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Technology readiness assessment of ultra-deep salt caverns for carbon capture and storage in Brazil

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ABSTRACT

This article presents a Technology Readiness Assessment (TRA) of a new concept called the Salt Cavern Hybrid Subsea Carbon Capture and Storage (CCS) System, which performs all the offshore natural gas and CO_2 separation process with subsequent storage in offshore underground salt caverns. Currently there is a demand for CCS of large quantities of CO_2 associated with CH_4 in the pre-salt offshore oil fields in Brazil. The pre-salt reservoirs have as caprock 2000 m of continuous rock salt. This hybrid system is expected to perform, at the same time, the separation between the natural gas and CO_2, and Carbon Capture and Storage of CO_2, allowing the monetization of the separated natural gas. The Technology Readiness Levels (TRL) approach is discussed in this paper for estimating the maturity of the CCS System. The TRL analysis concluded that no technological gaps were identified that would made the project unfeasible and the TRL level enables the project to advance to the field test stage within a reasonably short time horizon. Once implemented it could be one of the largest CCS projects in the world. Also, this paper describes the conceptual design of this hybrid system and presents the results of a TRA showing the methodology that was employed in the process, the technology critical items that were analyzed and the results obtained for each of them and the design of a salt cavern for the storage of 1 billion Sm^3 (Standard cubic meter) of a natural gas stream with high CO_2 content.

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 ~300 km from the coast. The oil in the reservoirs is of high quality with a remarkably high gas-oil ratio, above 220. The associated gas has a high CO_2 content of mantle origin, which cannot be ventilated in the atmosphere. Fig. 1 shows a typical geology section of the pre-salt reservoirs of the pre-salt reservoirs.

The produced gas with high content of CO_2 is treated at the production platform through membrane filters. Part of the treated gas is compressed and transported to shore through gas pipelines. The remainder gas with high content of CO_2 is reinjected into the reservoirs, working as EOR (Enhanced Oil Recovered) in the initial age of the reservoirs production. With time the recycled gas with CO_2 increases the global CO_2 content of the associated gas. Therefore, there is a demand for CCS of large quantities of CO_2 associated with CH_4 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 high pressure (about 2000−3000 m of rock depth and 2200 m of water depth). The main reasons include: (i) low permeability, the permeability of rock salt is about 10^{-21} - 10^{-24} m^2, thus can provide excellent sealing of the salt cavern; (ii) good mechanical properties, damage self-recovery capability of rock salt can ensure the safety of salt cavern with frequent changes of gas pressure; (iii) solution in water, rock salt is easily dissolved into water, which facilitates the construction and shape control of the salt cavern; (iv) abundant resources, as it is overlying the pre-salt reservoirs.

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

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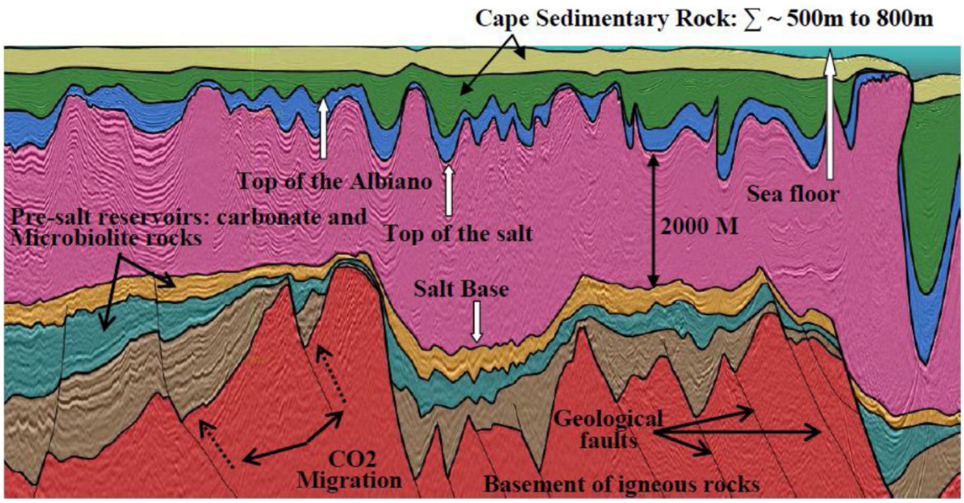


Fig. 1. Typical pre-salt geological section (Mohriak et al. (2008)).

fact it has already been thought by other countries. For example, the Gateway concept project in England (Gateway, 2020), 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. Another case where this technology could be applied are the West African oil fields, where is found a similar geology of the Brazilian offshore pre-salt oil fields.

