



Parametric study and geomechanical design of Ultra-deep-water Offshore Salt Caverns for Carbon Capture and Storage in Brazil

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ABSTRACT

This article describes a new concept to reduce carbon dioxide emissions of offshore oil production of high gas-to-oil ratio reservoirs and high content of CO₂, denominated Offshore Salt Cavern Ultra-deep Water CCS (Carbon Capture and Storage) System. This hybrid system is intended for natural gas storage, the gravitational separation between CO₂/CH₄, and CO₂ confinement for final destination. This development emerged from a current demand of some Brazilian pre-salt reservoirs to destinate a gas stream with high CO₂ contamination, produced during the oil extraction. These reservoirs have a continuous salt rock layer of 2000 m as caprock making the construction possible of salt caverns by leaching using seawater. In the first stage of technology development, the system will only store a gas stream contaminated with a high concentration of CO₂. In the second stage of its development, it will allow not only the separation of natural gas from the CO₂ but also its storage and the monetization of CH₄. This paper presents the conceptual design of this technology, showing the steps from the parametric study to select the best relation between flowrate, leaching time, structural stability, and the volume of gas with the high content of CO₂ storage, up to the final geomechanical design using the set of parameters selected.

1. Introduction

In 2006, one of the largest oil provinces in the world, known as the pre-salt, was discovered in Brazil. The hydrocarbon reservoirs consist of carbonaceous rocks of microbial origin and underlie a thick layer of salt rock with an average thickness of 2000 m, in a water depth of 2200 m, at 200 km–300 km from the coast. The oil in the reservoirs is of high quality with a very high gas-oil ratio, above 220. The associated gas has a high CO₂ content of mantle origin, which will not be disposal in the atmosphere.

The produced gas with high content of CO₂ is treated at the production platforms through membrane filters. Part of the treated gas with

a maximum CO₂ content of 3% is compressed and transported to shore through gas pipelines. The remainder gas with the CO₂ content of 70%–80% is reinjected into the reservoirs, working as EOR (Enhanced Oil Recovered). With time the recycled gas with CO₂ increases the global CO₂ content of the associated gas, which could cause restrictions at the gas treatment by the membrane filter system of the platforms. Therefore, there is a demand for CCS of large quantities of CO₂ associated with CH₄ in the pre-salt offshore oil fields in Brazil.

Salt has been identified as one of the best geological media for underground storage of gas at very high pressure. The main reasons include: (i) Low permeability, about 10⁻²⁰ m², providing excellent sealing for gas storage under high pressure; (ii) Creep phenomenon,

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providing the property of self-healing fractures and capability to absorb changes of gas pressure; (iii) Solution in water, enabling its construction by leaching using raw sea water; (iv) Presence in all pre-salt province, allowing its wide use in pre-salt fields.

The concept of using offshore salt caverns for gas storage can be applied in several areas in the world that have favorable geology, and in fact it has already been thought by other countries. For example, the Gateway concept project in England, foresees the construction of 24 underground offshore salt caverns for gas storage in the shallow waters of the east Irish Sea. Its main objective would be to enhance security of supply in the UK gas market and help meet the strategic objectives of the government's energy policy.¹

Another case where this technology could be applied are the West African oil fields, where is found a very similar geology of the Brazilian offshore pre-salt oil fields due to the drift between African and South American continents. The main characteristic of these fields is the presence of thick layers of salt rock above the oil reservoirs. In Kwanza Basin, offshore Angola, for example, recent discoveries aroused great interest from oil companies, which already operate in the Brazilian pre-salt oil fields, mainly due to the geological similarities of the two provinces. In the past decade a rapid increase in hydrocarbon exploration activities along the Brazilian and Angolan margin segment have triggered a revival of research and an enormous growth of interest in these areas and especially in the salt basins.

This paper describes the conceptual design of Hybrid Subsea CCS System, showing the steps from the parametric study to select the best relation between flowrate, leaching time, structural stability and the volume of gas with high content of CO₂ storage, up to the final geo-mechanical design using the set of parameters selected. Simulation results obtained show the technical feasibility of huge storage volumes of natural gas and CO₂ in ultra-deepwater offshore salt caverns. This paper presents a case study with salt caverns of 275 m high by 93 m in diameter able to store 1 billion Sm³ (Standard cubic meter) of natural gas with high content of CO₂ (90%). Fig. 1 illustrates this CCS system.

2. Material and methods

2.1. Parametric study

2.1.1. Site selection

Due to the genesis of geological formation of Santos Basin in Brasil older homogeneous non-stratified halite domes interceptes the stratified salt rock overlying the pre-salt reservoirs. These halite domes are the target areas for the construction of the salt caverns for gas storage and CCS to minimize the presence of interbedded non-soluble rock layers like shale and anhydrite and also to avoid the more soluble salts, carnalite and tachyhydrite. Based on interpretation of 3D seismic, a halite dome 10 km away from one of the major pre-salt oil fields in Santos Basin is selected, Fig. 2²

2.1.2. Parametric parameters

The parametric study aims to evaluate the influence of cavern height and diameter, leaching flow rate and well completion on the storage volume of the disposal gas stream. From the several analysed models, a screening is made to select the parameters set that present the highest yield between the construction time and the final storage volume of the caverns.

By the experience of the authors, the slenderness ratio of the caverns, $\lambda = \text{height/diameter}$, should be $(3 \leq \lambda \leq 6)$ and the caverns should keep a cylindrical shape as far as possible. By obeying these conditions, it considerably increases the fulfilment of the sizing criteria that will be certified, only in the cases within those limits, by numerical simulation excavations.³⁻¹³

The simulation of the leaching process of cavern models is conducted by the application of SALGAS software from the Solution Mining Research Institute.¹⁴ The simulation of the structural behaviour of the cavern selected in the parametric study is conducted by the COVES 2 simulator developed by da Costa.³

For the parametric study, a range of parametric variables are defined to be used as premises of the study. The flow rate for all alternatives is the same: 320 m³/h, 640 m³/h and 960 m³/h. The geothermal gradient at the location of the central cluster of caverns is shown in Fig. 3. The brine temperature is calculated based on the salt rock temperature at the depth of the leaching process. During the leaching the brine exchange

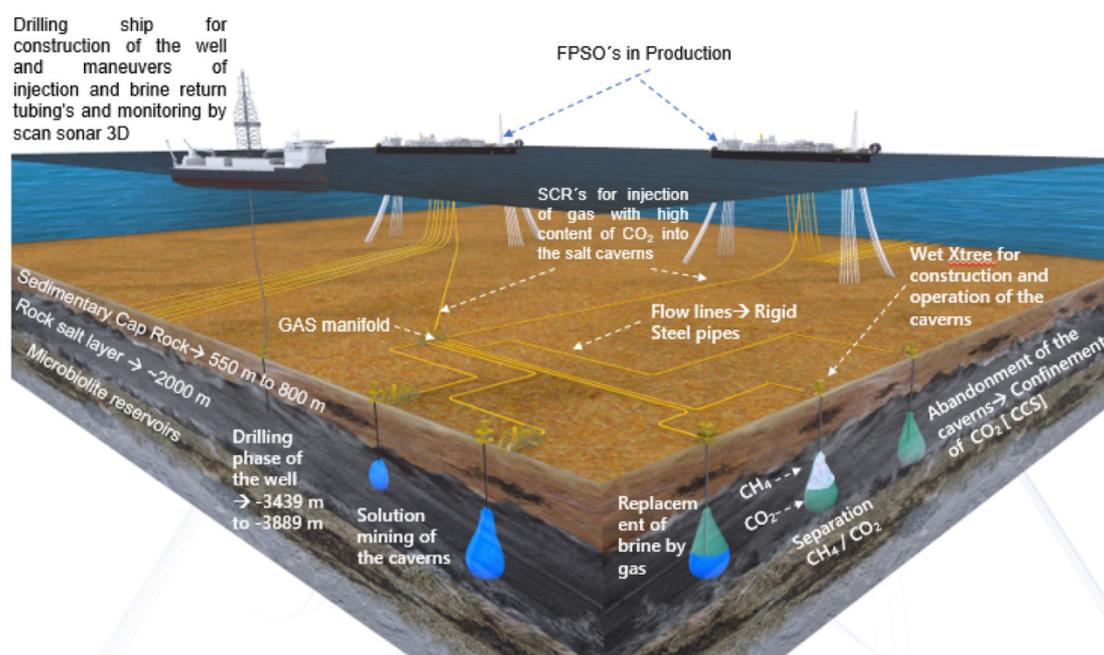


Fig. 1. General view of a typical site where the CCS in Salt Caverns Technology will be applied.

