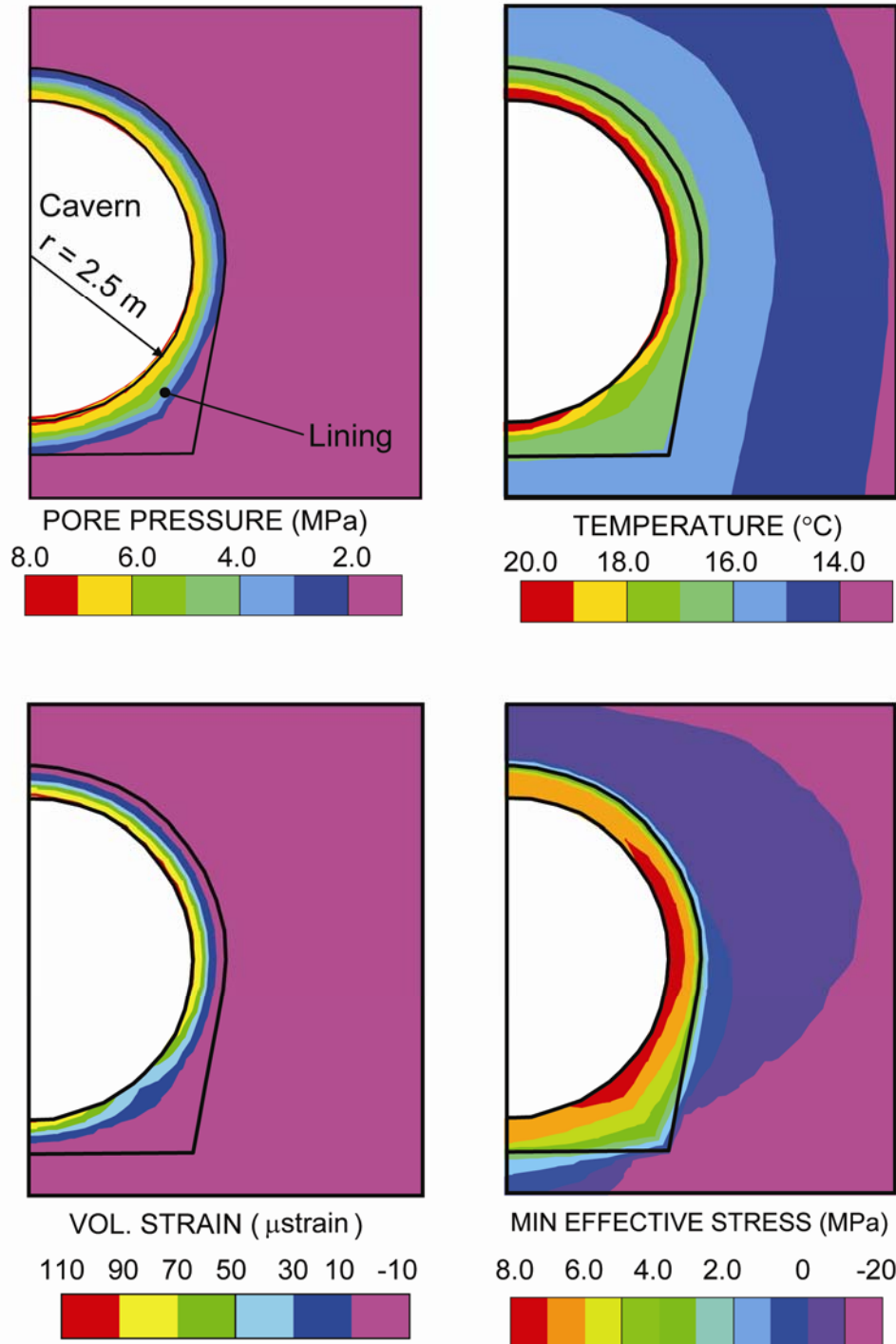


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