Overall, the use of salt caverns for storage of natural gas has increased its importance over time due to the technical advantages of these geological storage when compared to the other geological technologies, such as depleted petroleum & gas fields. According to the CEDIGAZ report it is the world's fastest growing gas geological storage technology with the largest number of projects under development (CEDIGAZ, 2017).

Technology Readiness Levels (TRLs) are a method for estimating the maturity of technologies developed at NASA during the 1970s. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology (Héder, 2017). A technology's TRL is determined during a Technology Readiness Assessment (TRA) that examines the technology concepts, requirements, and demonstrated its capabilities.

As the problem of the CO_2 content of some pre-salt oil fields has become critical and becoming a major concern for oil operators in Brazil, the Salt Cavern Hybrid Subsea CCS System concept presented in this paper has gained importance and interest for its development in a relatively short time. Thus, the TRA is essential to evaluate not only the TRL of the system, but also to determine where the development efforts should be concentrated.

2. Technology readiness levels (TRLs)

A better understanding of the technology readiness is critical in making good decisions about the inclusion, development and integration of new technologies in complex engineering projects. The most widely used tool for readiness assessment is the TRL scale (Bakke, 2017), developed at NASA in 1974.

A technology's TRL is determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements and demonstrated technology capabilities. The concept as Technology Readiness Level (TRL) was used by government agencies and industries across the USA and Europe and was adopted by API (Strutt and Wells, 2014) and tailored for assessing the readiness of subsea components for inclusion in subsea production systems. In 2013, the ISO 16290:2013 further canonized the TRL standard (Héder, 2017). A variety of industries have now generated customized standard guidelines for using TRLs for complex systems development, which includes USA Homeland Security (Meland Security Institute, 2009); USA Department of Defense (Katz et al., 2015) and (Jamier et al., 2018); oil and gas and infrastructure: DNV (Det Norske Veritas, 2011), API (Strutt and Wells, 2014), ABS (American Bureau of Shipping, 2017), UK Ministry of Defense (UK Ministry of Defence, 2006), and Nolte (Nolte et al., 2003).

NASA formally defined in 1989 the Technology Readiness Levels. The original definition included seven levels (Sadin et al., 1989) in Table 1.

The primary purpose of using technology readiness levels is to help management in making decisions concerning the development and transitioning of technology. It should be viewed as one of several tools that are needed to manage the progress of research and development activity within an organization (Deutsch et al., 2011).

TRLs provide a common understanding of technology status, it helps on risk management, can be used to support decision making concerning technology funding and transition of technology. In the other hand readiness does not necessarily fit with appropriateness or technology maturity; a mature product may possess a greater or lesser degree of readiness for use in a particular system context than one of lower maturity; and numerous factors must be considered, including the relevance of the products' operational environment to the system at hand, as well as the product-system architectural mismatch (Dawson, 2007).

The analysis carried out in this Article were based on the TRL definitions provided by the (Strutt and Wells, 2014), shown on the Table 2.

Achievement of API's TRL 4 (Strutt and Wells, 2014) is one of several pieces of evidence that is used in the decision-making process in committing to the major capital investment. Thus, the TRL 4 is critical

Table 1
Technology Readiness Levels (Sadin et al., 1989).

Level	Description
1	Basic Principles Observed and Reported
2	Potential Application Validated
3	Proof-of-Concept Demonstrated, Analytically and/or Experimentally
4	Component and/or Breadboard Laboratory Validated
5	Component and/or Breadboard Validated in Simulated or Realspace Environment
6	System Adequacy Validated in Simulated Environment
7	System Adequacy Validated in Space

Table 2
Definition of the development stages of API 17 N's TRL (Yasseri and Bahai, 2018).

API 17 N's TRL	Development Stage Completed	Definition of the development stage
0	Unproven Concept (Basic R&D, paper concept)	Basic scientific/engineering principles observed and reported; paper concept; no analysis or testing completed no design history
1	Proven Concept (As a paper study or R&D experiments)	a) Technology concept and/or application formulated b) Concept and functionality proven by analysis or reference to features common with/to existing technology c) No design history; essentially a paper study not involving physical models but may include R&D experimentation
2	Validated Concept (experimental proof of concept using physical model tests)	Concept design or novel features of the design is validated by a physical model, a system mock-up or dummy and functionally tested in a laboratory environment; no design history; no environmental tests; materials testing and reliability testing is performed on key parts or components in a testing laboratory prior to prototype construction
3	Prototype Tested (System function, performance and reliability tested)	a) Item prototype is built and put through (generic) functional and performance tests; reliability tests are performed including reliability growth tests, accelerated life tests and robust design development test program in relevant laboratory testing environments; tests are carried out without integration into a broader system b) The extent to which application requirements are met are assessed and the potential benefits and risks are demonstrated
4	Environment Tested (Pre-production system environment tested)	Meets all Requirements of TRL 3; designed and built as production unit (or full scale prototype) and put through its qualification program in simulated environment (e.g. hyperbaric chamber to simulate pressure) or actual intended environment (e.g. subsea environment) but not installed or operating; reliability testing limited to demonstrating that prototype function and performance criteria can be met in the intended operating condition and external environment
5	System Tested (Production system interface tested)	Meets all the requirements of TRL 4; designed and built as production unit (or full-scale prototype) and integrated into the intended operating system with a full interface and functional test but outside the intended field environment
6	System Installed (Production system installed and tested)	Meets all the requirements of TRL 5; production unit (or full-scale prototype) built and integrated into the intended operating system; full interface and function test program performed in the intended (or closely simulated) environment and operated for less than three years; at TRL 6 new technology equipment might require additional support for the first 12–18 months
7	Field Proven (Production system has been fielded proven)	Production unit integrated into the intended operating system, installed, and operating for more than three years with acceptable reliability, demonstrating a low risk of early life failures in the field

