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GREENHOUSE GASES SCIENCE AND TECHNOLOGY

Potential of storing gas with high CO_2 content in salt caverns built in ultra-deep water in Brazil

Alvaro Maia da Costa, University of São Paulo (USP), São Paulo, Brazil and Modecom-Technology in Geomechanics and Computing Modeling, Rio de Janeiro, Brazil
Pedro V. M da Costa, Modecom-Technology in Geomechanics and Computing Modeling, Rio de Janeiro, Brazil
Okhiria D. Udebhulu and Ricardo Cabral Azevedo, University of São Paulo (USP), São Paulo, Brazil
Nelson F. F. Ebecken, Federal University of Rio de Janeiro (COPPE-UFRJ), Rio de Janeiro, Brazil
Antonio C. O. Miranda, University of Brasília (UnB), Brasília, Brazil
Sérgio M. de Eston, Giorgio de Tomi, Julio R. Meneghini and Kazuo Nishimoto, University of São Paulo (USP), São Paulo, Brazil
Felipe Ruggiere, Argonautica, São Paulo, Brazil
Edgard Malta, Technomar, São Paulo, Brazil
Mauro Élis Rocha Fernandes, University of São Paulo (USP), São Paulo, Brazil
Camila Brandão and Alexandre Breda, Shell Brazil, Rio de Janeiro, Brazil

Abstract: Salt caverns have been identified as one of the best options for the underground storage of gases due to salt rock's excellent sealing capabilities and interesting mechanical properties, such as self-healing when damaged or cracked. It is feasible to build salt caverns in the Brazilian pre-salt ultra-deep water environment for gas storage. However, the peculiar geology of the Brazilian province considered here is characterized by the stratification of thick layers of halite with intercalations of carnallite and tachyhydrite salt rock, whose creep strain rate is almost two orders of magnitude higher than halite's creep strain rate under the same conditions of temperature and pressure. Computational mechanics is being used for the design of offshore salt caverns opened by dissolution mining for the storage of natural gas. The challenge presented in this paper requires the storage of natural gas with high CO_2 content offshore in ultra-deep water (2140 m) in salt caverns. If the economics proves feasible, this offshore gas storage station will be the first of its kind in the world. A technical feasibility rock mechanics study of giant salt caverns, 450 m high by 150 m in diameter, has shown that one cavern can store 4 billion Sm^3 or 7.2 million tons of CO_2. The salt dome studied can accommodate the construction of 15 caverns, thus providing the confinement of approximately 108 million tons of gas.

Keywords: salt caverns; gas storage; rock salt; creep strain rate; stability analysis

Correspondence to: Pedro V. M da Costa, Avenida Vice Presidente José Alencar, N: 1400, Block 3/Apt 704, Condomínio Mayaan, Cidade Jardim, Jacarepagua, Rio de Janeiro, Brasil 22775-033.
Email: pedromaiadacosta@gmail.com
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Introduction

Governments, corporations, and other organizations increasingly recognize the importance of stabilizing the atmospheric concentration of greenhouse gases (GHG). Climatologists agree that increasing concentrations of GHG contribute to global climate change, and CO_2 is reported to dominate these emissions. The process of carbon capture and storage in geologic media has been identified as an important means of reducing anthropogenic GHG emissions.[1] Noting various ways to sequester CO_2 in geological media, including utilization in enhanced oil recovery (EOR)[2] operations, disposal in disused oil and gas reservoirs, replacement of methane in coalbeds, injection in deep saline aquifers, and storage in salt caverns, Bachu (2000) suggested several criteria to be considered when evaluating the potential of a sedimentary basin for CO_2 sequestration. These criteria include its tectonic setting and geology, the basin geothermal regime, the hydrodynamic regime of formation waters, the hydrocarbon potential and basin maturity, economic aspects relating to access and infrastructure, and socio-political conditions.[2]

Salt caverns have been identified as one of the best options for the underground storage of gas, the main advantages including the following:

- Low permeability. The permeability of salt rock is about 10^{-21} to 10^{-24} m^2 ($1.01325*10^{-6}$ – $1.01325*10^{-9}$ mD); thus, it can provide excellent sealing for the salt cavern.
- Good mechanical properties. The damage self-recovery capability of salt rock can ensure the safety of a salt cavern even with frequent changes of gas pressure.
- Solution in water. Rock salt is easily dissolved in water, which facilitates the construction and shape control of the salt cavern.[3]
- Abundant resources. Salt rock is a very rich mineral resource with wide distribution and large reserves. Sites for the construction of salt caverns for gas storage near where they are required can therefore be found easily.[4] Salt formations can be found in almost every part of the world. With some exceptions around the Pacific Rim, salt caverns can be constructed in naturally occurring thick salt domes, deep underground. Salt caverns can be formed through a leaching process by pumping fresh water or sea water to dissolve the salt and removing the resulting brine via a single well, which then serves for both gas injection and withdrawal.[5]

Wellbore integrity has been identified in many studies as a key risk factor affecting the viability of geologic carbon capture and storage (CCS) projects.[6,7] Wellbore integrity depends strongly upon the integrity of the interfacial bonding of the cement to the formation and the casing.[6,8,9] Loss of well integrity leads to several consequences, including negative financial consequences, and significant environmental impacts, such as groundwater contamination, gas leakage, and fluid spills and seepage among others.[7,10] Carbon capture and storage in geological media, also known as CO_2 geosequestration, has been identified as a viable climate-change mitigation technology.[1] For CCS to be successful, three fundamental conditions have to be met by the storage medium. First, the medium must have the capacity to store a large volume of CO_2; second, the injectibility of CO_2 into the medium must be ensured; and finally, the medium must be able to confine the stored CO_2 for a very long time without leakage.[11]

In 2006, through the pioneer well TUPI (RJS-628), one of the largest oil provinces in the world for pre-salt reserves was discovered, stretching from the north to the south of the Brazilian continental front, between 200 km and 300 km away from the coast.[12] It consists of carbonate reservoirs underlying approximately 2000 m of stratified salt rock. Many provinces producing oil and natural gas globally are associated with reservoirs underlying thick layers of salt, consisting largely of halite (NaCl), whose mechanical resistance favors the drilling of wells. The peculiar geology of the Brazilian province is characterized by the stratification of thick layers of halite with intercalations of carnallite and tachyhydrite salt rock, whose creep strain rate is approximately two orders of magnitude higher than halite's rate for the same temperature and pressure state variables.[12] The stratified halite layers are perforated by giant pure halite diapirs coming from the bottom due to the creep movement of older geological layers of halite. These diapirs are the best choice for the construction of salt caverns.

The petroleum in the pre-salt reservoirs in Brazil usually possesses a very high gas–oil ratio (GOR) with a high carbon dioxide content. The high GOR of the pre-salt reservoir fluid with high CO_2 content poses another great challenge to be overcome for the continuity of hydrocarbon production from these reservoirs.

Laboratory analyses have shown that CO_2 found in the pre-salt reservoirs in Brazil are of mantle origin, migrating to the pre-salt reservoirs through the intense presence of geological faults between crystalline carbonate reservoirs.[12] Due to the pressure and temperature state variables in the reservoirs, CO_2 is usually in a liquid or supercritical state and mixed with hydrocarbon inside the reservoirs. However, when it is produced at the surface, it gasifies and mixes with the other monetizable gases, such as methane (CH_4), and ethane (C_2H_6).[12]

Some of these gasses are treated and separated on the platform using membrane separation technology, reducing the CO_2 content to 3%, and it is possible to transfer a portion of the natural gas to shore through carbon steel pipelines. The remainder, consisting mainly of CO_2 gas, is reinjected into the reservoir. At the beginning of the life of the fields, the reinjection of this gas was used to support EOR in a process called water alternated gas (WAG). However, as the same molecule of CO_2 recycles several times within the drainage radius of the wells, the CO_2 content starts to increase significantly, making its treatment in the platform infeasible, which may force the closure of some production wells.

From the inception of production of pre-salt reservoirs, in the field development plan, there was a hypothesis that the CO_2 gas stream could be reinjected into nearby saline aquifers, which could only be selected below the pre-salt reservoirs. This was due to the small layer thickness of the sediment above the salt layer (between 500 m and 800 m) which cannot withstand the envisaged volume of CO_2 at the required injection pressure and temperature.[12]

However, a saline aquifer below the pre-salt is intercepted by a large number of geological faults, which naturally feed, without anthropogenic action, the pre-salt reservoirs with mantle CO_2. The injection of CO_2 under high pressures into these reservoirs possessing non-sealing geological faults or even with some sealing faults in place would only increase their permeability. This process would create a vicious cycle, increasing the level of reservoir contamination and adversely affecting field production over time.