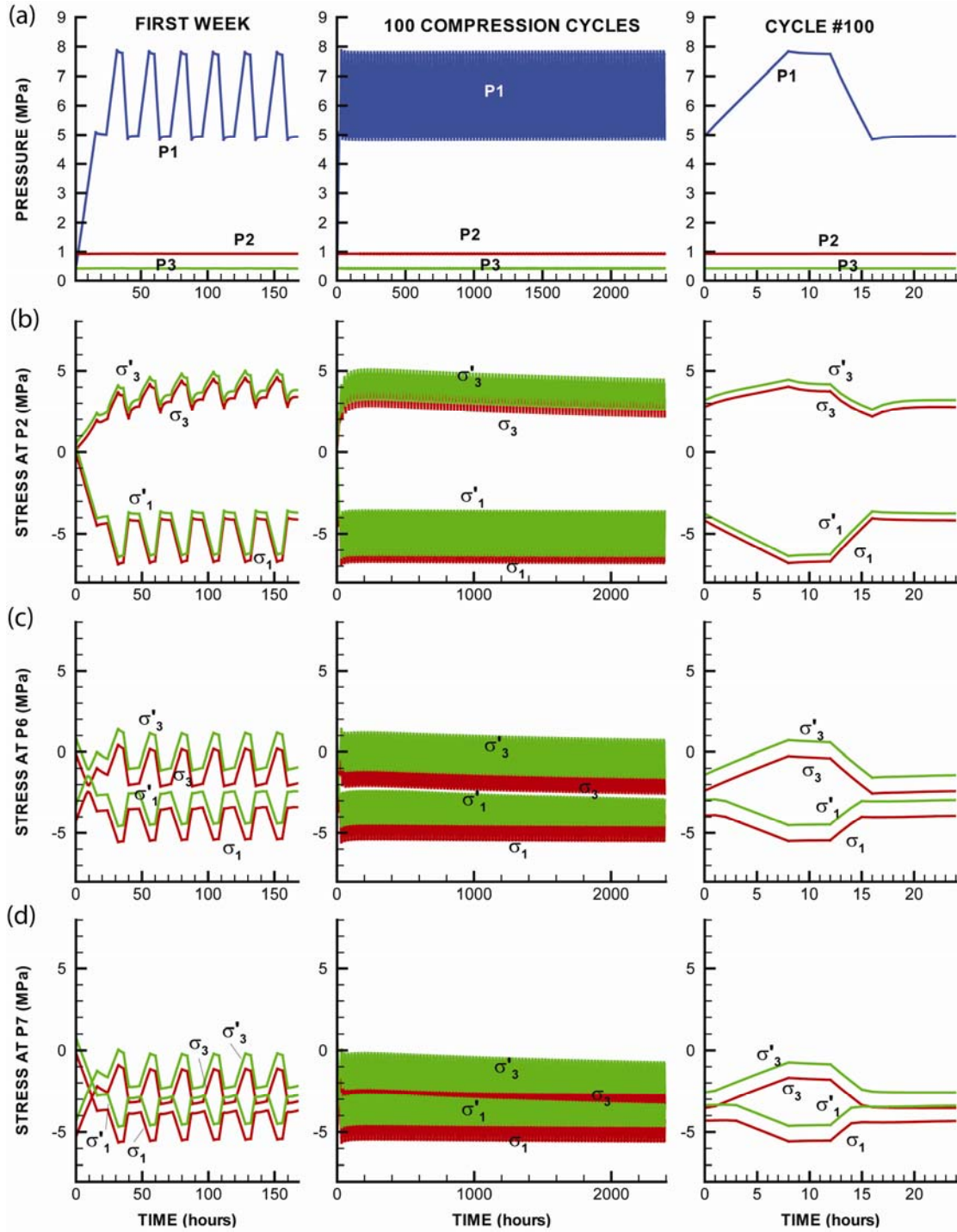