for making the decision on whether to go forward with the investment. TRL 5 arguably is the most important stage (technically) during the subsea development process. At API's TRL 5 (Strutt and Wells, 2014) stage readiness of all necessary components must be demonstrated; it also involves a demonstration that the components work together as a system. Thus, achieving a TRL of 5 is a prerequisite for the integration and installation of assemblies. Validation at this level must go beyond discrete component level, it must consider testing of the assembly of components (or subsystems); testing at the quayside, and possibly in shallow water (i.e. a relevant environment) and/or the operational environment.

During the TRA process some question must be answered to make the system be the most effective as possible. Some of the questions that need to be answered and backed by evidence in the subsea context are (Yasseri and Bahai, 2018):

- Is technology (equipment) widely used by other operators?
- Is technology demonstrated in the final form (in a system somewhere in the world)?
- Is technology demonstrated in the relevant environment (field conditions)?
- What is the target performance/efficiency level (technically and economically)?
- What is currently achieved performance/efficiency? What are the materials involved and what is their availability?
- Is infrastructure available for deployment for this technology?
- What are the main barriers impeding the higher performance?

The TRL analysis of the **Salt Cavern Hybrid Subsea "CCS System"** is based on the Offshore engineering experience of Shell Brazil, USP (University of São Paulo) departments and on the Offshore engineering and geomechanical underground design of salt cavities vast experience of associated "Based Technology Companies" (A.M. Costa et al., 2020; P.V.M. Costa et al., 2020a,b,c; A.M. Costa et al., 2019a,b,c; P.V.M. Costa et al., 2019; A.M. Costa et al., 2018a,b,c; P.V.M Costa, 2018; P.V.M. Costa et al., 2017; P.V.M. Costa et al., 2015; A.M. Costa et al., 2015; P.V.M. Costa et al., 2014; A.M. Costa et al., 2014; P.V.M. Costa et al., 2015; A.M. Costa et al., 2015)

There is no specific TRL scale for Natural gas storage / CO_2 in salt caverns, therefore it was decided to adopt the table used in the oil and gas industry, defined by API 17 N in "Recommended Practice for Subsea Production System Reliability, Technical Risk & Integrity Management" (Technology readiness levels 0–7) (Strutt and Wells, 2014). Table 3 presents the description of TRL levels analyzed on the project.

The State of the Art of the offshore ultra-deep-water CCS (Disposal) system was first analyzed together with Shell Brazil work group with emphasis in technologies of the main disciplines of the storage system: well design; salt cavern design; subsea arrangement; and flow assurance and process plant.

Based on the research, it is possible to infer about the TRL of the macro disciplines with direct focus on gas storage in offshore salt caverns.

2.1. TRL for storage system

Tables 4 to 7 show the TRL levels of the main technologies to be used in the storage system for the 4 macro disciplines: well engineering, cavern design, subsea arrangement and flow assurance and process plant, respectively. These tables are based on the offshore oil and gas industry in ultra-deep water, which has mature and renowned technologies in the construction and operation of wells drilled at depths above 5000 m below sea level, as an example in the Santos Basin, a scenario where gas storage caves will be built.

For the extraction of oil and gas in these severe environments, subsea systems and production platforms are required with robust and highly tested technologies. As mention before, these technologies area mature and will be used in the construction and operation of the caves. In addition, the storage of natural gas under high pressure in onshore

Table 3
TRL Levels Used by the Oil and Gas Industry (Strutt and Wells, 2014).