Thus, the high concentration of CO_2 in the pre-salt reservoirs presents another adverse technological challenge requiring the separation and safe storage of CO_2. Even implementing conventional membrane separation technology for a CO_2/ natural gas mixture would not be technically and economically feasible for reservoir fluids possessing high GOR with very high CO_2 content.

With these prevailing limiting conditions of pre-salt reservoirs, salt rock has become a strategic geomaterial for the process of confining gas streams with high CO_2 content because such gas can be injected and contained in salt caverns rather than being reinjected into reservoirs.

The innovative technology presented in this paper is peculiar to the environment in which the research project is being developed with very unique characteristics. It is unprecedented worldwide and requires a deep multidisciplinary knowledge of offshore oil engineering in ultra-deep waters, drilling of wells through very thick layers of salt rock, geomechanical design of salt caverns offshore in ultra-deep water, cavern construction technologies for offshore dissolution, fluid mechanics, gas thermodynamics, and CCS in salt caverns.

To date, there are no natural gas or other hydrocarbon storage systems in offshore salt caverns. Only the Gateway Project in the Irish Sea is upcoming; it involves a project to store natural gas in offshore salt caverns in shallow water 25 meters deep, but it has not been built yet.[13]

Simulation results obtained shows the technical feasibility of huge storage volumes of natural gas and CO_2 in giant salt caverns offshore. For the case study presented in this paper, using giant salt caverns, 450 m high by 150 m in diameter, one cavern can store 4 billion Sm^3 or 7.2 million tons of CO_2. The salt dome studied can accommodate the construction of 15 caverns, thus providing the confinement of approximately 108 million tons of CO_2.

Technical feasibility study of salt cavern construction for carbon dioxide storage in ultra-deep water offshore

Basic simulation data

In the process of selecting potential areas for the development of salt caverns by solution mining, salt diapirs are selected to minimize the presence of interbedded non-soluble rock layers, such as shale and anhydrite, and to avoid the more soluble salts, namely carnallite and tachyhydrite, as much as possible. Some

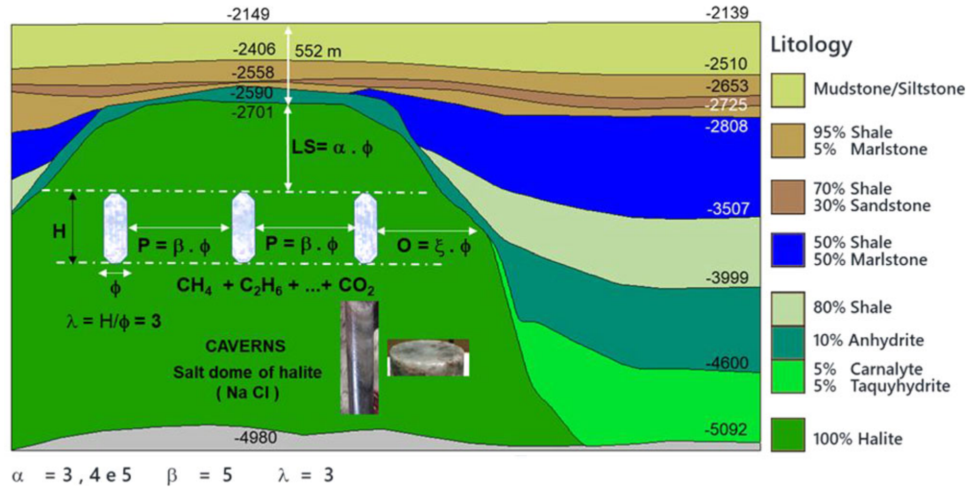
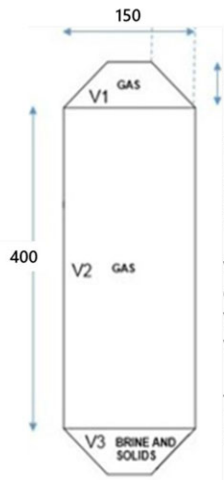


Figure 1. Vertical geology section with indication of the parametric variables studied.[14]



Geometrical volume of the caverns

Height of the vertical section of the cavern: H (m)	400
Height of the cone trunk of the base and top of the cavern: h (m)	25
Radius of the cone trunk base: R (m)	75
Radius of the cone trunk top: r (m)	50
Volume of the cone trunk at the base of the cavern: Insolubles deposit during solution mining : V3 (m^3)	310887,5
Volume of the cylindrical section of the cavern: V2 (m^3)	7068600
Volume of the cone trunk at the top of the cavern: V1 (m^3)	310887,5
Total volume of the cavern: V_T (m^3)	7690375
Net volume of the cavern for CO_2 storage: V_L (m^3)	7379488

Figure 2. Proposed geometry of the cavern.[15]

other criteria were also established, such as the maximum depth from the top of the rock salt dome and the distance of the salt domes from the oil fields.

Based on the interpretation of 3D and 2D seismic data, a cluster of salt domes 10 km away from one of the major pre-salt oil fields in the Santos Basin was selected.[14] Figure 1 shows the vertical geology section of the salt diapir and the geometrical variables used in the parametric study necessary to assess the technical feasibility of the salt-cavern design.

Due to the large volume of the salt dome selected, the distance between the caverns was calculated to eliminate the group effect so that the redistribution of stresses induced by the dissolution of one cavern would not influence the stability of a neighbor cavern in the cluster. Under these conditions, the simulation of the structural behavior of the caverns was conducted by the application of axisymmetric structural models. Due to the very large size of the salt dome it is possible to construct giant salt caverns. Vassalo[4] recently presented a very elegant procedure to design giant salt caverns in shallow water. In terms of geomechanical analysis, he also reported that there is no appreciable difference in the simulations and criteria used in the design of caverns of any size.[15] Figure 2 shows the proposed geometry of the target cavern, and Fig. 3 shows the cross-section of the basic geometrical data used for building the structural geomechanical model.

To evaluate the salt caverns' stability, some basic assumptions based on the authors' experience were adopted:[4,14–17]

- Specific weight of the sedimentary rock → 22.56 kN/m^3.

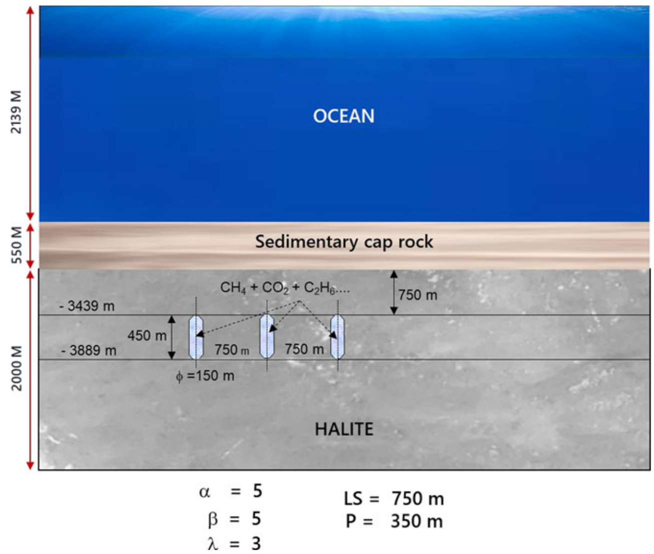


Figure 3. Basic geometric data used for building the structural geomechanical model.

- Specific weight of the rock salt →21 kN/m^3.
- Slab protection of rock salt at the top of the cavern → $\alpha \times ø = 750$ m.
- Minimum distance between caverns to avoid interference → $\beta \times ø$ (between axis) = 750 m.
- Temperature of the sea bed = 4°C.
- Geothermal gradient in sedimentary rock = 30°C /1000 m.
- Geothermal gradient in rock salt = 12°C / 1000 m.
- Slenderness ratio of the cavern →λ = h/ø = 3.
- Shape → cylindrical.
- Height and diameter of cavern → 450 m and 150 m respectively.
- Initial state of stress at the top of the cavern → $\sigma_0 = 2{,}139 * 10 + 550 * 22.56 + 750 * 21 = 21\,390 + 12\,408 + 15\,750 = 49\,548$ kPa.
- Maximum internal pressure of CO_2 inside the cavern → 90% of the effective initial stress.
- At the top of the cavern (P_{max}) = 44 593.20 kPa.
- The geometric volume of the cavern is indicated in Fig. 4.