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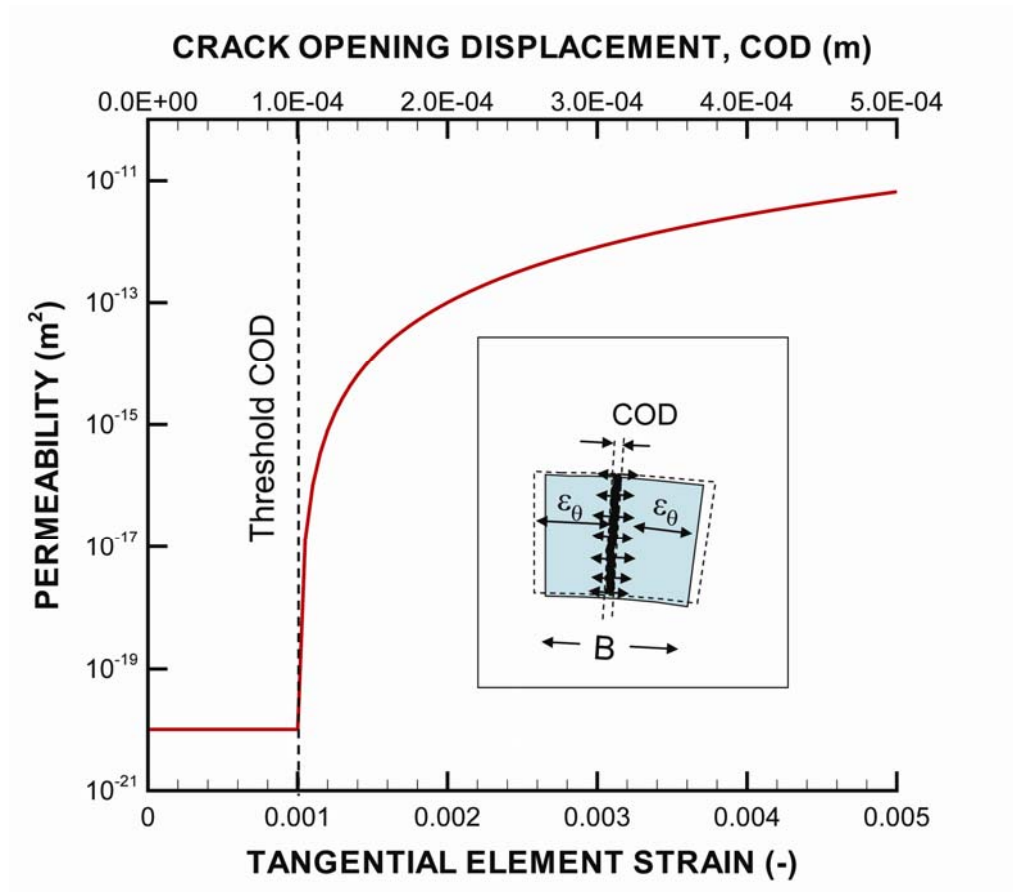