Technology Readiness Level	Description
TRL 0	Unproven idea/proposal paper concept. No analysis or testing has been performed.
TRL 1	Concept demonstrated. Basic functionality demonstrated by analysis, reference to features shared with existing technology or through testing on individual subcomponents/subsystems. Shall show that the technology is likely to meet specified objectives with additional testing.
TRL 2	Concept validated. Concept design or novel features of design validated through model or small-scale testing in laboratory environment. Shall show that the technology can meet specified acceptance criteria with additional testing.
TRL 3	New technology tested. Prototype built and functionality demonstrated through testing over a limited range of operating conditions. These tests can be done on a scaled version if scalable.
TRL 4	Technology qualified for first use. Full-scale prototype built and technology qualified through testing in intended environment, simulated or actual. The new hardware is now ready for first use.
TRL 5	Technology integration tested. Full-scale prototype built and integrated into intended operating system with full interface and functionality tests.
TRL 6	Technology installed. Full-scale prototype built and integrated into intended operating system with full interface and functionality test program in intended environment. The technology has shown acceptable performance and reliability over a period.
TRL 7	Proven technology integrated into intended operating system. The technology has successfully operated with acceptable performance and reliability within the predefined criteria.

caves began in the 1960s, with thousands of caves in operation in the world. Several technologies used onshore are fully used in the offshore environment. For these reasons, Tables 4 to 7 receive high TRL compared to Tables 1 to 3.

3. Material and methods

The Salt Cavern Hybrid Subsea CCS System is being developed under the coordination of the Research Center for Gas Innovation (RCGI) in Brazil and it is sponsored by the oil company Shell Brazil and São Paulo Research Foundation (FAPESP). The project is being developed in two phases: in the first phase the main objective is to develop a procedure for the disposal of large volumes natural gas with high CO_2 content and its confinement within the caverns indefinitely (CCS). In the second phase will be studied the process of gravitational separation of CO_2 and natural gas (patent: BR 10 2018 005769 − 3) for large quantities of contaminated NG produced in some pre-salt reservoirs. With the design described herein, methane separation, storage and future extraction will be possible, with the consequent monetization at a substantially lower cost than conventional separation methods (membrane or other technique).

The environment in which the project is being developed has very peculiar characteristics, being unprecedented worldwide and requiring deep multidisciplinary knowledge, such as: ultra-deep-water offshore engineering, well drilling through thick layer of stratified salt rock, geomechanical design of underground salt caverns, solution mining excavations, onshore and offshore cavern construction by leaching technologies, fluid mechanics, gas thermodynamics, molecular dynamics and CCS.

This Research and Development project presents high TRL, since all the processes necessary for its development and operation are already carried out in the production of pre-salt oil fields for even more extreme conditions. Similarly, the technology of using salt caverns for storing high pressure gases has a long history of development and the largest growth in number of projects in the world, since salt caverns projects represent almost 40 % of projects under construction (17 projects) in the world. Most of them are built in Europe (mainly Turkey), but emerging markets (China and Iran) are also building this type of underground gas storage (UGS). There are 142 projects under construction, planned or potential, totaling 101 bcm (billion cubic meters of natural gas) of working capacity (CEDIGAZ, 2017).

3.1. Description of the first phase of the R&D project

The technological solution of phase 1 consists of the development of a storage system for natural gas stream with high CO_2 content, divided into 3 subsystems: production platform, submarine arrangement and salt caverns opened by solution mining. The proposal is to use, whenever possible, the entire infrastructure already available in production systems to perform all stages of technology development, from the construction of the caverns to the system operation.

It is noteworthy that the process of excavating salt rock caverns by leaching process on land is a mature technology) and has been applied since the 1960s (P.V.M. Costa, 2018). However, in the proposed invention, this process is performed offshore, and the salt rock leaching can be done by using pumps of the production platform or submerged pumps installed on the seafloor using deep raw seawater.

In the case of offshore application, the caverns can be operated directly from the production platforms without using a dedicated vessel for this purpose, using all the facilities already available on the platform, such as gas compressors, pumps, risers and multiplexed umbilicals (data, signals and hydraulics).

In the case of a dedicated vessel, the cavern construction and operation platform is equipped with gas turbo generators for submerged pump power supply, drill rig, cavern dissolution pipeline handling and logistical support for all elements of the system that will be integrated

Table 4
Well engineering technology.