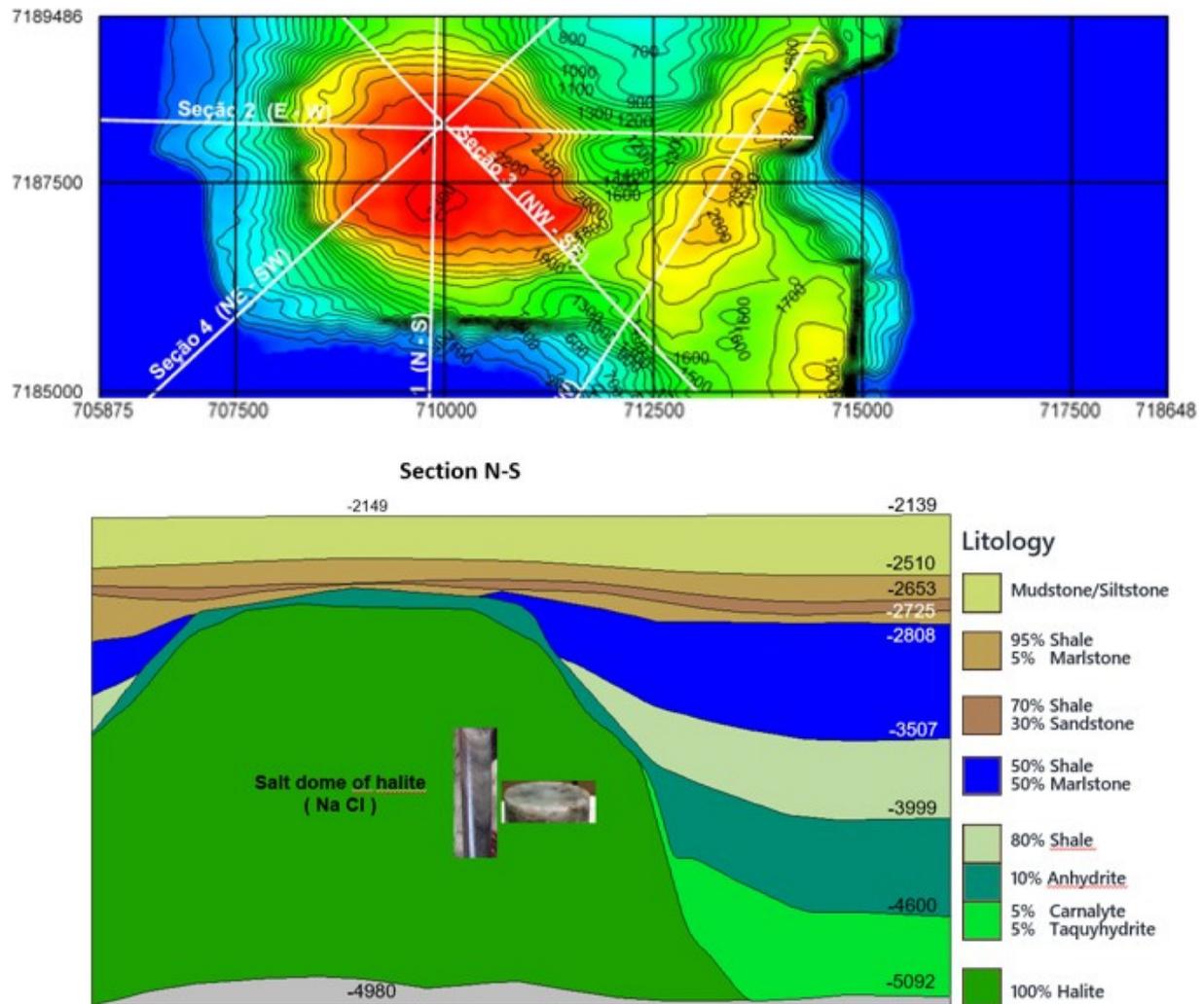


Fig. 2. Salt dome of halite selected for the Offshore Natural Gas Storage and CCS appraisal.

temperature with the salt rock. Larger the cavern more exchange occurs, and the brine reaches the same temperature of the salt rock 42 °C. The height of the alternative caverns are 150 m, 250 m, 350 m, and 450 m. The bottom of all alternatives is the same to gain in confinement and gas pressure at 1750 m below the sea floor. The construction and operation well of the caverns consider three phases: 36”/30”, 26”/20” and 18 1/8”/16”. One well and tubing’s is the same for all alternatives. The brine return casing/gas injection casing are: 14” 114 lb/ft C-125 HC. The Seawater injection casing/brine return casing are: 7 5/8” 51.2 lb/ft. The slenderness ratio lower limit is 3 and the ratio upper limit is 6.

2.1.3. Dissolution factor calibration

To simulate the leaching of the caverns a data set must be provided to the simulator SALGAS.¹⁴ SALGAS is a proprietary simulator of the Solution Mining Research Institute (SMRI), licenced to the members of the institute. Among the parameters used in the simulations, the dissolution factor “F” calibrates the rate of dissolution of the cavern as a function of the physical-chemical characteristics of the salt and the water used in the leaching, such as salinity and water temperature. The higher the salinity the lower the rate of dissolution and the higher the temperature the greater the dissolution of the salt.

The dissolution factors (F) used in the “Parametric Study” are calibrated by comparison with the dissolution rate of the Sandia Labs SANSMIC simulator,¹⁵ taking into consideration the influence of water temperature and salinity. Sandia Labs obtained the following empirical equation:

$$R_d = (a_0T^2 + a_1S^2 + a_2TS + a_3T + a_4S + a_4) \cdot C_r \tag{1}$$

where R_d is dissolution rate ($cm^3/cm^2/s$), T is temperature ($^{\circ}C$), S is salinity (% saturation), C_r is roughness coefficient of the salt rock face subjected to the leaching (2.57), and a_i are interpolation constants.

The calibrated F is used in the simulation of real Brazilian salt caverns, for brine production,¹⁶ obtaining excellent results. Table 1 shows the calibration of the “Dissolution Factor” of SALGAS using the experimental data from Sandia Labs.¹⁷ From this calibration, the “Dissolution Factor” to be used in the leaching simulation of the real salt cavern is 2.54.

Considering the average temperature of the salt interval at the real brine operation in Brazil of 72 °C, the dissolution factor is 2.54. Introducing this value in the SALGAS code the difference between the measured and simulated results is 4.2%. The halite of Santos Basin has the same genesis of geology formation of the onshore salt deposit at the north-east region of Brazil. Solution mining in these deposits show a volume percentage of insoluble in the halite body of ~1%.

2.1.4. Models of the parametric study

According to the premises of the parametric study, 12 models were simulated, considering a dissolution factor of 1.52 for the temperature of 42 °C in Table 1. The leaching process simulation of models uses the same completion string, as is shown in Fig. 4. The inner tubing is the casing 7 5/8” 51.2 lb/ft Scr13/110 ksi, with special metallurgy, and for

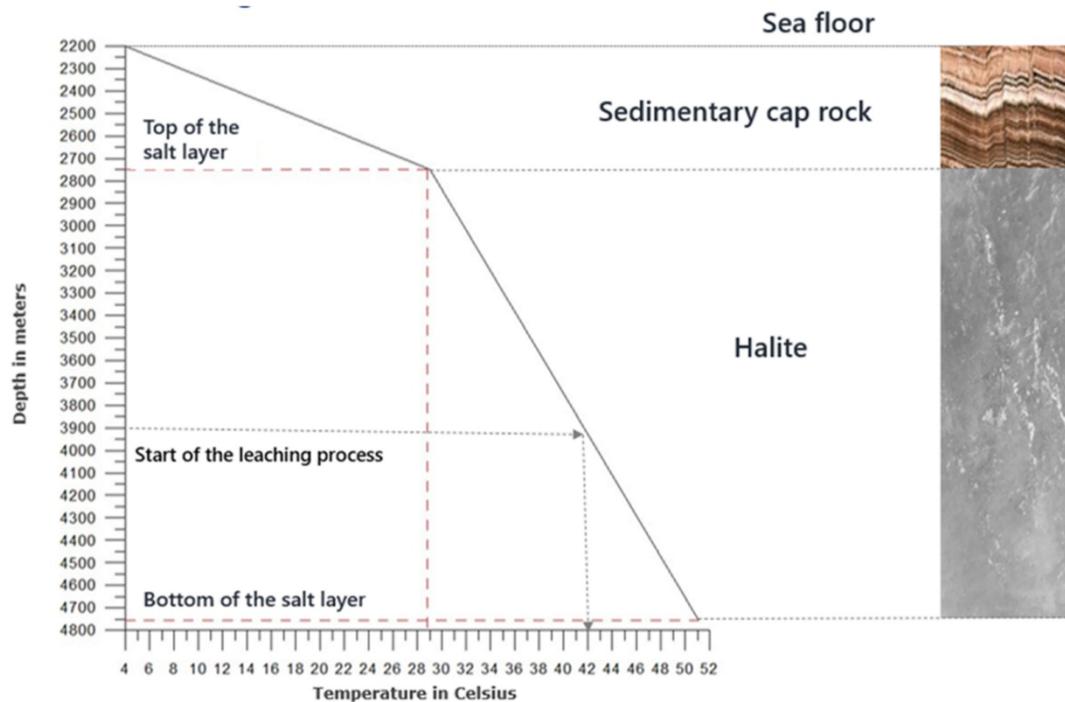


Fig. 3. Geothermal profile at the location of the central cluster of caverns.

the outer tubing the casing 14” 114 lb/ft C-125 HC is used.