The creep strain rate of halite is activated by the temperature. The rock salt layer is divided into small layers to take into consideration the variation of the temperature with depth. Figure 4 shows the structural geomechanical model used in the simulation. COVES 2 is the simulator used for the structural geomechanical modeling.[18]

An explanation of the physical–mathematical formulation of the computer code, COVES 2, and the rock mechanics properties used in the geomechanical simulation has already been presented by one of the authors in another paper titled: 'UGS in giant offshore salt caverns to substitute the actual Brazilian NG storage in LNG vessels.'[15] As a recent development, the COVES solver was customized in GiD software.[19] GiD is an adaptive pre- and post-processor for numerical

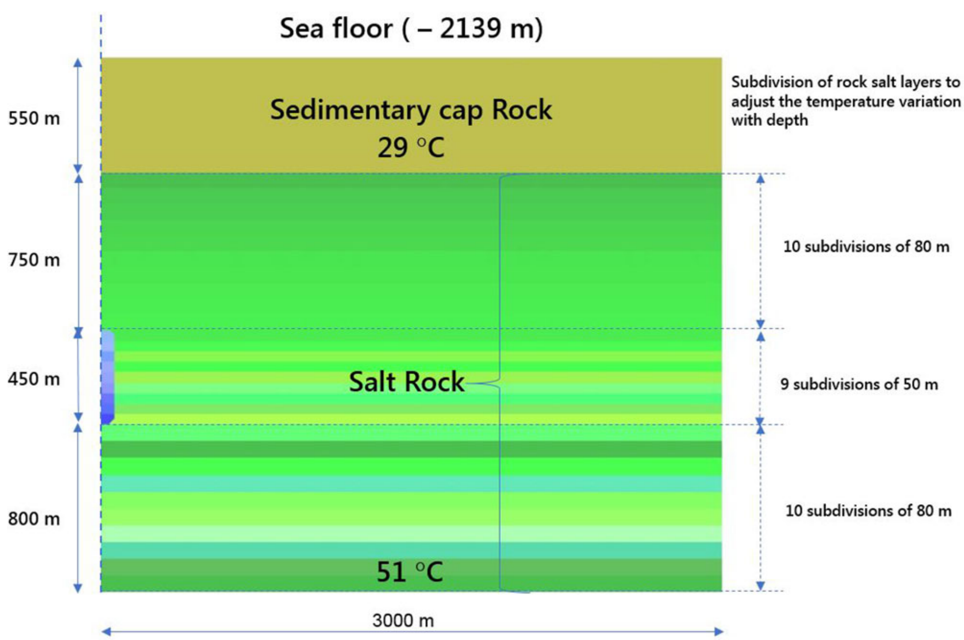


Figure 4. Geomechanical structural model of a CCS salt cavern in ultra-deep water.

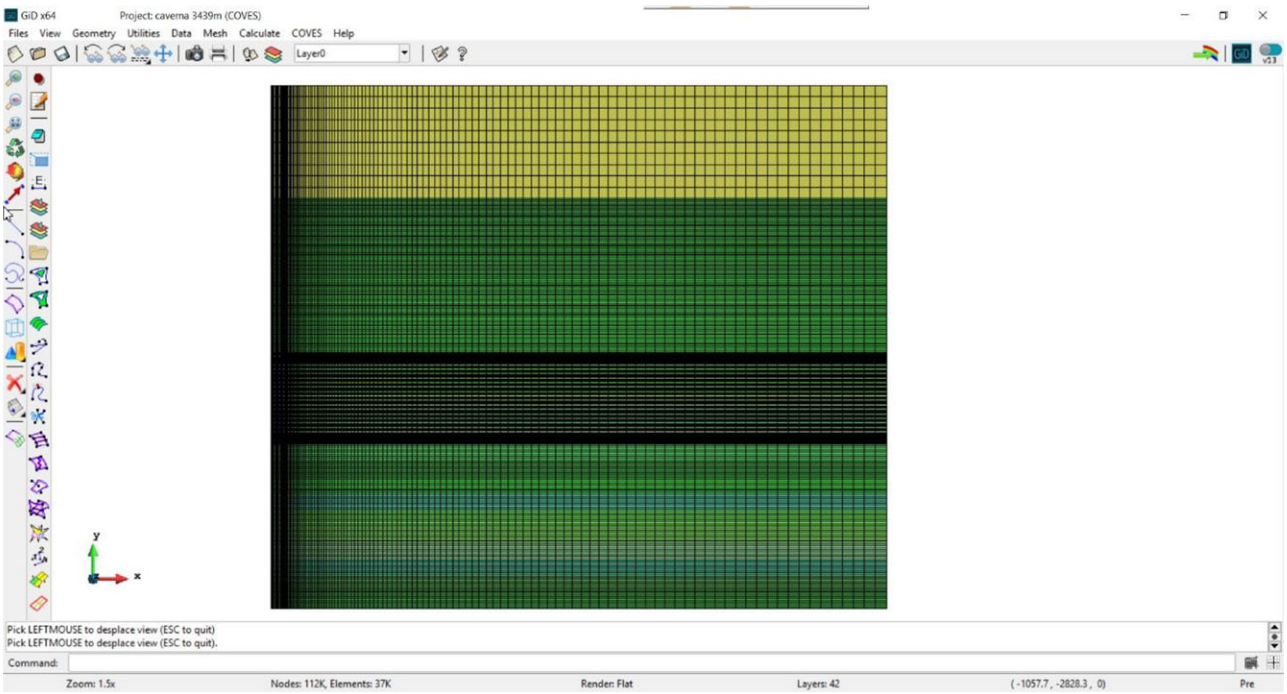


Figure 5. Finite-element mesh generated on the structural geomechanical model. (Solver COVES 2[18] – pre-post-processor GiD.[19])

simulations in science and engineering, where it is possible to implement conditions, material, and general data for specific purpose. All attributes of COVES were customized in menus, and the input data of COVES is written in its format using the tcl program language. The analysis results, which include many time steps and mesh modifications during analysis, are exported to GiD file format by an external developed software. Using this approach, COVES uses almost all the capability of the pre- and post-processor. For example, in the pre-processor, it is possible to create complex geometries with a CAD system, meshes, and import / export geometries. In the post-processor, it is possible to analyze results with fill and contour lines, vector plots, isosurfaces, animation, and so forth. In summary, the COVES solver is integrated in a complete environment of finite-element (FE) analysis.

An FE mesh is generated on the structural geomechanical model as depicted in Fig. 5. This is an FE axisymmetric model with 37 163 quadratic isoparametric elements of eight nodes and 112 352 nodal points.

Simulation results

COVES 2 was used to simulate the excavation of the cavern in nine steps of 50 m each, from the bottom to

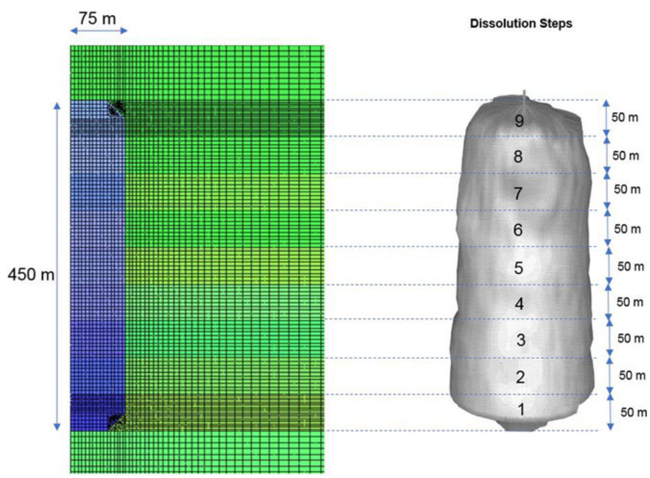


Figure 6. The 50 m excavation steps of the model.

the top of the cavern. This approach is like the technique employed in the stability analysis of salt caverns for brine production in Salgema Mineração.[20] Coincidentally, the steps of 50 m are directly related to the interval time between inspections by scan sonar 3D. Figure 6 shows the 9 excavation steps of 50 m each.