Aspects	Comments	TRL
1 Drilling	Pre-salt well 4 phases	7
2 Drilling fluid	Olefins Synthetic based fluid	7
3 Casings	Standard size with special metallurgy (super-duplex)	7
4 Cement	High strength with visco-elastic properties	3
5 Dissolution tubing	Stander casings with special metallurgy	7
6 Casing set and cementing procedure	Barrier for high pressure gas and relative movement between the casings and cavern deformation to eliminate gas leak	3
7 Well head	Special design to accommodate the subsea Christmas tree for construction and operation of the caverns	5
8 Subsea Christmas tree	Special design for dissolution of the cavern, operation with gas at high pressure and abandonment in special metallurgy	5
9 Well design	Application of the methodology used in the pre-salt wells considering different properties for cement and drilling fluid	7
10 Subsea pumps	well coupling with subsea pumps	7
11 Hydraulics design	High pressure and high flow rate	7
12 Well control	Monitoring during cavern construction, gas injection and cavern abandonment	7

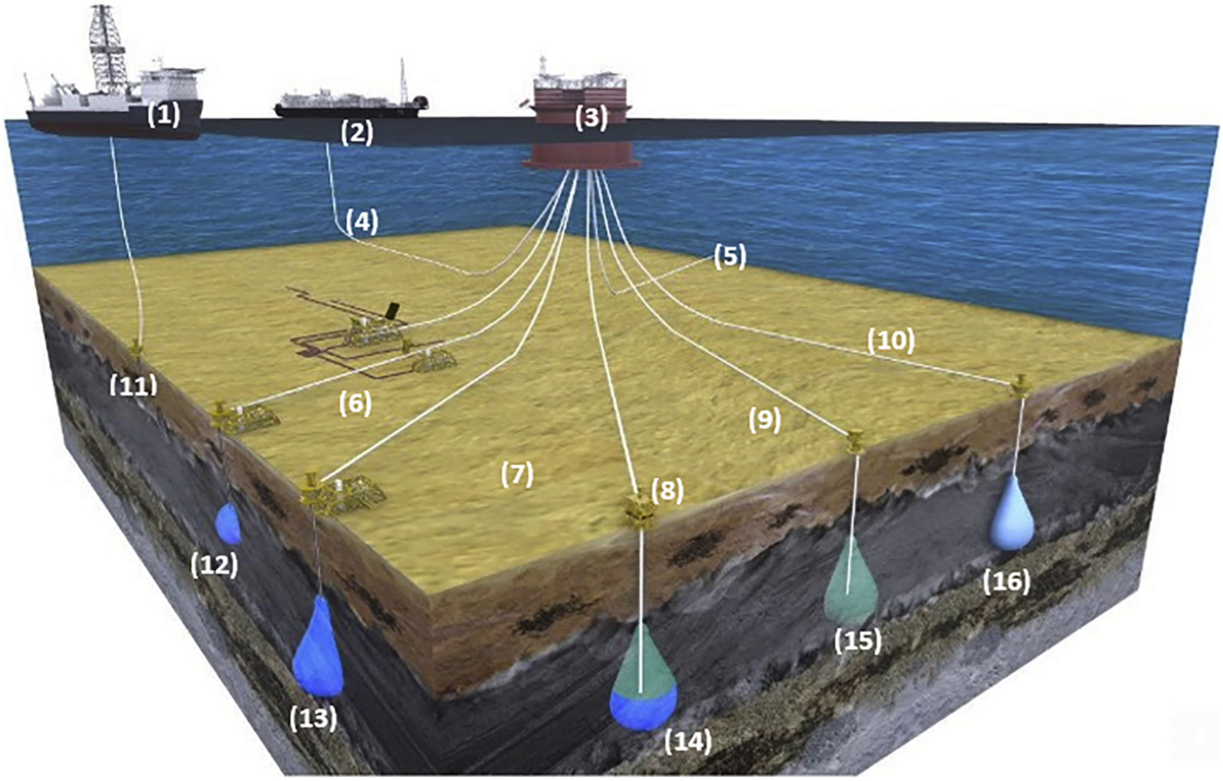


Fig. 2. Processes of the natural gas storage system with CO_2 in salt caverns opened by solution mining.

and equipped with interlocking at all stages: gas phase importation, cavern injection and natural gas exportation.

Figs. 2 to 6 (numbers in Figures are used in next paragraph) describe all the processes that are part of the technological solution idealized for the storage system for the case of a giant salt cavern (450m × 150m) (A.M. Costa et al., 2018a), using two wells for the leaching and gas injection processes due to the size of the cavern.

The implementation of the Ultra-Deep-Water Offshore Salt Caverns for Carbon Capture and Storage (CCS) goes through a few processes (the numbers into parentheses refer to the numbers in the Figs. 2–5):

a The well (11) is built up to an approximate depth of - 3889 m (29), corresponding to the base of the caverns (27). The well will be made in 4 or 5 phases (A.M. Costa et al., 2019) with the respective casings setting (Table 4-itens 1, 2 and 3 →TRL = 7). After each phase, a CBL/VDL (Cement Bond Log / Variable Density Log) profiling will be performed to check the cementation quality (Table 4-item 4→ TRL = 3). Upon completion of the well, it will undergo a mechanical