Four cavern heights were considered in the models 150 m, 250 m, 350 m and 450 m and the leaching flowrate of 320 m³/h, 640 m³/h and 960 m³/h. Two natural gas volume curves with 90% CO₂ were generated, considering the gas pressure at 80% and 90% of the initial lithostatic stress at the top of the caverns.

From the appraisal of the four models studied is selected the cavern with height of 250 m, which has the best relation between time for the leaching process and final volume of gas storage.

Fig. 5 shows the results for the cavern with 250 m of height (the arrows on the Figure are stability legends). On the axis of the ordinates, on the left side of the plot, one has the volume of gas that can be stored in the cavern considering the compression factor of the waste gas at (10% CH₄ + 90% CO₂), for the conditions of temperature and pressure of the cavern. On the axis of the ordinates of the right side of the plot is presented the slenderness ratio of the cavern, height/diameter ratio. On the abscissa has the time of leaching of the cavern.

As the leaching evolves, the diameter increases and therefore the slenderness ratio decreases. Two gas storage curves are presented, for 80% and 90% of the initial lithostatic stress at the top of the cavern. The upper and lower limits of the slenderness ratio of the caverns are only intended to precondition a form factor for the caverns that will increase the chance of these caverns to meet the criteria of stability and gas tightness. The total time of the geomechanical simulations will be in line with the logistic plan of the construction and operation of the salt caverns. In the present paper a leaching time of 540 days is considered, based on salt cavern simulations.¹⁸

The results of the parametric study define the set of parameters that optimize the design of the caverns, establishing the most appropriate relation between the leaching flow rate, distance between the injection and brine return tubes and the maximization of the volume of disposal gas to be confined in the caverns. The final set of parameters selected must be certified by the simulation of the geomechanical behaviour of the caverns. Table 2 shows the final set of parameters selected by the parametric study. Fig. 6 shows the evolution overtime of the leaching progress of the cavern with height of 250 m .

3. Theory and calculation

3.1. Numerical simulator

The computational numerical simulator has a long history of application in rock mechanics analysis of underground excavations³ and considers the non-linear visco-elastic and elasto-plastic phenomena, with different constitutive laws for representing the geomechanical behaviour of geomaterials. The use of this program in hundreds of engineering projects has demonstrated its excellent performance on the prediction of the creep phenomenon even high complexity analysis as HPHT excavations (high-temperature and high-differential stresses of rock salt conditions).¹⁹

The program has different constitutive creep laws, for representing the creep of the salt rock. For salt cavern project is used the constitutive creep law developed by Munson,²⁰⁻²⁵ considering a new constitutive creep law based on mechanisms of deformation, similar to the behaviour of steel under high temperature.

The constitutive creep law that incorporates all the parts related to the creep deformation mechanisms (multi-mechanism deformation – MD) considers the following mechanisms, which depend on the temperature and stress and intergranular behaviour of salt. The Slipping dislocation movement (dislocation glide) is given by

$$\epsilon_1 = A_1 \cdot e^{\left(\frac{Q_1}{RT}\right)} \cdot \left(\frac{\sigma}{G}\right)^{n_1} \quad (2)$$

Salt rock grains solubilization of intergranular contacts, as a result from undefined mechanisms or pressure similar, are similar to Eq. (2)

$$\epsilon_2 = A_2 \cdot e^{\left(\frac{Q_2}{RT}\right)} \cdot \left(\frac{\sigma}{G}\right)^{n_2} \quad (3)$$

The climbing dislocation movement (dislocation climb) is defined by.

Table 1
Calibration of the Dissolution Factor of SALGAS simulator.

DISSOLUTION RATE EXPERIMENTAL LAW OBTAINED BY SANDIA LABS FOR SANSMIC- > CORRELATION WITH DISSOLUTION FACTOR OF SALGAS	
SANSMIC REFERENCE TEMPERATURE = 23.9 °C	Experiments to Determine Salt Dissolution Rate as a function of Brine Properties Tim O'Hern Engineering Sciences Center
SALGAS REFERENCE TEMPERATURE = 23.9 °C	David Lord and David Rudeen Energy, Nonproliferation, and High-Consequences Security Center Sandia National Laboratories November 18, 2014
$R_d = (a_0T^2 + a_1S^2 + a_2TS + a_3T + a_4S + a_5)^* C_r$	
Where	
$R_d =$ Dissolution Rate (cc/cm ² /s)	
T = Temperature (°C)	
S = Salinity (% Saturation)	0
Cr = Roughness coefficient = 2.57	2.57
$a_0 = 1.647 \times 10^{-8}$	1.6470E-08
$a_1 = 8.425 \times 10^{-9}$	8.4250E-09
$a_2 = -4.293 \times 10^{-8}$	-4.2930E-08
$a_3 = 3.064 \times 10^{-6}$	3.0640E-06
$a_4 = -1.269 \times 10^{-6}$	-1.2690E-06
$a_5 = 6.185 \times 10^{-5}$	6.1850E-05
Temperatures (°C)	R_d
	DISSOLUTION FACTOR (SALGAS) - Salgema Mineração Mina 31
23.9	0.000371332691759
25	0.0003822714375
30	0.00043328401
35	0.0004864129775
40	0.00054165834
41	0.0005529613799
42	0.0005643490756
45	0.0005990200975
50	0.00065849825
55	0.0007200927975
60	0.00078380374
65	0.0008496310775
70	0.00091757481
71	0.0009314175239
72	0.0009453448936
73	0.0009593569191
74	0.0009734536004
75	0.0009876349375
76	0.0010019009304
Salt interval	-900 m to -1200 m
Average temperature	72
Dissolution factor	2.5458164998129

$$\epsilon_3 = H \cdot (\sigma - \sigma_0) \cdot \left[B_1 \cdot e^{\left(\frac{Q_1}{RT}\right)} + B_2 \cdot e^{\left(\frac{Q_2}{RT}\right)} \right] \cdot \sinh \left[\frac{Q(\sigma - \sigma_0)}{G} \right] \quad (4)$$

where the following additional nomenclatures are adopted:

- σ_0 – effective stress reference (yield stress of the slipping deformation mechanism);
- Q – activation energy (kcal/mol), Q = 12 kcal/mol³;
- Q₁ and Q₂ – activation energy constants (kcal/mol) obtained by fitting the laboratory creep test results.
- R – universal gas constant (kcal/mol.K), R = 1.98·10⁻³;
- G – shear modulus;
- H – heaviside step function;
- A_i and B_i – constants;
- n_i – stress exponent.

The MD law is used in engineering projects of evaporitic rocks underground mining, or well design projects through stratified salt layers. Its application is restricted to the steady-state creep interval, what is the majority in these types of projects^{6, 13, 18} Eq. (5). The double deformation mechanism equation is used for stationary or permanent creep:

$$\dot{\epsilon} = \dot{\epsilon}_0 \cdot \left(\frac{\sigma_{ef}}{\sigma_0} \right)^n \cdot e^{\left(\frac{Q}{RT} - \frac{Q}{RT} \right)} \quad (5)$$

where $\dot{\epsilon}$ is the creep strain rate in steady state condition, $\dot{\epsilon}_0$ is the creep strain rate reference (steady state), σ_{ef} is the creep effective stress (generalized stress), T₀ is the reference temperature (K), n = n₁ for $\sigma_{ef} \leq \sigma_0$ and n = n₂ for $\sigma_{ef} > \sigma_0$.

equation (4) represents the steady-state creep equation as described by equations (2) and (3). The transient part, equation (4) of the total creep strain is disregarded.

3.2. Rock mechanics properties

The rock mechanics properties used in the simulation follow the recommendations of Da Costa.³ Table 3 shows the basic rock mechanics properties.

3.3. Cavern sizing

To adequate the shape of the cavern the position of the brine return tube was adjusted, raising its position by about 50 m. Fig. 7 shows the volume of the cavern considering height of 300 m and diameter of 100 m, slenderness ratio of 3.0. The leaching simulation results is shown in Fig. 8, for a seawater injection flow rate of 640 m³/h.

3.4. Simulation basic data and finite element model

For evaluating the salt cavern stability, some basic data were adopted.^{2, 18}

- Sedimentary rock specific weight: 22.56 kN/m³;
- Salt rock specific weight: 21 kN/m³;
- Salt rock slab protection at the top of the salt cavern: 900 m;
- Salt caverns minimum distance to avoid interference (between axis): 600 m;
- Sea bed temperature: 4 °C;
- Cavern slenderness ratio: $\lambda = h/\varphi \cong 3$;
- Shape: close to cylindrical;
- Size and shape of cavern: 275 m × 93 m;
- Depth of the bottom of the cavern: 3890 m;
- Depth of the top of the cavern: 3590 m;
- Depth of the top of the salt layer: 2690 m;
- Depth of sea floor: 2140 m;
- Maximum gas pressure and initial stress at the top of the salt cavern: $\sigma_0 = 2140 \times 10 + 550 \times 22.56 + 900 \times 21.00 = 21400 + 12408 + 18900 = 52.708$ kPa;
- Pg = 80% (52.708): 42.166 kPa;
- Pg = 85% (52.708): 44.801 kPa;
- Pg = 90% (52.708): 47.437 kPa;
- Hydrostatic pressure of the brine at the base of the cavern assuming the return of the brine in the well head: P_{hs} = 2140 × 10 + 550 × 12 + 1200 × 12 = 21400 + 6600 + 14400 = 42.400 kPa
- Isothermal compressibility of the disposal gas with 90% of CO₂: K = 265.000 kPa.