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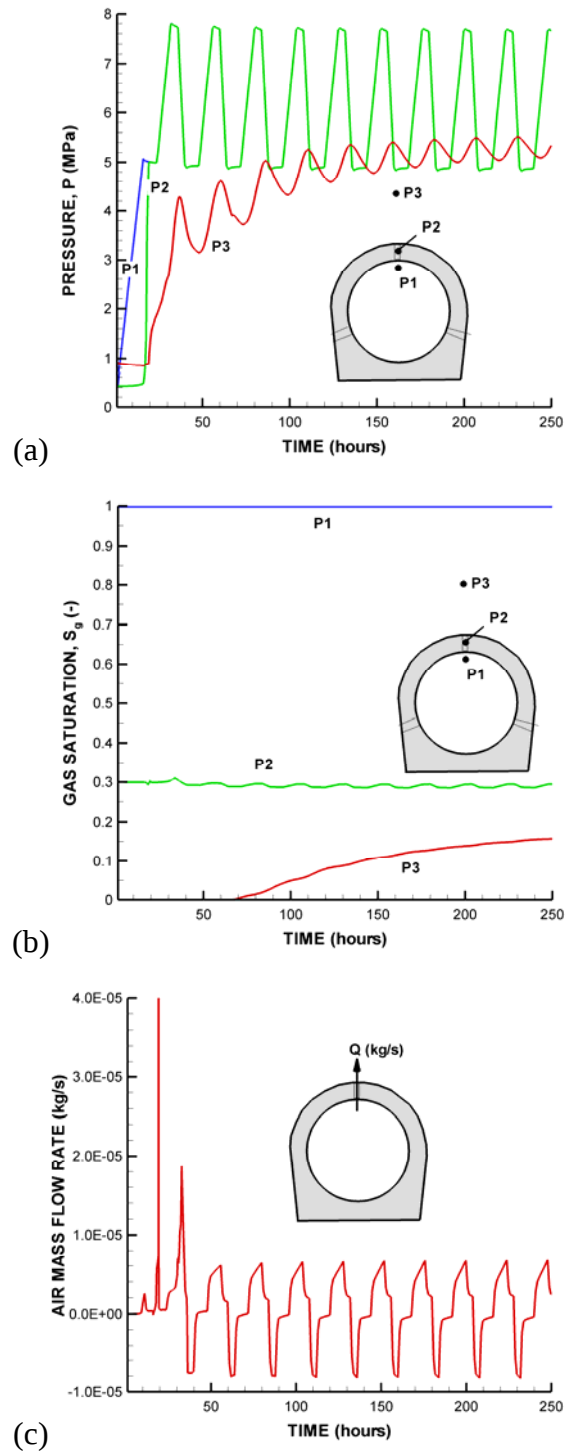
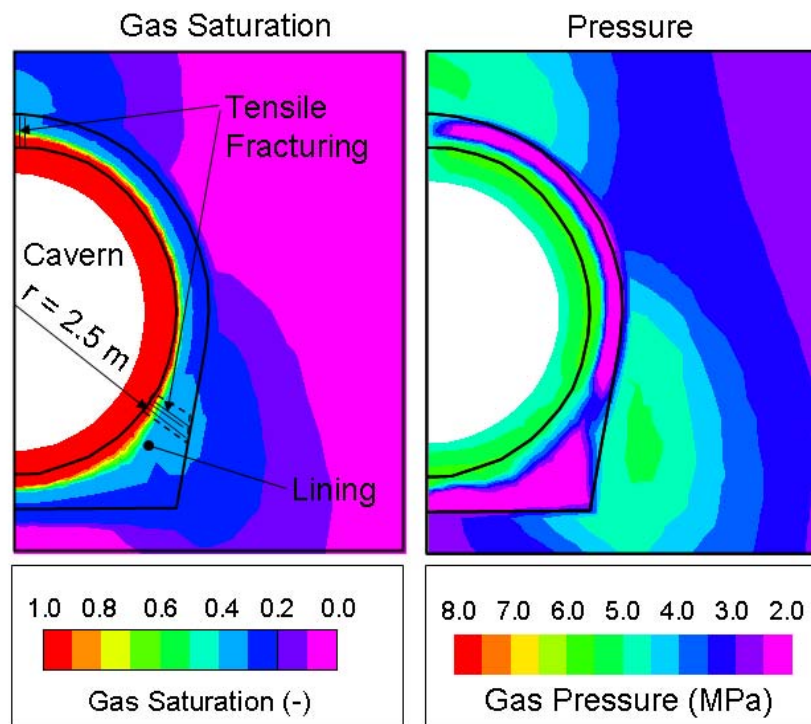


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(a)

(b)

Figure 7. Calculated distribution of (a) gas saturation and (b) pressure after 10 pressure cycles.