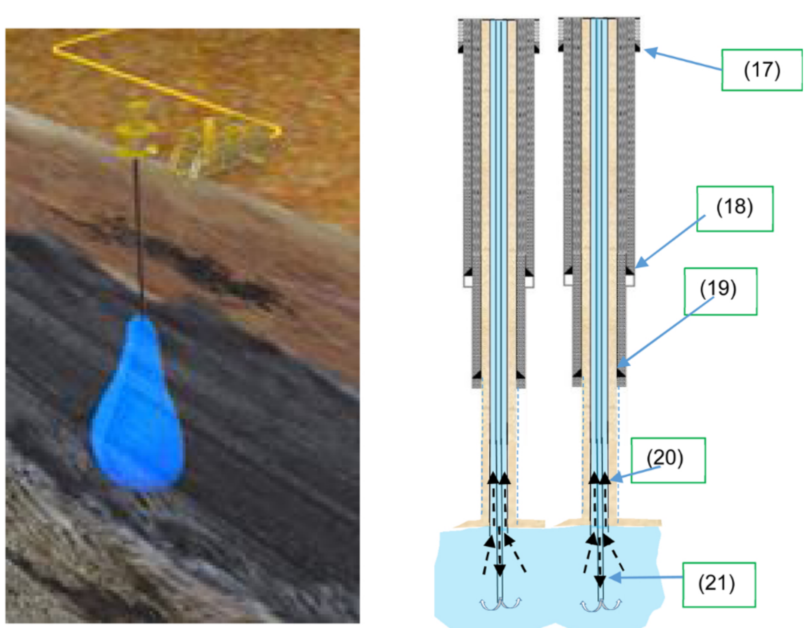


Fig. 3. Cavern dissolution process by seawater injection (leaching process).

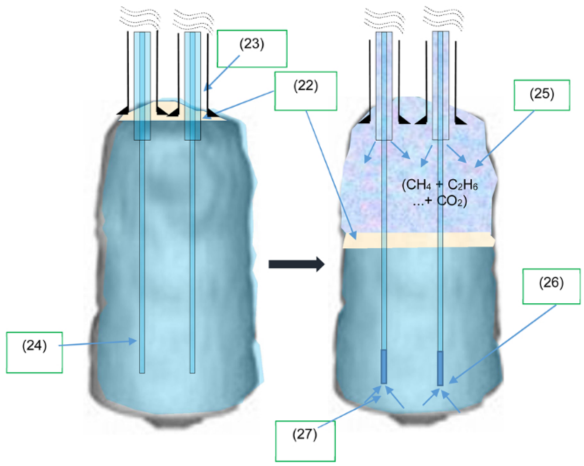


Fig. 4. Replacement of brine by gas phase.

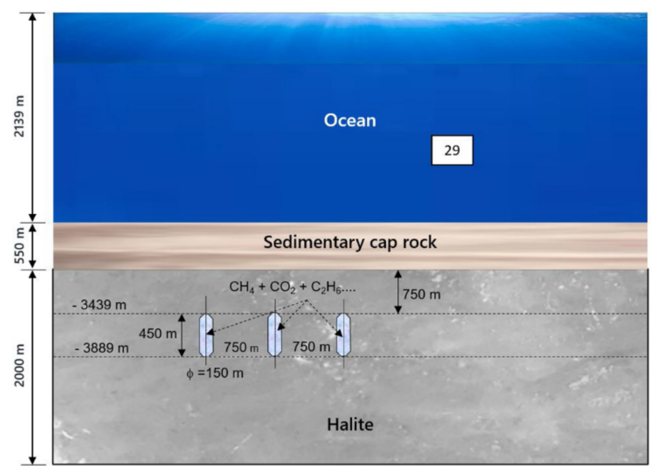


Fig. 5. Design bases of the storage system.

integrity test (MIT) using the nitrogen / synthetic drilling fluid interface method;

b Once is completed the well acceptance testing, if the well has met all the criteria authorizing its use in the operation of the high pressure gas cavern, the same vessel that drilled the well will install the tubing´s for the seawater injection and the brine return (Table 6 – item 10 → TRL = 7). The tubing´s will be housed in the wellhead. The injection tubing will be lowered to the base of the cavern in the current case study, at the depth of -3889 m. The brine return tubing will be hanged to the depth corresponding to the top of the cavern in the current case study, at the depth of −3439 m (P.V.M. Costa, 2018). From this stage seawater will be injected, preferably using production vessel water injection pumps, which nowadays are used to inject water into the pre-salt reservoirs, with an approximate flow rate of 144.000 barrels / day or about 1.000 m^3/hour (Table 6 –item = 2→ TRL = 3);