For efficient simulation of the stepwise cavern excavation, it is necessary to consider the dissolution time for each step of 50 m. From the alternatives studied for the construction of the cavern it was

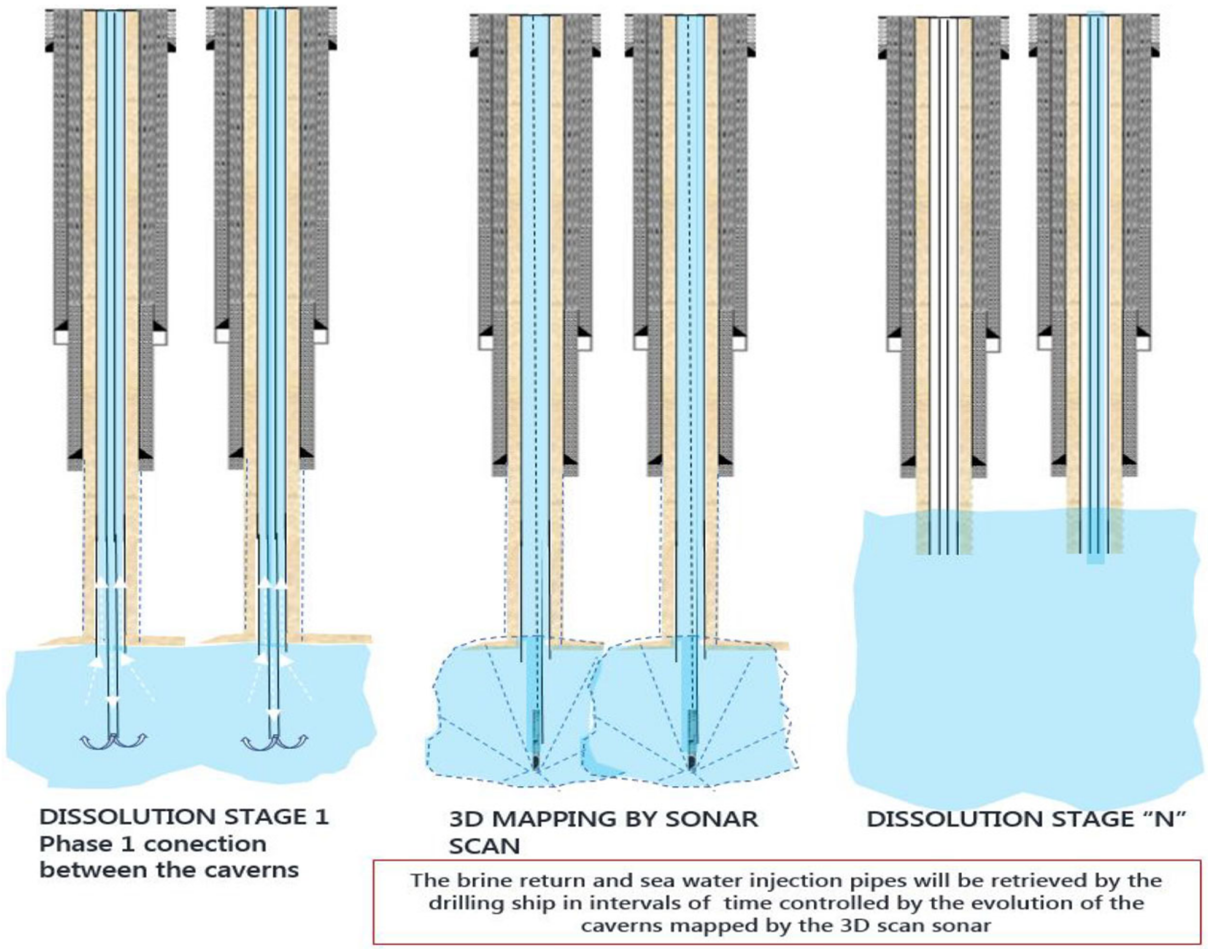


Figure 7. Dissolution process of the giant salt cavern.

assumed that two wells would be used for the dissolution with an injection flow rate of 140 000 barrels of sea water per day. The time to excavate each 50 m step would be approximately 15 weeks. Every 15 weeks the cavern would be monitored by scan sonar to control the diameter and shape. In case of any deviation from the predicted size and shape, in practice the stability of the cavern would be reanalyzed by structural geomechanical simulation. The SALGAS computer code was used to predict the dissolution time.[21]

Figure 7 shows how the dissolution of the giant cavern should be done. Two wells are drilled close to each other, and two caverns are constructed utilizing both wells. After some time the individual caverns intercept each other, becoming one giant cavern in the process of dissolution. During the dissolution process, the caverns are monitored by scan sonar 3D in each cavern.

COVES 2 simulates the excavation of the cavern step by step on a non-linear viscoelastic basis with time, excavating the elements included in each 50 m section, keeping the global structural equilibrium of the full model.

Figure 8 shows the positions of the nodal points with a continuous output from the simulation of the radial displacements to explain the effect of the excavation steps on the perimeter closure of the cavern. Figure 9 shows the evolution with time of the radial displacement of the cavern perimeter at the points shown in Fig. 8.

Each curve starts at a different time when the excavation reaches that position. The maximum closure of the cavern is about 1 m at the bottom of the cavern. The total time required for the dissolution of the cavern is 135 weeks, or approximately 2.5 years.

The effect of each excavation or dissolution step can be felt in the perimeter of the cavern, increasing the

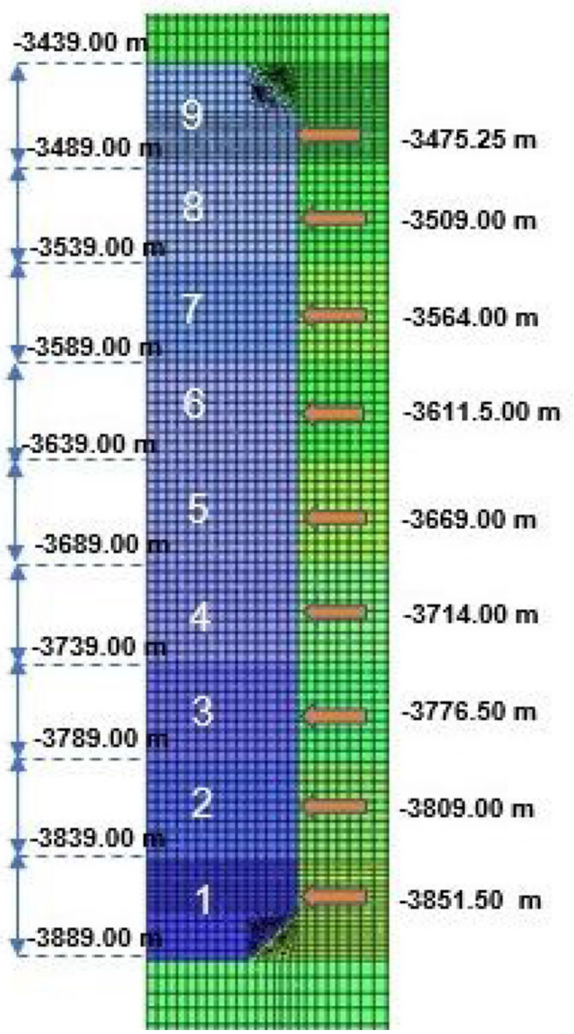


Figure 8. Dissolution stages and nodal points with continuous output of the radial displacements at the perimeter of the cavern.