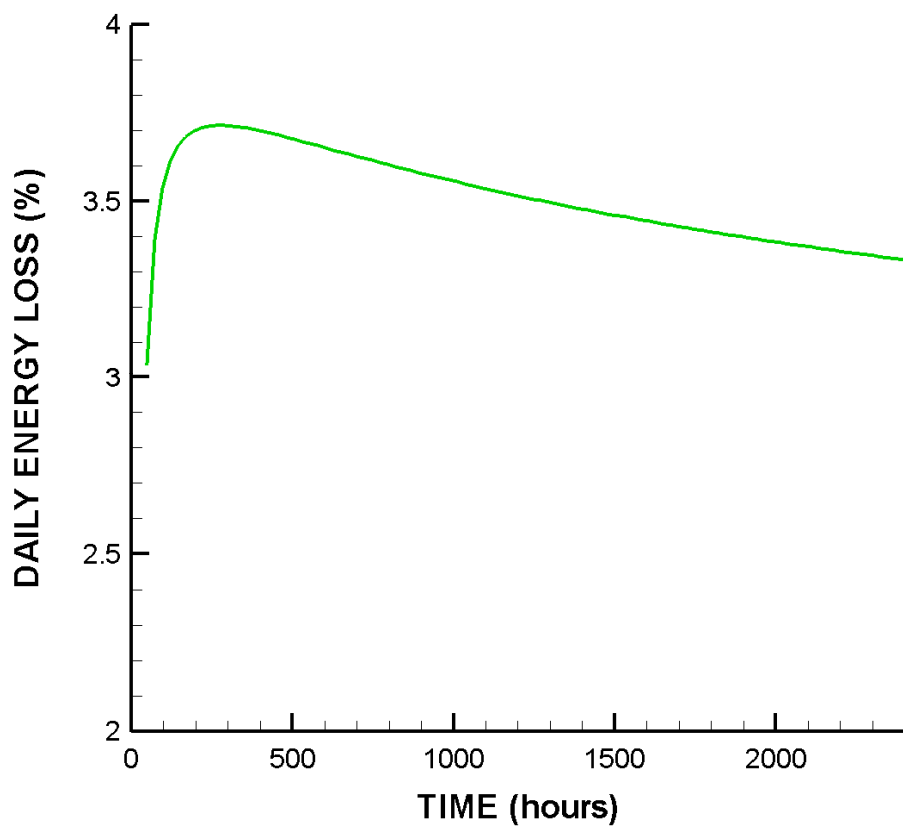


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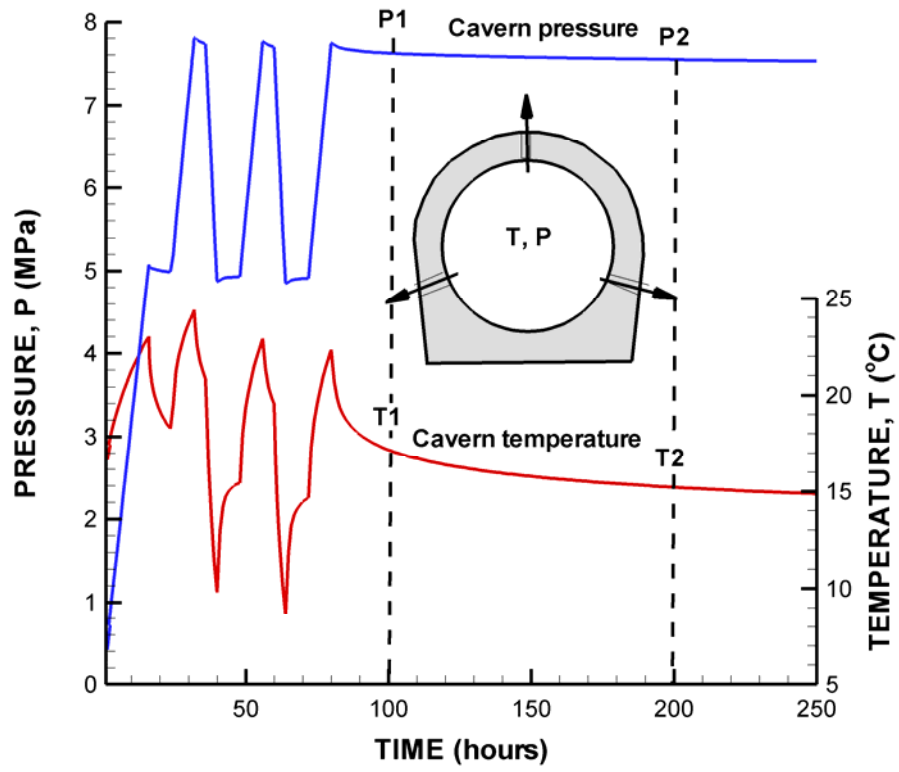


Figure 9. Calculated evolution of cavern pressure and temperature during simulated shut-in test for the case of air leakage through the cracks in the concrete lining.

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