c Considering the cave under study with 450 m in height and 150 m in diameter, a geometric volume between 5.5 million m^3 and 7.5 million m^3 is estimated. If pumps on the production platform cannot be used for cavern leaching, high pressure submersible pumps (6) will be used to inject “in-nature” seawater near the sea floor. Seawater at a depth of 2200 m is at a temperature of 4 °C Table 6-item 3→TRL = 2). The higher the temperature of the injection water, the higher the dissolution rate. Under this condition, the water should be preheated to a minimum temperature of 15 °C, added to the temperature gain with the geothermal gradient of the saline rock, which is between 37 °C (−3439 m) and 42 °C (-3889 m), the leaching process should be performed at an average temperature around 40 °C, which produces a minimum dissolution rate of 80 %;

d The cavern (12) will be opened by dissolution from the bottom to the top. Two wells 25 m (17) apart will be used (A.M. Costa et al., 2018a). Each cavern will be built independently using two identical wells with the same completion. The caverns will intersect and give rise to a giant cavern 450 m high and 150 m in diameter. Throughout the dissolution process it is foreseen to monitor the cavern every 50 m interval, which corresponds to about 15 weeks of time, by the application of Sonar 3D Scanner introduced in the cavern through the brine return tubing (Table 5-item 4→ TRL = 2). These caverns can have CO_2 storage capacity of 4 billion m^3 at a temperature of 44 °C and a pressure of 450 bar (A.M. Costa et al., 2018a). In this phase the drilling vessel will be used again, which should first remove the water injection tubing and then introduce the wireline cable hanging sonar;

e Throughout the leaching process, in the annulus between the last casing setting phase and the brine return tubing (23), synthetic fluid, possibly the olefin base, will be injected to protect the top of the cavern (22). The fluid is kept pressurized so that the injection water cannot leach the top of the cavern due to the pressurized synthetic fluid cushion (Table 7-item 10→ TRL = 5);

f Once the cavern has been completed, it will pass through the Mechanical Integrity Test (MIT) using pressures between 90 % and 120 % of the initial stress at the top of the cavern. The nitrogen / brine interface method will be used again (Table 7-item 4→ TRL = 7);

g If the cavern passes the integrity and tightness tests, it starts the injection of natural gas with high CO_2 content into the cavern using the brine return tubing. Both wells will be used at this stage. To avoid mixing CO_2 with brine, the olefin cushion at the natural gas / brine interface will be preserved (22). The pressures predicted by the geomechanical calculation indicate values between 350 bar and 450 bar and may reach 520 bar. BCSS (Submerged Submarine Centrifugal Pump) type pumps (26) may be used in each water injection pipe, which now drains the brine from the cavern. The pumps will be used to aid brine removal, thereby preventing the rupture of the synthetic fluid interface cushion between the brine and natural gas (Table 5-item 12→ TRL = 7);

h During the leaching and gas injection process two Christmas trees may be used. The first for the construction process and the second for natural gas operation. In the second case, the Christmas tree will be made of special metallurgy, for example, super duplex (8). In the phase of natural gas injection in the cavern (25) will be used the compressors or pumps of the production platform (2). The same equipment that is used today in the WAG (Water Alternating Gas) process in the production of pre-salt reservoirs (Table 4-item 8 → TRL = 5);

i Injection of natural gas can be done through rigid lazy wave catenary risers (9), manufactured in special metallurgy or cladded in the regions of higher stress concentration in the top and in the TDP (Touch Down Point) region (Table 6-item 5→TRL = 6). The cavern (15) after being filled with natural gas will have the Christmas tree closed at the head of the two wells;

j In this phase begins the abandonment of the cavern (16). The cavern (16) will be controlled for 5 years through an umbilical connected to the Christmas tree (9), using a Christmas tree pressure measurement system (8), with the sensor installed through the injection tubing and brine return, at the base and top of the cavern (Table 6-item 15→ TRL = 2). The measurements will be compared to simulation results to verify the tightness condition of the cavern.

Historically, the problems of loss of cavern tightness storing natural gas comes from problems in the well and never as a result of fractures or micro fractures in the cavern perimeter, as long as the correct geomechanical design of the cavern is made, especially in a cavern that will

Table 5
Salt cavern storage of natural gas and CCS technology.