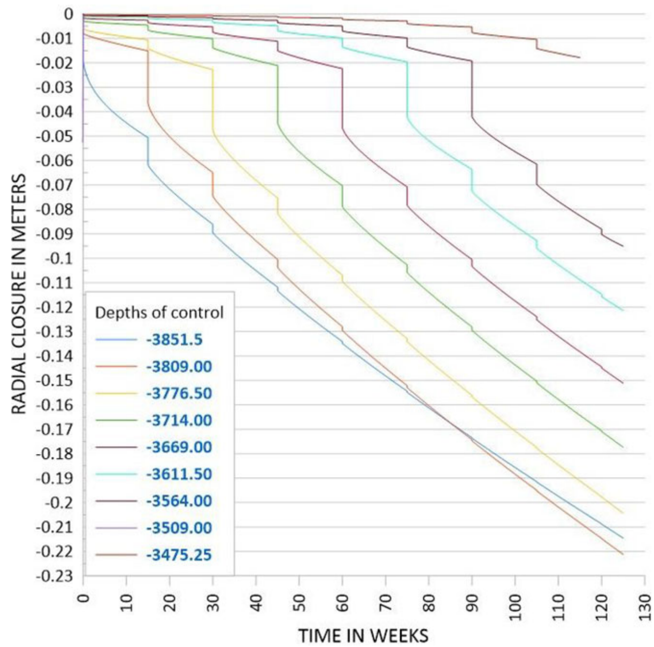


Figure 9. Radial displacement in various positions of the vertical cavern perimeter evolution with time. (Solver COVES 2[18] – pre- and post-processor GiD.[19])

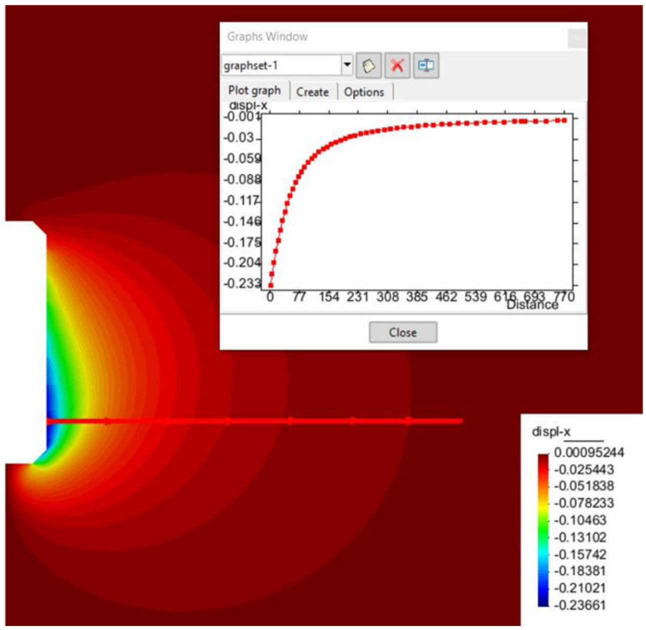


Figure 10. Isosurfaces of radial displacements at t = 135 weeks. (Solver COVES 2[18] – pre and post-processor GiD.[19])

closure velocity, as indicated in Fig. 9. The perimeter of the cavern is subjected to a differential stress of only 10% of the lithostatic stress (about 50 bar). At the same time the salt rock halite is quite cold at the position of the cavern, around 44°C, which justifies the small closure obtained by the simulation. A differential stress of 100 bar to approximately 150 bar is present at the openings of the underground potash mine at the state of Sergipe.[4,18,22] A comparison between the closures measurements made in the mine, taking into consideration the volume of excavation and the differential stresses applied, validates the results obtained from the computer simulation of the cavern.

Figure 10 shows the isosurfaces of the radial displacements after 135 weeks, immediately after the dissolution of the cavern is completed. The isosurfaces and the decay of the displacement as a function of the point distance to the excavation perimeter is a perfect representation of the physical phenomenon of an underground excavation that is subject to creep.

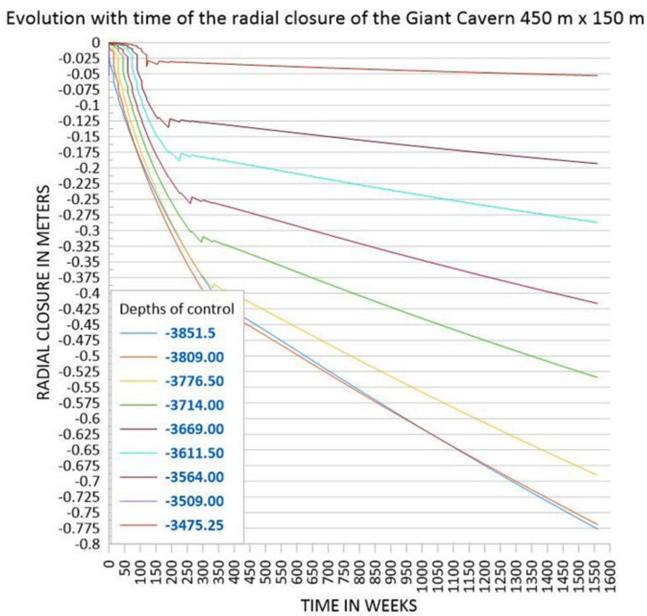


Figure 11. Radial displacement evolution with time showing the reaction of the cavern as gas is injected from the top. (Solver COVES 2[18] – pre- and post-processor GiD.[19])

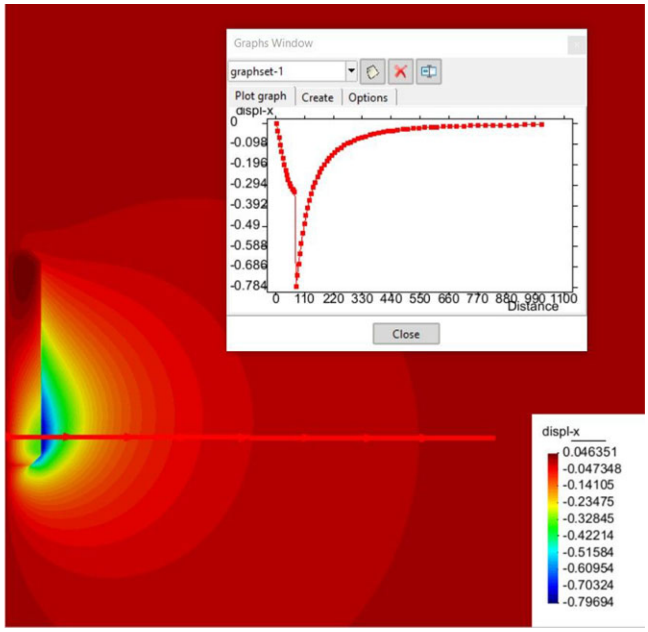


Figure 12. Isosurfaces of the radial displacements during the abandonment of the cavern at $t = 30$ years. (Solver COVES 2[18] – pre- and post-processor GiD.[19])

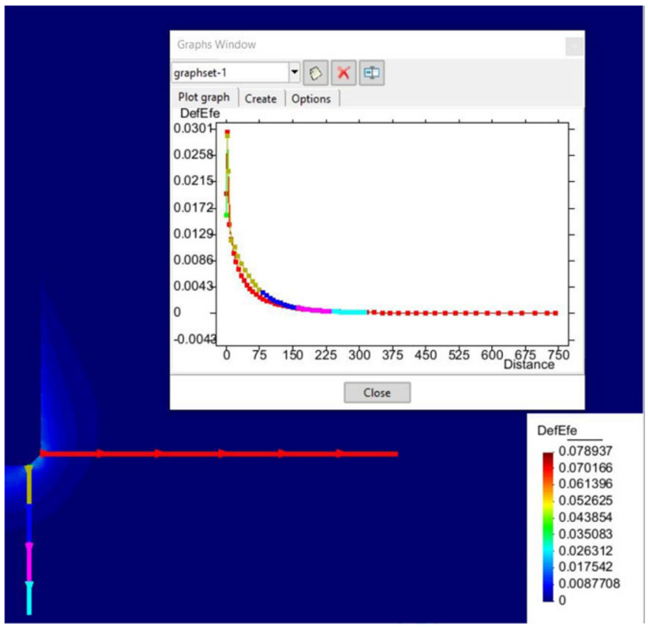


Figure 13. Isosurface of the effective creep strain in $t = 30$ years. (Solver COVES 2[18] – pre and post-processor GiD.[19])

Gas with high CO_2 content is injected after 125 days from the top to the bottom of the cavern, replacing the brine. Gas produced in the Floating Production Storage and Offloadings (FPSOs) that is not reinjected into the reservoir is separated by the membrane separation equipment at the process plant. The cleaned gas, with the maximum grade of 3% of CO_2, is compressed and transported through a gas pipeline to shore. The remaining gas, now with a high CO_2 content, will be reinjected into the reservoir for EOR, and part of it will be injected in the salt caverns. It is inferred that it will take 30 weeks to fill each 50 m section of the cavern from top to bottom. Figure 11 presents the reaction of the cavern as the gas is injected from the top downwards, replacing the brine.

For the geomechanical simulation, it was assumed that 270 weeks would be required to completely fill the cavern and replace the brine. After 395 weeks, the cavern is conditioned for abandonment. It was also assumed for the geomechanical simulation that 52 weeks would be required to close the cavern with all the monitoring instrumentation in place. At this point, the closure rate of the cavern is reduced with increasing injected gas pressure. At the critical state, the creep closure deformation of the cavern with time is stabilized. It is interesting to note that during the injection time, the nodal points used to monitor the simulated closure of the cavern continue to increase at the bottom with time due to the creep of halite. It stops only when the gas reaches that position.