The creep strain rate of the halite, equation (3), is activated by the temperature. The rock salt layer is divided in small layers to take into consideration the variation of the temperature with depth. Fig. 9 shows the structural geomechanical model used in the simulation by COVES 2.

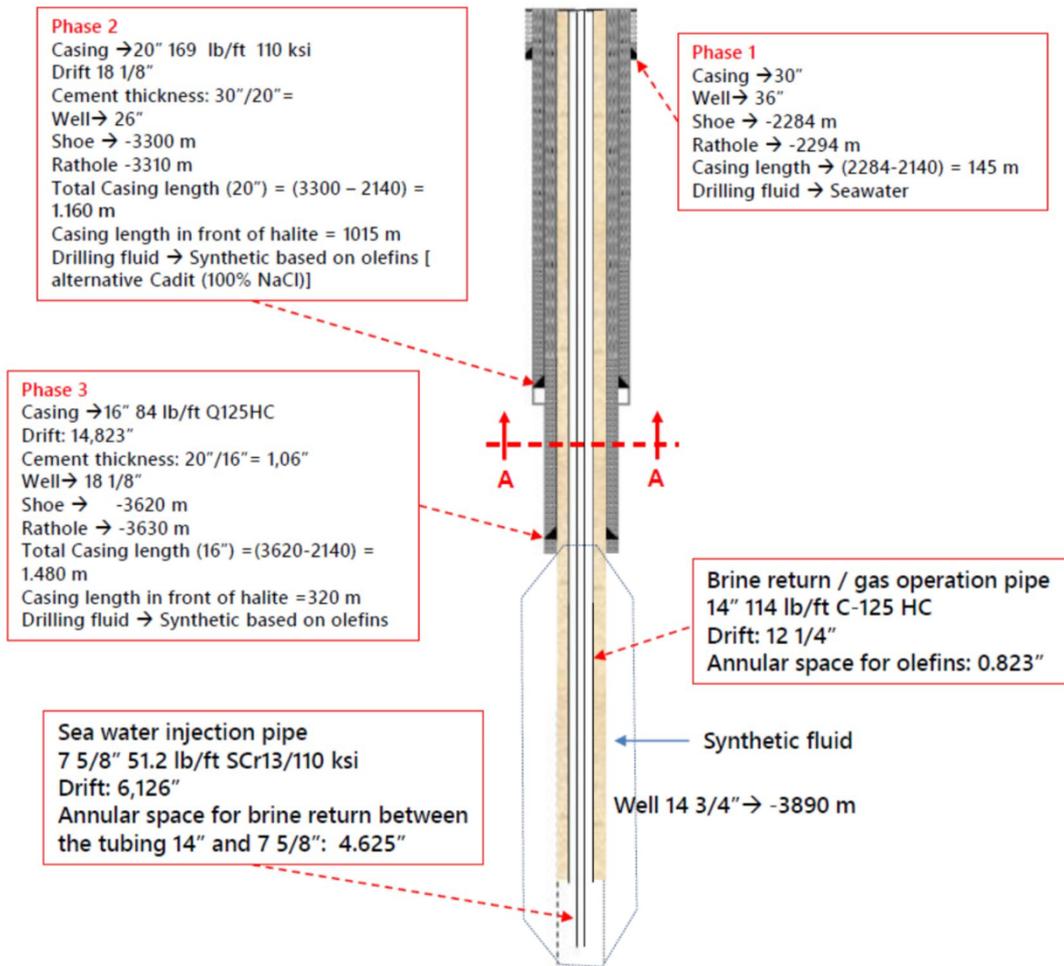


Fig. 4. Completion string used in the parametric study.

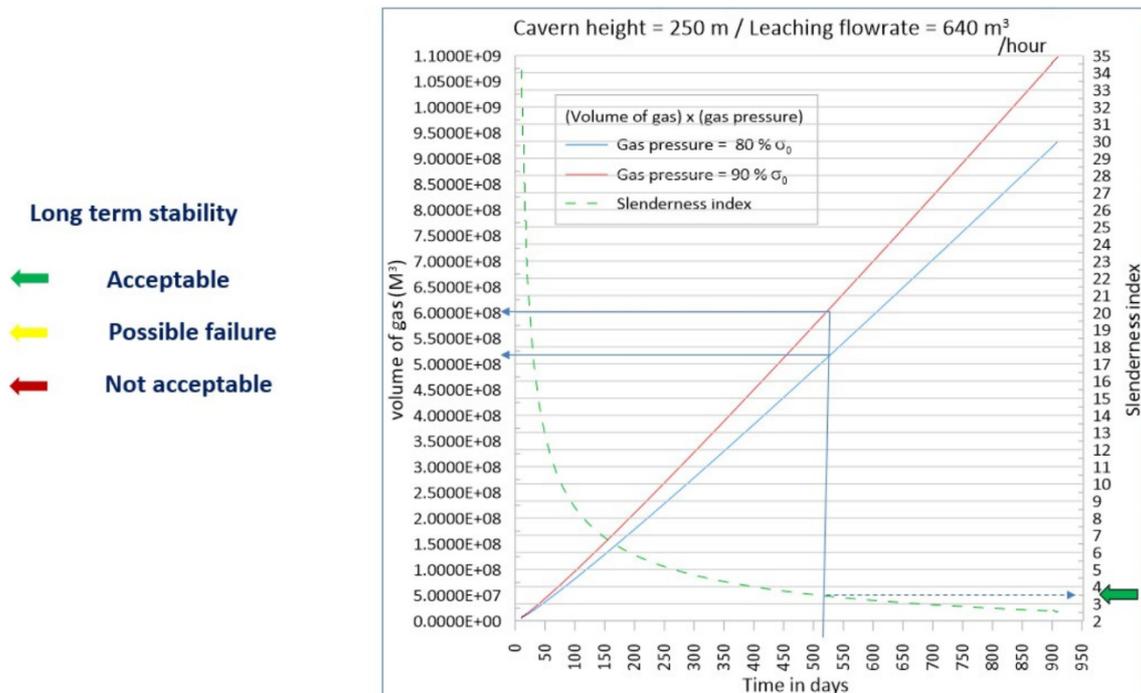


Fig. 5. Evolution with time of disposal gas storage for cavern with height of 150 m.

Table 2
Design parameters for disposal of gas, with high content of CO₂, in offshore ultra-deep-water salt caverns opened by solution mining.

Parameter	Value
Reference height (m)	250
Height of the net value of the cavern (m)	215
Average diameter (m)	81
Brine flowrate (m ³ /hour)	640
Brine temperature (°C)	42
Outer tubing of the well completion	14"
Inner tubing of the well completion	7 5/8"
Leaching time (days)	~540
Gas pressure % (lythostatic pressure)	80
Control index (slenderness ratio $\lambda = H/\phi$)	3.08

From this model was possible to generate a finite element mesh with 21,894 quadratic isoparametric finite elements of 8 nodes and 66,353 nodal points.

3.5. Simulation process

The cavern excavation is simulated by the program COVES 2 in 3 steps, 120 days, 360 days and 600 days, following the leaching profile obtained by the leaching simulation results of SALGAS.

After the cavern reaches its full size, specified by the geomechanical design, starts the extraction of the brine by the injection gas, a field proof practice used in all natural gas storage in the world.¹⁸

Fig. 10 shows 6 steps of withdrawing the brine from the cavern by gas injection. Pressure load functions are applied to the wall of the cavern and, at the same time, counter pressure is applied to consider the lowering of the brine inside the cavern.