COVES 2 simulates, in a single run, the excavation, replacement of the brine by a gas with high CO_2

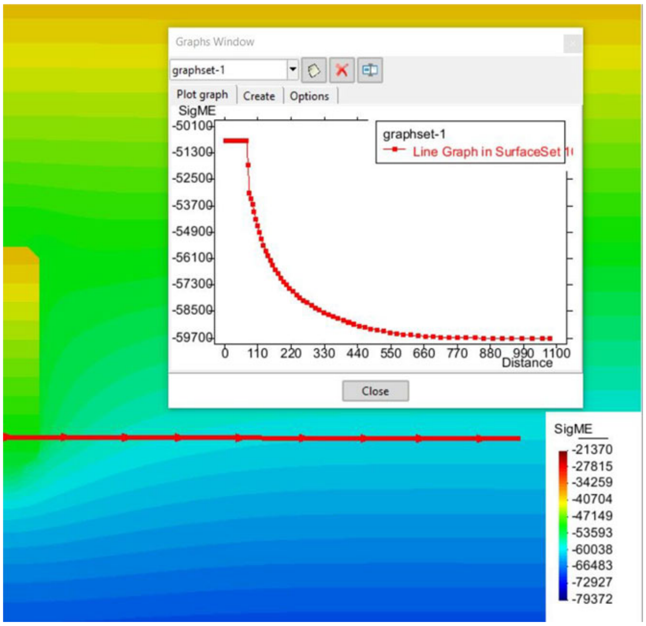


Figure 14. Isosurface of first invariant of stresses after abandonment for 30 years. (Solver COVES 2[18] -- pre and post-processor GiD.[19])

content, and the final abandonment of the cavern. When the cavern is completely filled with gas, for the geomechanical simulation, it is necessary to have the bulk modulus of the gas/CO_2 at the critical state. To simulate the abandonment process, it was assumed that the cavern would be filled only with CO_2 due to lack of data for mixtures of gases with varying compositions. Currently, laboratory tests are focusing on obtaining these thermodynamic parameters of gas mixtures at the University of São Paulo in Brazil. For this simulation, a bulk modulus of $K = 80\,000$ kPa was used based on the data generated in the site: webmaster@peacesoftware.de.

Figure 12 shows the isosurface of the radial displacement to be expected in 30 years. One can easily observe the effect of the abandonment of the cavern. The isosurfaces of the displacements show the simulation results with the immediate smooth distribution of deformation between the rock and CO_2 at the critical state. Immediately after the commencement of abandonment of the cavern by closing the wet Christmas tree, the deformation goes to

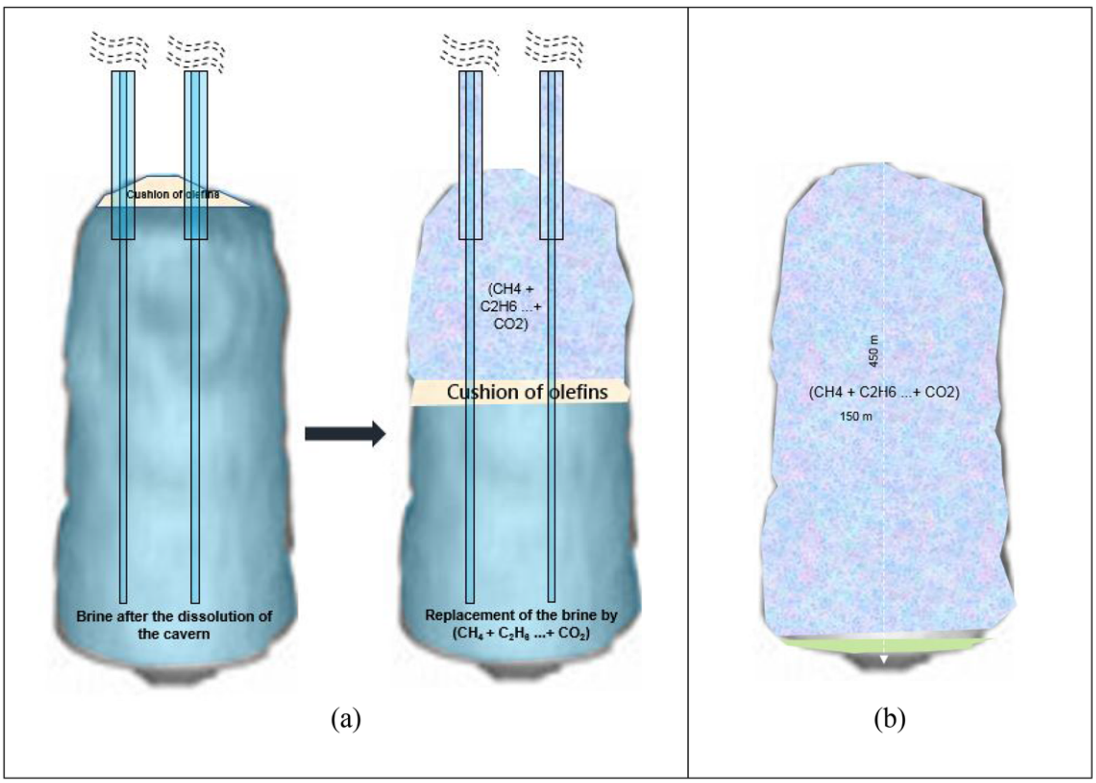


Figure 15. (a) Replacement of brine with gases at the critical state and (b) abandonment of the cavern filled with gases.

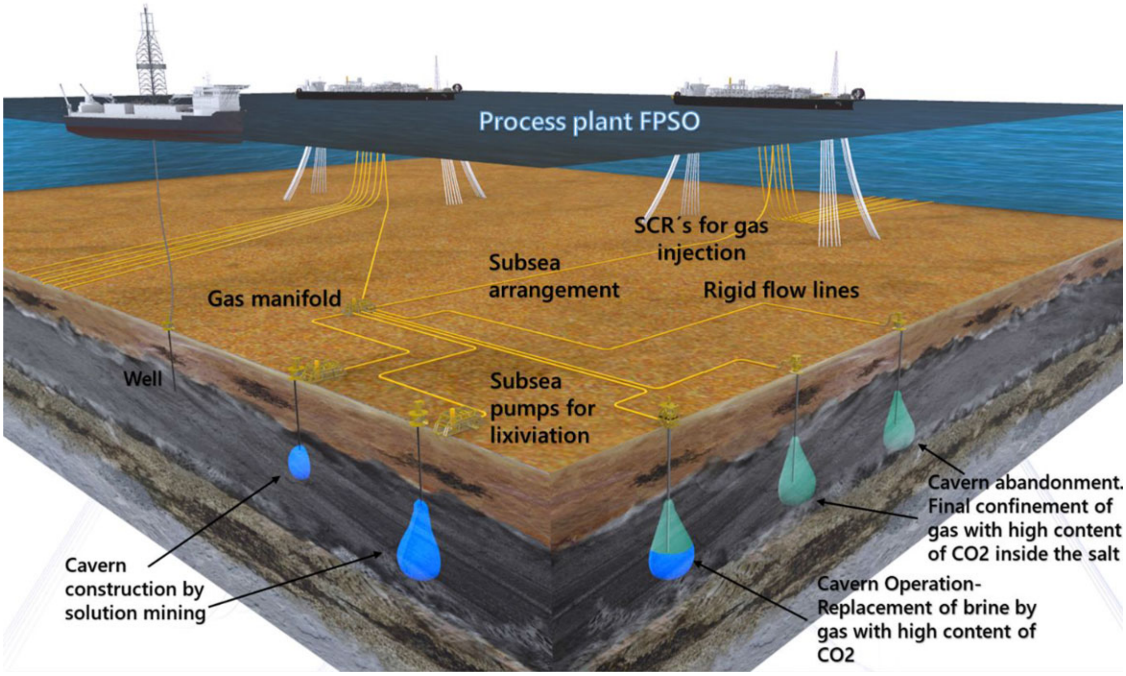


Figure 16. Logistics concept of the CCS system.

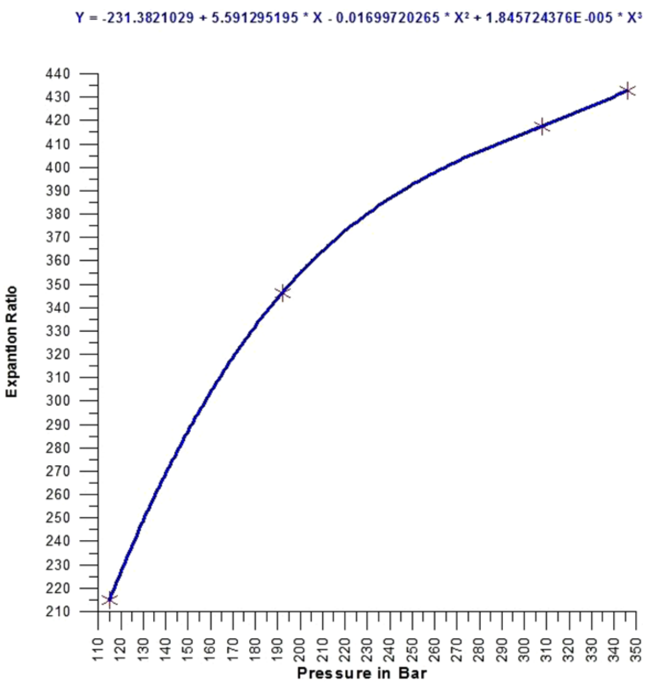


Figure 17. Expansion coefficient of a gas stream with 90% of CO_2 at the temperature of 44°C.

a steady-state condition with very small creep closure rate.

The process of scaling of the cavern wall starts when the creep strain reaches values ranging between 5% and 10% in conventional mining without counter pressure. For this case study, the maximum effective creep strain occurs only in the corner of the cavern wall, which will be smoothed over time. Figure 13 shows the isosurface of the effective creep strain accumulated in 30 years with the cavern already abandoned for 22 years.

The phenomenon of halite scaling at the cavern wall is negligible, which allows the use of this giant salt cavern for CCS application with an abandonment pressure of ~450 bar.

Another criterion that must be analyzed is the state of stresses of the cavern after abandonment. The cavern must always support itself against internal pressure limiting the closure tendency and thereby always creating a compressive stress distribution in its surroundings. This prevents the formation of micro-cracks or micro-fractures that may allow gases to permeate to another formation or even to the surface. Figure 14 shows the isosurface of the first invariant of stresses $\{\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3\}$ after 30 years of abandonment. The pressure inside the cavern is the gas injection pressure of about 450 bar, and in the boundary of the cavern wall, the pressure is about 600 bar at the bottom of the cavern. The cavern is protected by a compressive state of stresses, eliminating the possibility of gas leakage over time. Figure 15(a) illustrates brine replacement by gases after the dissolution of the cavern.

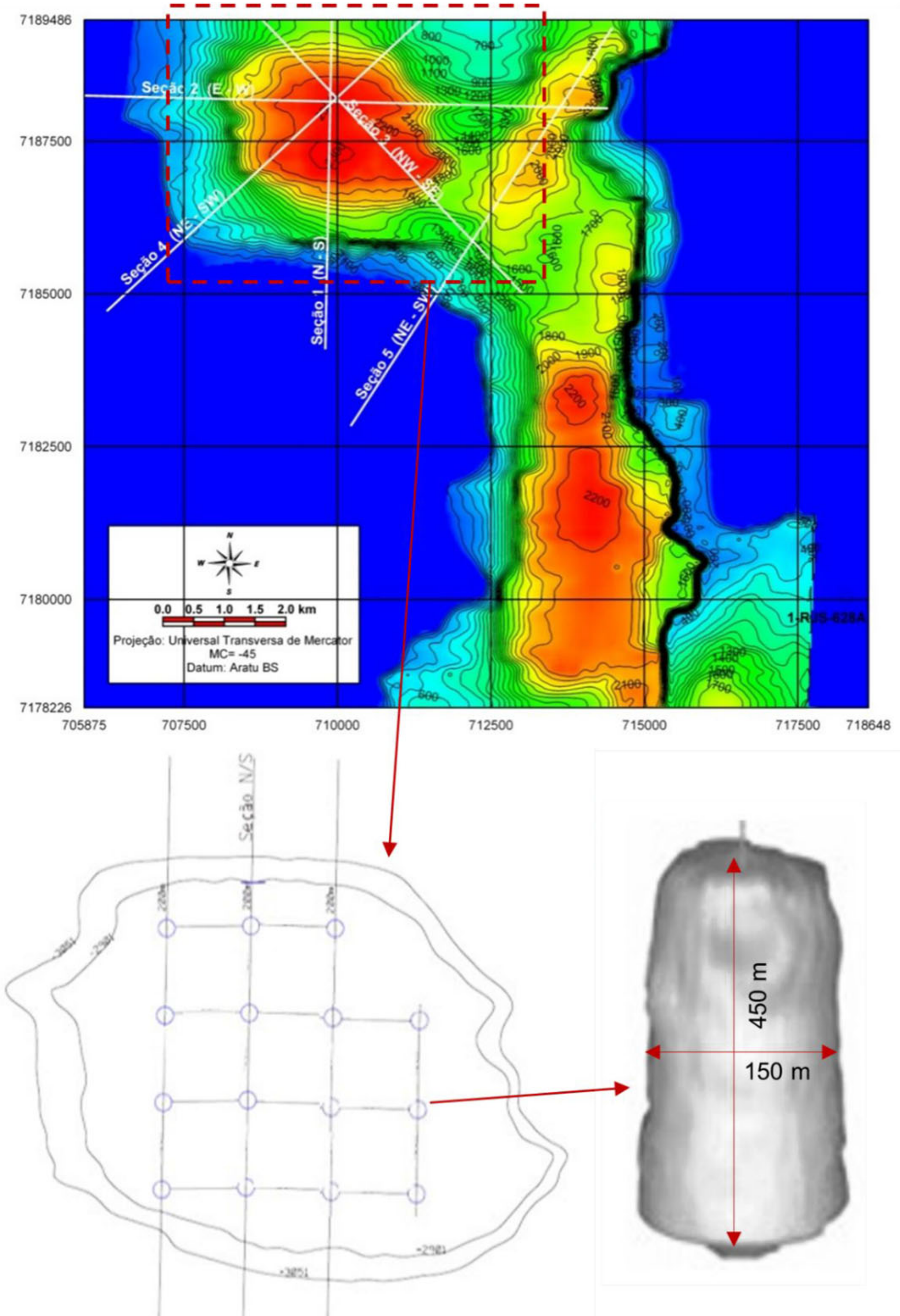


Figure 18. Cluster of salt caverns for CCS in ultra-deep water.
Source: Adapted from[9].

Figure 15(b) shows the final stage of the cavern at abandonment filled with gases, and Figure 16 shows the logistics concept of the proposed system of CCS for ultra-deep water hydrocarbon production.

Figure 17 shows the curve of the expansion ratio of a gas stream with 90% of CO_2 for the temperature of 44°C as a function of pressure.

By interpolating the expansion curve using the gas pressure inside the cavern, it is possible to calculate the CCS volume of the cavern:

- Storage volume of gas stream with high CO_2 content (90% σ_0) $\rightarrow$ 518,78 * 7.4 $\times 10^6$ = 3 840 000 000 Sm^3.
- P = 446 bar, T = 42°C, ρ = 966.9848 kg /m^3.
- CO_2 mass storage = 7.4 $\times$ 106 * 966.9843 $\cong$ 7.2 billion kg of CO_2 = 7.2 million tons of CO_2.

For the salt dome selected, it is possible to construct 15 caverns, and Figure 18 shows the proposed cluster configuration. Hence, the CCS storage station in ultra-deep water will have the capacity to confine 108 billion kg of CO_2 or 108 million tons of CO_2, as seen in this case study.

Conclusions

This article presents the potential of gas storage in salt caverns built in ultra-deep water in Brazil. Salt caverns are formed through a leaching process, which involves the pumping of hot water at regulated pressure to dissolve the rock salt and remove the resulting brine via a single well, which serves for both injection and withdrawal. The geology of the Brazilian province considered here is characterized by stratification of thick layers of halite with intercalations of carnallite and tachyhydrite salt rock, whose creep strain rate is almost two orders of magnitude higher than halite's creep rate under the same conditions of temperature and pressure. Addressing this challenge requires the adoption of similar technique based on experience gained from an operational sylvanite mine in Sergipe State, Brazil. The mining activity has been very successful with the mine operating for more than 30 years, producing 500 000 tons of potash per year.