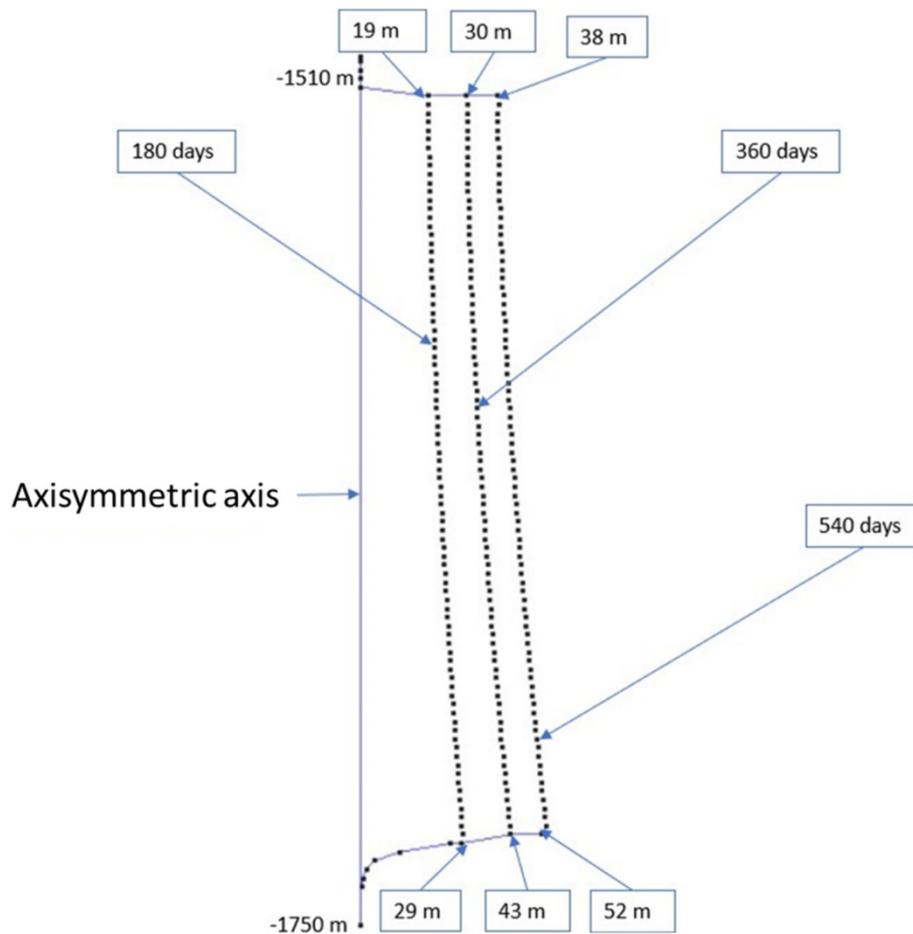


Fig. 6. Axisymmetric representation of cavern with height of 250 m. Lixiviation time of 180 days, 360 days and 540 days.

Table 3
Rock mechanics properties determined in the potash mine at Sergipe.

Material	Elastic properties		Creep properties			
	Young's modulus <i>E</i> (MPa)	Poisson's ratio ν	Reference effective stress σ_0 (MPa)	Creep effective strain ϵ_0 (year ⁻¹)	Stress exponent n_1	Stress exponent n_2
Sylvinitite	15742	0.33	10	0.0016	3	5.8
Halite	20403	0.36	10	0.0016	3	5.8
Carnalite	4020	0.36	8	0.0072	3	5.8
Tachyhidrite	4920	0.33	10	0.2200	3	3
Shale	18971	0.15				
Carbonate	31044	0.24				
Sandstone	20696	0.15				

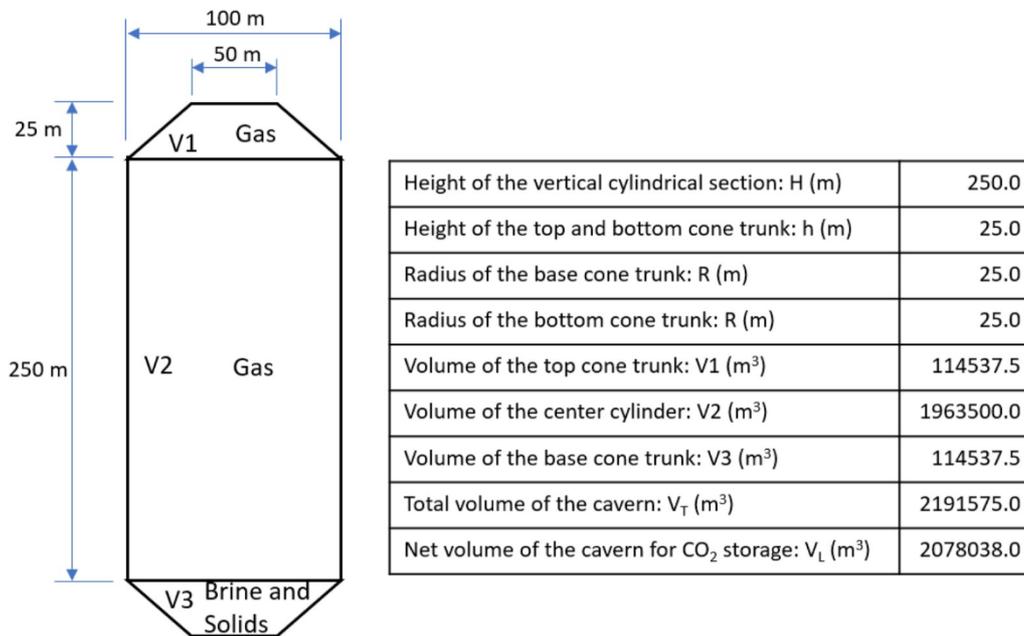


Fig. 7. volume of the cavern.

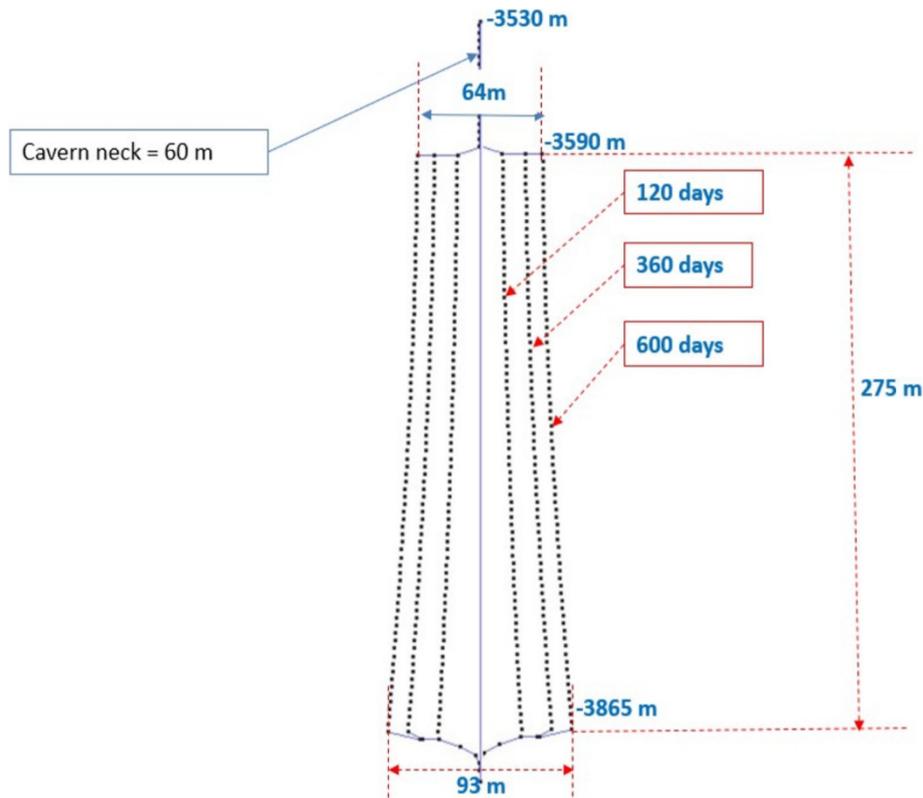


Fig. 8. Leaching simulation results with seawater injection rate = 640 m³/h.

After the gas pressure reaches the maximum specified by the geo-mechanical design of the cavern, the Xtree is closed and the disposal gas is confined inside the cavern. At this moment the cavern walls start to react against the confined gas due to the creep of the salt.

4. Results

4.1. Simulation results

Fig. 11 shows the evolution with time of the radial displacements of the cavern perimeter. When the excavation reaches a certain stage/time it generates a curve. The evolution with time of the radial displacements shows the effect of the filling process and the abandonment of the

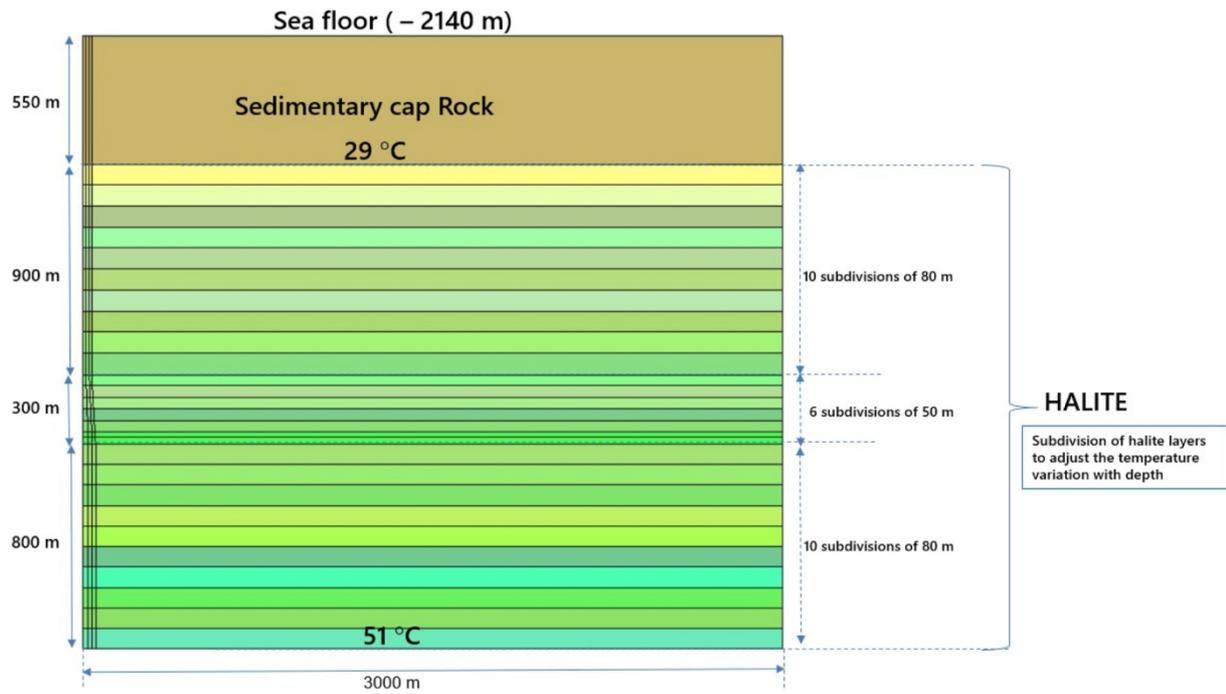


Fig. 9. Geomechanical structural model of a CCS salt cavern in ultra-deep water.