The topology of the giant cavern considered in the design is summarized as follows:

- Thickness of the safety halite slab protection between the top of the cavern and the bottom of the sedimentary cap rock: 750 m.
- Depth of the top of cavern: −3440 m.
- Depth of the bottom of the cavern: −3890 m.
- Diameter: 150 m.
- Height: 450 m.
- Geometrical volume of the cavern: 7.4 E + 06 m^3.

Computational FE simulations using COVES software provided the following findings and conclusions:

- The creep deformation of the experimental cavern is very small because of the support from the brine and gas pressure inside the cavern and due to the low temperature within the cavern. The interval of halite between −2700 m and −3898 m is at a temperature that varies within the following interval: 29°C $\leq$ T $\leq$ 42°C.
- The cavern can be construct by dissolution at a water depth of 2140 m through the injection of seawater flowing at 1000 m^3/hour.
- For the brine return/gas operation tube, the casing should be 11 7/8' 71.80 lb/ft C-125 HC; for the seawater injection tube, the casing should be 7 5/8' 51.2 lb/ft SCr13/110 ksi.
- The storage volume of the gas stream with a high CO_2 content in one cavern: 3 840 000 000 Sm^3.
- Maximum gas pressure expected after abandonment: 465 bar.

Based on the salt dome studied for CCS application, one cavern can store 4 billion Sm^3 or 7.2 million tons of CO_2. Considering the pillar size between caverns of 750 m, which is five times the diameter of one cavern, the salt dome can accommodate the construction of 15 caverns, thus providing space for the confinement of approximately 108 million tons of CO_2.

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Alvaro Maia da Costa

Dr Alvaro has PhD and MSc degrees from the Federal University of Rio de Janeiro (UFRJ). He is a renowned scientist in the field of rock mechanics and the author of patents and software widely used in large projects in Brazil. He is a member of the National Academy of Engineering, and has received the SPE Award for Technical Excellence, and the Navy's Tamandaré Mérit medal, among other honors.

Pedro V. M da Costa

Dr Pedro V. M da Costa has a PhD from the Energy Planning Program of the Federal University of Rio de Janeiro and an MSc in production engineering from PUC-Rio University. He is one of the authors of a patent that seeks to sequester CO_2 in salt caverns built in ultra-deep water. He has been working on consulting projects for the Brazilian oil and gas industry since 2010 and is a partner in MODECOM engineering.

Okhiria D. Udebhulu

Okhiria Dickson Udebhulu is an assistant-lecturer at Alex Ekwueme Federal University Ndufu-Alike, Ikwo (AE-FUNAI), Nigeria. He holds a bachelor of engineering degree in chemical engineering from Ahmadu Bello University, Zaria, Nigeria and a master of science in petroleum engineering from the African University of Science and Technology, Abuja, Nigeria. His research interests include carbon capture and storage (CCS) in geological media especially in salt caverns; wellbore integrity management in deep water, management of sand production in oil and gas wells, and reservoir engineering and flow assurance.

Ricardo Cabral Azevedo

Ricardo Cabral Azevedo, PhD, Professor at the Mining and Petroleum Engineering Department of the University of São Paulo, Brazil (USP), Mining Engineer with Post-Doctorate in Petroleum Engineering at the University of Stavanger, Norway (2014), Specialization in Occupational Safety Engineering (2013), PhD (2007) and MSc (2002) in Mineral Engineering, all from USP.

Nelson F. F. Ebecken

Nelson F. F. Ebecken has been a professor of computational systems at COPPE/Federal University of Rio de Janeiro since 1990. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE) and the Association for Computing Machinery (ACM). He develops models for complex systems, big data and integrates ideas and computational tools. In 2005 he was awarded membership of the Brazilian Academy of Sciences.

Antonio C. O. Miranda

Antonio C. O. Miranda is a researcher and professor at the University of Brasília, Department of Civil and Environmental Engineering. He has a BSc, an MSc, and a PhD in civil engineering. From 1999 to 2009 he worked in oil and gas industry developing finite element modeling and mesh generation solutions to simulate oil extraction. His main research areas are modeling and mesh generation, fatigue and fracture mechanics (in concrete and alloys), and computer graphics applied to engineering.

Sérgio M. de Eston

Sérgio M. de Esto gained his MSc from Stanford in 1975 and his PhD in 1982, and was made a full professor in (2000). He was the head of the Mining Engineering Department (2001–2009), and is presently the coordinator of graduate courses on safety and industrial hygiene and of the safety, hygiene and environmental control laboratory in the University of São Paulo (USP).

Giorgio De Tomi

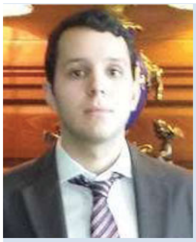
Giorgio De Tomi is the head of the Department of Mining and Petroleum Engineering at University of São Paulo (USP). He is also the director of the Center for Responsible Mining, at USP, which is a research center dedicated to innovation and applied research focused on responsible practices for small-scale mining. Dr De Tomi has a degree in mining engineering from USP, a PhD from Imperial College, London, and an MSc from Southern Illinois University. His areas of expertise include innovation management, mine planning and scheduling, mineral reserves assessment, management of the mineral value chain, and production management, with special emphasis on responsible practices in the mining, petroleum and gas industries.

Julio R. Meneghini

Julio R. Meneghini is a full professor of applications and principles in mechanical engineering at the Escola Politécnica, University of São Paulo. He has a PhD in aeronautics, from Imperial College – University of London (1993). He also has a DIC diploma in aeronautical engineering from Imperial College (1993), a Livre Docente in fluid mechanics from the University of São Paulo (USP) (2002), and a master of science in mechanical engineering, USP (1989). He has a BSc in physics from Instituto de Física (1989) and a degree in civil engineering, Instituto Mauá de Tecnologia (EEM, 1984). He is the scientific director of the Research Center for Gas Innovation (RCGI), sponsored by FAPESP-SHELL. He is the coordinator of the Fluid and Dynamics Research Group (NDF) at Escola Politécnica da Universidade de São Paulo (EPUSP). He is the author or co-author of more than 150 published papers.

Kazuo Nishimoto

Kazuo Nishimoto is a professor of naval architecture in the Ocean Engineering Department, director of the program of CO_2 abatement, director of the Numerical Offshore Tank Laboratory, and research representative of the Department of Naval Architecture and Ocean Engineering and Graduate Programs of Ocean Engineering at the University of São Paulo.



Felipe Ruggiere

Dr Ruggeri has a master's degree and DSc degree in naval architecture and ocean engineering from the University of São Paulo, Brazil. He founded Argonáutica Engineering and Research and he has worked on offshore oil exploration projects with leading oil companies in Brazil.

Edgard Malta

Edgard Malta gained his PhD in 2014 from the University of São Paulo in the Naval and Oceanic Engineering Department. He works on research projects for floating systems, mainly in the area of seakeeping with numerical and experimental simulation. He is an expert on the modeling and calibration of hydrodynamic systems. He is a director at Technomar Engenharia.

Mauro Élis Rocha Fernandes

Mauro Élis Rocha Fernandes is a master student at the University of São Paulo (USP), Department of Mining and Petroleum Engineering. He has an MBA in project management from Fundação Getúlio Vargas (FGV) and a bachelor's degree in petroleum engineering from the University of Norte Fluminense (UENF). He is a director at Unika Consulting.

Camila Brandão

Camila Brandão has an MBA in project management from Fundação Getúlio Vargas (FGV). She has a specialist degree in petroleum engineering and a BSc in chemical engineering from Universidade Federal Fluminense (UFF), and has 14 years' experience in oil and gas developments, acquired in several positions. Her previous assignment was at a pre-salt project as the lead subsea systems engineer, responsible for subsea concept design, front-end engineering and quality assurance. As a member of Shell she assumed a role at Technology Division of Shell (PtX), developing and managing projects for the CO_2 Abatement Platform in Brazil.

Alexandre Breda

Alexandre is Shell's CO_2 abatement technology lead. He holds a BSc in mechanical engineering from the University of Campinas with a master in energy from University of São Paulo. He has solid experience in new business development, gas supply chains, climate change and greenhouse gases, project management, contract negotiation, renewables integration with natural gas, and end-use of gas, mainly cogeneration and air conditioning. At Shell he is responsible for the CO_2 abatement R&D projects in Brazil, working to grow carbon capture, utilization and storage (CCUS) and methane emissions technology solutions with leading universities and suppliers through open innovation.

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