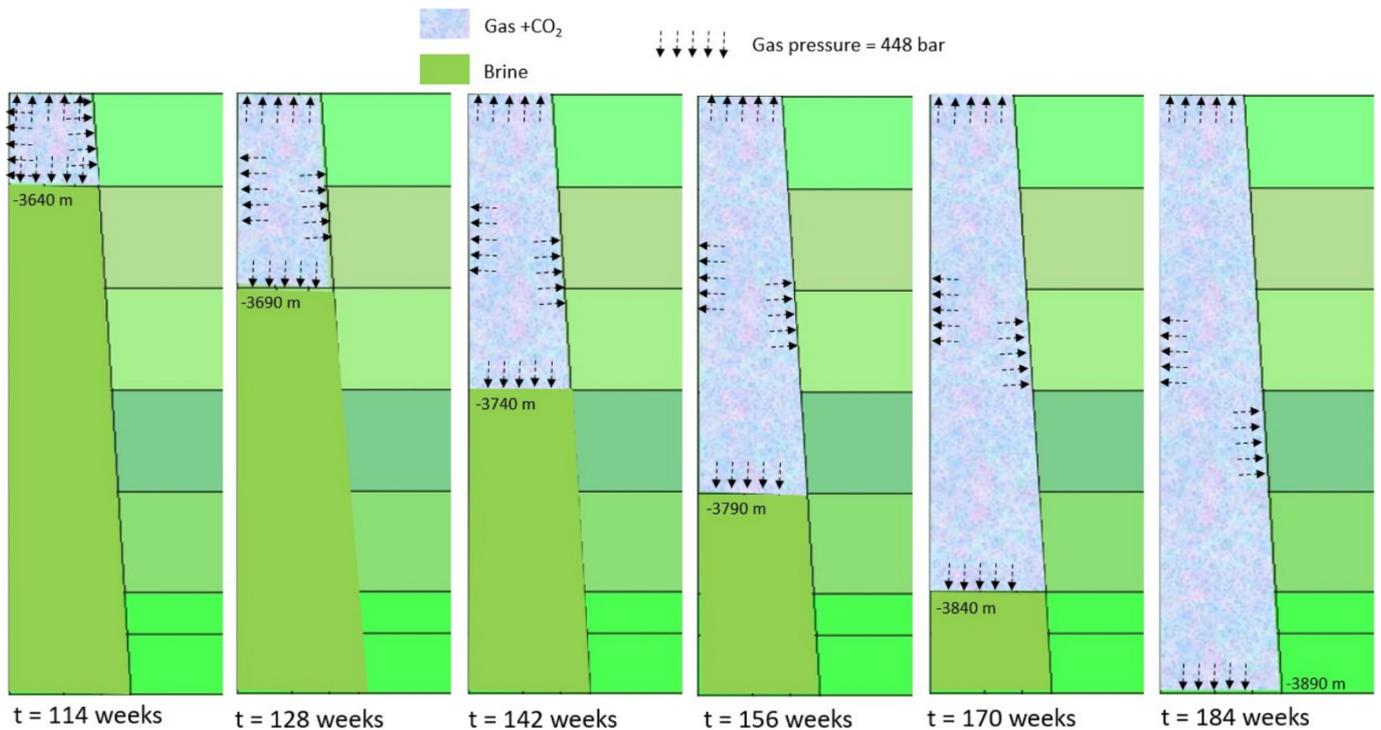


Fig. 10. Withdrawal of the brine by gas injection.

cavern.

After the cavern is abandoned the reaction occurs of the confined fluid against the wall closure, due to the creep of salt and therefore, this interaction causes the deceleration and almost stops the deformation of the cavern, the expected indication of the structural stabilization with time of the cavern.

For the geomechanical simulation, a time of 184 weeks to completely fill the cavern and replace the brine was assumed. At the time equal to 184 weeks the gas reaches the bottom of the cavern. As the gas is

injected and pressurized inside the cavern the creep closure deformation rate is reduced and stabilized with time. During the injection time, the nodal displacement points used to monitor the simulated closure of the cavern due to the creep of the halite, continue to increase but in a progressive smaller rate.

It will take 14 weeks more to finish the filling of the cavern with gas at the pressure of 85% of the lithostatic pressure. At the time equal to 198 weeks the Xtree is closed.

The evolution over time of the pressure of the gas inside the cavern

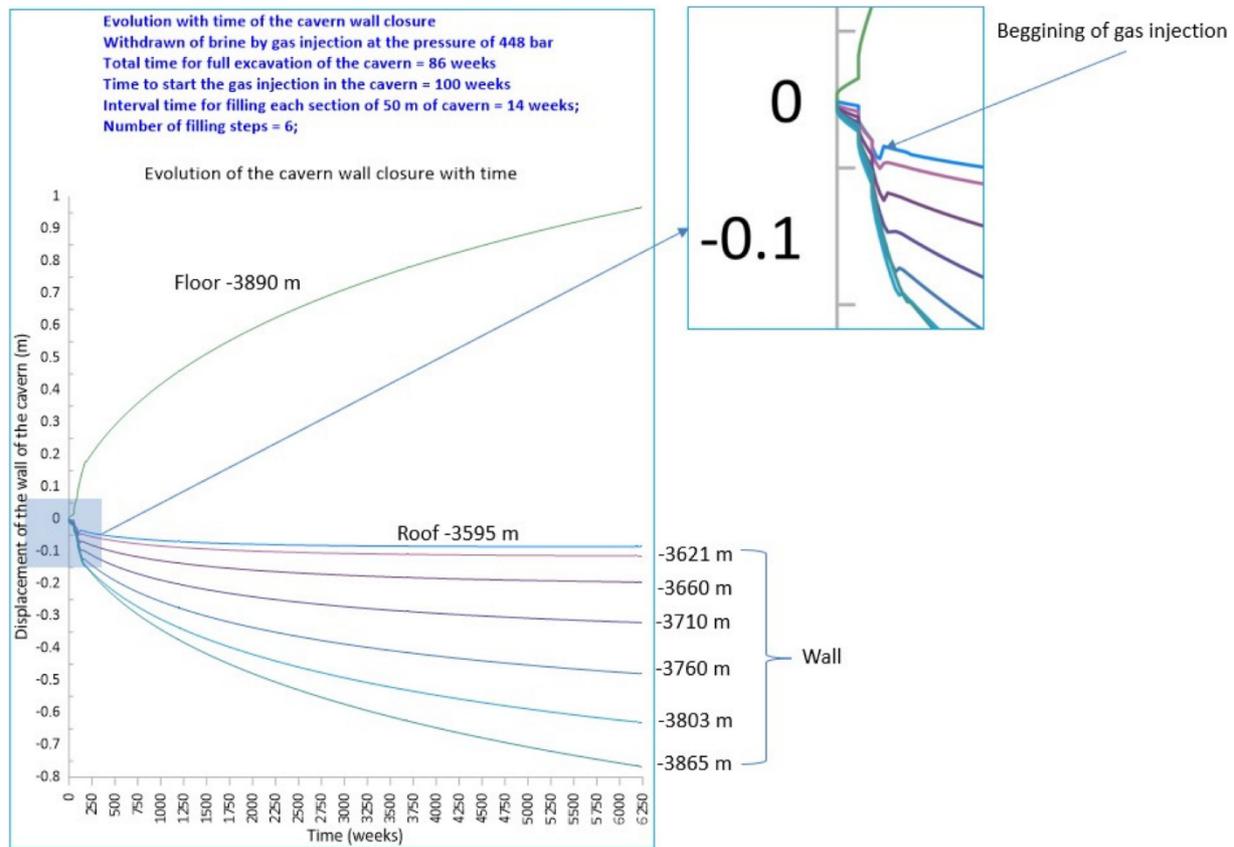


Fig. 11. Evolution with time of the cavern wall closure.

due to the phenomenon of squeezing by the wall closure of the cavern is presented in Fig. 12(a). After 30 years, the gas pressure increases to 46,000 kPa, and after 120 years, the gas pressure increases to 48,000 kPa.

Of the displayed stress distribution, the major principal stress is the one that offers greater risk to the leakage of the cavern, as expected, because it is the same as the most positive state of stresses (The least stress) in a point of the continuum. Fig. 12(b) shows the distribution of σ_1 30 years after the abandonment of the cavern and Fig. 12(c) shows the distribution of σ_1 120 years after the abandonment of the cavern.

The minimum compression stress after 30 years (σ_1) is 50,600 kPa, as shown in Fig. 12(b). This value increases to 52,800 kPa after 120 years, as shown in Fig. 12(c). The minimum safety factor against the phenomenon of leakage is 1.1 at 30 years and 120 years.

COVES 2 simulates in one run the excavation with time, the replacement of the brine by the gas with high content of CO₂ and the final abandonment of the cavern. Fig. 13(a) shows the iso-surface of the radial displacements at 120 years, or 6240 days. Due to the reaction of the confined fluid (Gas + CO₂) inside the cavern and the stabilization of the deformation, the final accumulated radial displacement is only 0.75 m.

The iso-surfaces of displacements confirm the simulation results due to the immediate smooth distribution of deformation between the rock and (Gas + CO₂), inside the cavern. Once the Xtree is closed the squeezing of the gas inside cavern deaccelerate the creep closure of the cavern, reaching a steady-state condition.

The process of perimeter scaling of the cavern wall in conventional mining starts when the effective creep strain reaches 5%–10%.³ In this project the maximum effective creep strain occurs only in the corner of the cavern wall, which will be smoothed over time. Fig. 13(b) show the iso-surface of the effective creep strain at 6240 weeks or 120 years, certifying that the cavern will be kept in a very good condition even after

120 years of abandonment.

The cavern walls must always keep a closing tendency against the internal pressure, distributing in its surroundings a compressive stress that prevents the formation of micro-cracks or micro-fractures that may allow permeation of gases to another formation or even to surface. Fig. 13(c) shows the iso-surface of the first invariant of stresses $\{\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3\}$ at $t = 190$ weeks, 8 weeks before the Xtree is closed. Close to the perimeter of the cavern the first invariant of stresses is ~51600 kPa. The maximum internal pressure in the gas is 42400 kPa, so a safety factor of ~1.21.

5. Discussions

5.1. Gas volume analysis

To calculate the volume of gas that is possible to be confined inside the cavern, it is necessary to have the expansion coefficient of the gas with different contents of CO₂ for several state variables (temperature and pressure). For the pressure of ~480 bar and temperature 42 °C, the estimation of the coefficient is shown in Fig. 14.

The CCS volume of the salt cavern can be calculated with the interpolation of the expansion curve, Fig. 15. This volume achieves 1,000,000,000 Sn³.

The pressures provided by the geomechanical calculation indicate values between 350 bar and 450 bar. CO₂-rich gas will undergo a natural gravitational separation between CH₄ and CO₂ by the density difference of the CO₂ that is at the supercritical state. The CH₄ will remain at the top of the cavern and CO₂ at the bottom. The natural gas can be recovered and after the total filling of the cavern with CO₂ the same will be conditioned for the definitive abandonment.

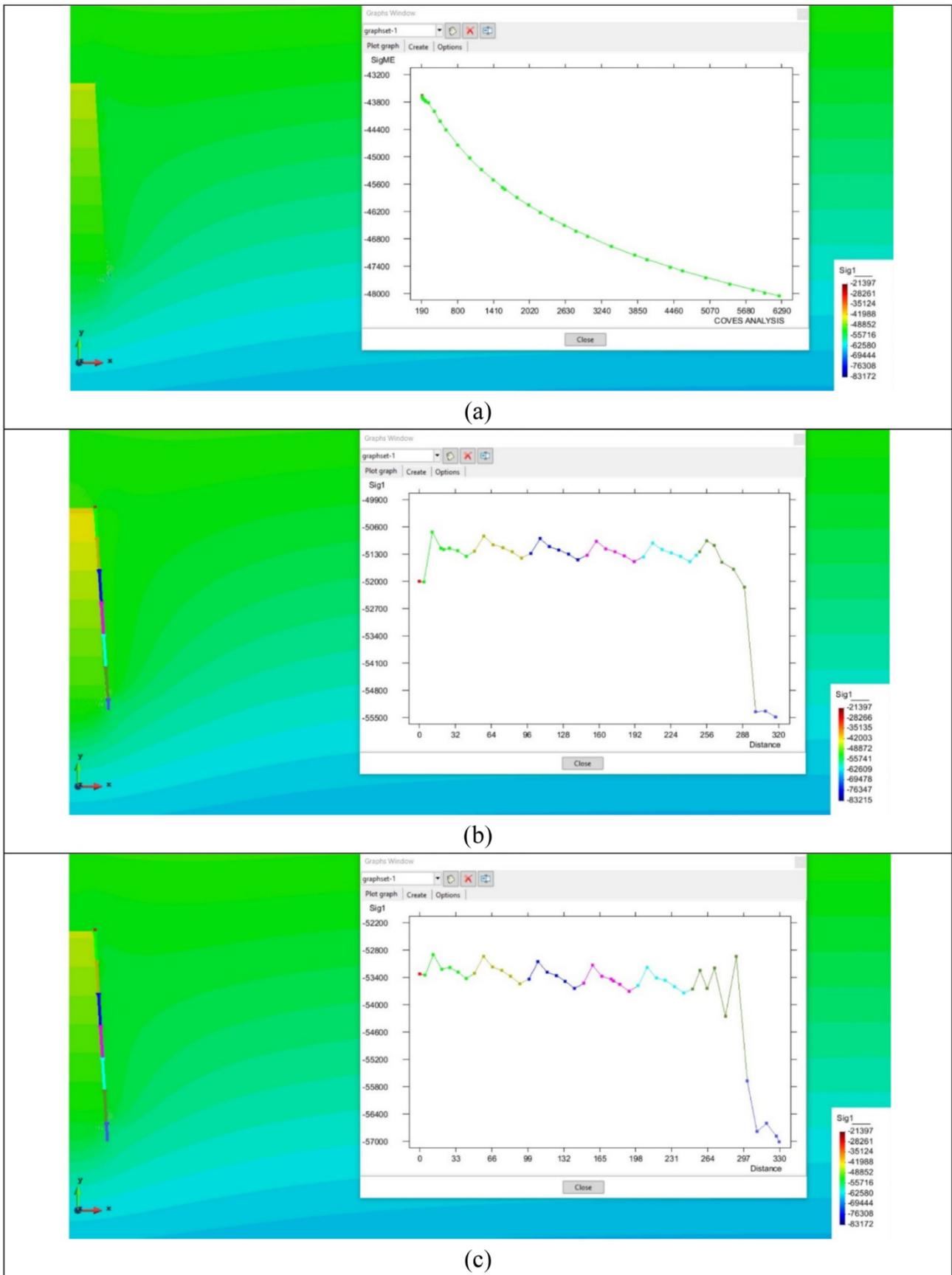


Fig. 12. (a) Evolution over time of the gas pressure inside the cavern, (b) Distribution of σ_1 at $t = 1560$ weeks or 30 years, and (c) Distribution of σ_1 at $t = 6240$ weeks or 120 years.

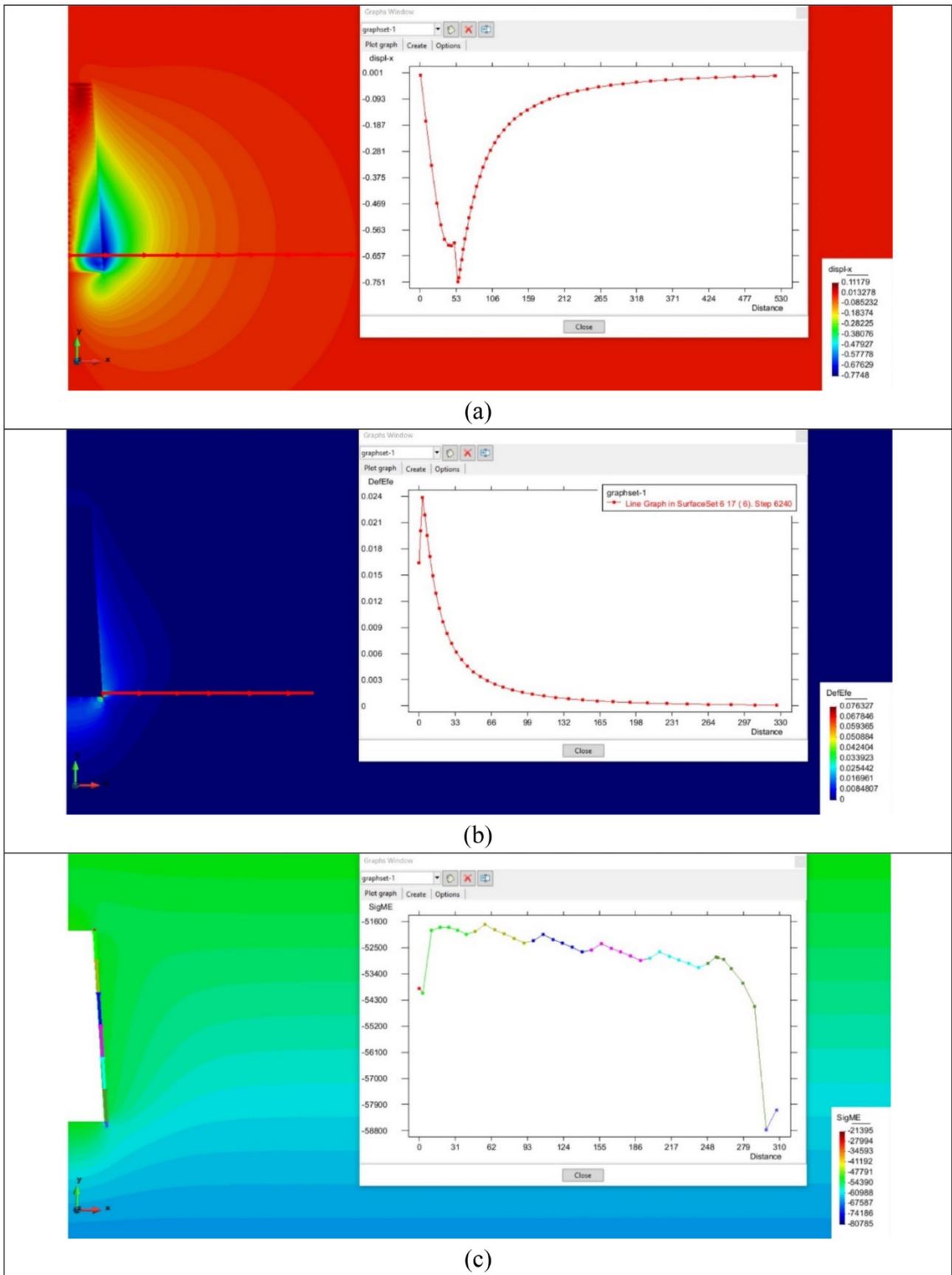


Fig. 13. (a) Iso-surface of the radial displacement in meter at 120 years, (b) Iso-surface of the effective creep strain in $t = 6240$ weeks or 120 years, and (c) Iso-surface of σ_m (Pa) at $t = 190$ weeks.

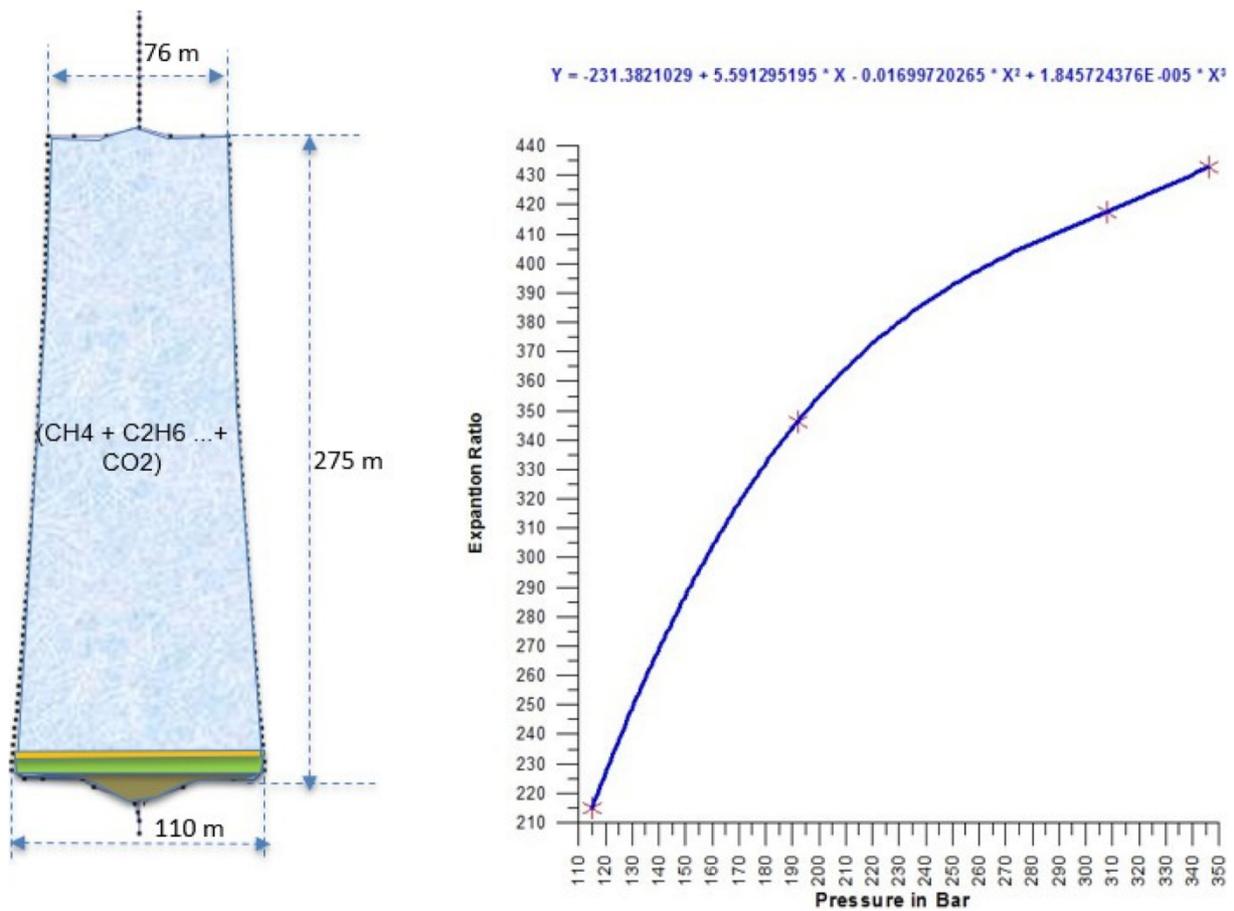


Fig. 14. Expansion coefficient of gas stream with 90% of CO₂ at the temperature of 44 °C.²⁶

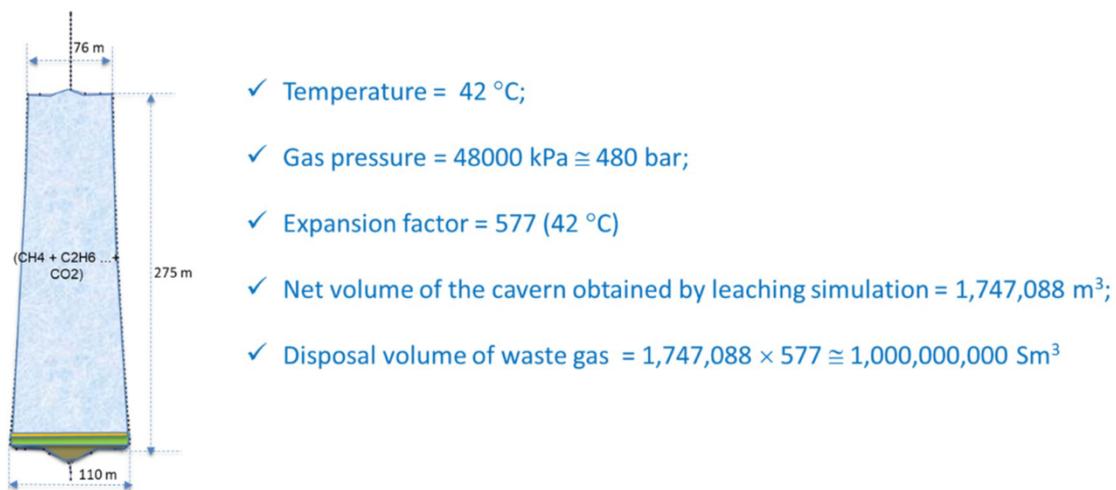


Fig. 15. volume of CCS inside the cavern 275 m by ~93 m.

6. Conclusions

This paper described the conceptual design to reduce carbon dioxide emissions of offshore oil production of high gas-to-oil ratio reservoirs and high content of CO₂, showing the steps from the parametric study to select the best relation between flowrate, leaching time, structural stability, and the volume of gas with the high content of CO₂ storage. The CCS volume achieves 1,000,000,000 Sm³.

Based on the set of parameters selected by the parametric study it is

possible to find a cavern with a more attractive storage volume, increasing the volume of CCS to 1 billion Sm³ of disposal gas. The cavern can be constructed by dissolution in water depth of 2140 m using an injection of seawater flowrate of 640 m³/h. The proposed dimensions of the cavern certified by the geomechanical project are: 900 m of halite slab protection thickness, between the bottom of the sedimentary cap rock and the top of cavern; -3590 m of depth of the top; -3890 m of depth of the bottom; Diameter of ~93 m; and height: ~275 m.

The results achieved by the research and development project so far

demonstrate that it is technically feasible to store natural gas with high content of CO₂, under high pressures, in salt caverns opened by leaching in water depth of 2200 m. No technological gaps have been detected that make it impossible to extend the worldwide practice of onshore caverns storing natural gas under high pressures to the offshore ultradeep water environment.

Finally, it has been decided to proceed with the project and to go for a field test through a smaller experimental cavern to obtain the field parameters that will allow the final certification of the technology and its use in the oil fields of the ultra-deep water pre-salt reservoirs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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