Aspects	Comments	TRL
1 Drilling	Pre-salt wells already drilled to a depth of ~5000 m below sea level with 4 or 5 phases (Mohriak et al. (2008))	7
2 Drilling fluid	Olefins Synthetic based fluid already used in the pre-salt wells of Santos basin (Mohriak et al. (2008))	7
3 Solution mining Onshore	There are several caverns constructed by solution mining onshore for gas storage and brine production (P.V.M. Costa, 2018)	7
4 Solution mining Offshore	Salt cavern Offshore in shallow or ultra-deep water	2
5 Cavern design Onshore	There are several caverns constructed by solution mining onshore designed for gas storage and brine production (P.V.M. Costa, 2018)	7
6 Cavern design Shallow Offshore	Cavern design for gas storage in shallow water already studied (P.V.M. Costa et al., 2017)	7
7 Cavern design Deep Offshore	Oil and Gas Offshore in ultra-deep Water	2
8 Cavern design for CO_2 or (CH_4 + CO_2) Onshore	Onshore	2
9 Cavern design for CO_2 or (CH_4 + CO_2) Deep Offshore	Shallow or ultra-deep water	2
10 Gas storage operation Onshore	There are several caverns constructed by solution mining onshore in operation for gas storage (P.V.M. Costa, 2018)	7
11 Gas storage operation Shallow Offshore	Gas storage operation offshore in shallow water in depleted reservoirs (Mohriak et al. (2008))	7
12 Gas storage operation Deep Offshore	The operation will be the same used in the injection of gas in the presalt reservoirs for EOR (P.V.M. Costa, 2018)	7
13 CO_2 capture in salt caverns Onshore	Onshore	2
14 CO_2 capture in salt caverns Deep Offshore	Shallow and ultra-deep water	2
15 Salt cavern survey during construction Onshore	Onshore	7
16 Salt cavern survey during construction Offshore	Offshore (shallow and ultra-deep water)	2
17 Salt cavern gas storage monitoring during operation – Shallow and ultra-deep water	During construction it will be used sonar scan 3D and during operation will be used PDG´s (Permanent down hole gages-both technologies certified by the mining and oil&gas industries (Costa, 2018)	7
18 Salt cavern CO_2 storage monitoring during operation	onshore, shallow, and ultra-deep water	2
19 Geomechanical salt cavern simulation Onshore	R & D projects and basic engineering projects of salt caverns developed for on shore sites for gas storage (P.V.M. Costa, 2018, 2013)	7
20 Geomechanical salt cavern simulation shallow Offshore	R & D projects and basic engineering projects of salt caverns developed for offshore shallow water sites for gas storage (P.V.M. Costa, 2018, 2013)	7
21 Geomechanical salt cavern simulation Deep Offshore	R & D projects and basic engineering projects of salt caverns developed for offshore ultra-deep water sites for gas storage (P.V.M. Costa, 2018, 2013)	7
22 CFD of salt cavern	Onshore, shallow and ultradeep water.	2

be abandoned indefinitely with pressurized natural gas with high CO_2 content.

3.2. Description of the second phase of R&D Project - Gravitational separation of natural gas and CO_2 inside the cavern

At this stage of the project a method of separating large volumes of CO_2 from the main fractions of natural gas (methane and ethane) in caverns under high pressure with liquid or supercritical CO_2 is studied. Thus, this design enables oil production in fields that have already reached the treatable CO_2 limit, mitigating the risks and costs of current systems used for CCS in combination with hydrocarbon production.

In addition, the separation method of the present technology also allows the extraction of the separated natural gas allowing its monetization.

The method comprises the following steps:

a Built one or more caverns in salt rocks by leaching process in an offshore environment by applying submerged pumps using raw seawater from sea floor, or by the injection of seawater by the production platform itself; (Table 5-item 4→ TRL = 2);
b Inject associated natural gas into a salt cavern until it is completely filled and reaches the maximum allowable pressure (Table 5-item 12→ TRL = 7);
c Close the upper part of the cavern and monitor the gravitational separation between natural gas and CO_2 (Table 7-item 15→ TRL = 6);
d Extract natural gas from the top of the cavern, leaving the supercritical CO_2 at the bottom. Fig. 6 (Table 7-item 15→ TRL = 6).

Table 6
Subsea engineering technology.

Aspects	Comments	TRL
1 Raw water injection	Shallow and deep water	7
2 Raw water injection	Ultra-deep water	3
3 Application of subsea pumps for lixiviation of salt caverns	Shallow, deep and ultra-deep water	2
4 Rigid flow lines with special metallurgy	Ultra-deep Water	6
5 Lazy wave Steel catenary riser	Ultra-deep water with special metallurgy/clade for FPSO (Injection of gas stream with high content of CO_2	6
6 Subsea power cables for the RWI pumps	Ultra-deep water	6
7 Hydraulic and data umbilical's for cavern construction and operation	Ultra-deep water	7
8 Subsea Christmas Tree (system control) for cavern construction and operation	Shallow, deep and ultra-deep water	7
9 Raw water injection pumps installation for cavern construction	Ultra-deep water	7
10 Maneuvers with sea water injection and brine return tubing´s	Deep and ultra-deep water	7
11 Flow lines installation for cavern construction	Ultra-deep water	6
12 Pull in of LW SCR for gas stream injection into the salt caverns	Ultra-deep water	6
13 Salt cavern gas waste storage monitoring during operation	Ultra-deep water	7
14 Sea floor gas waste seepage monitoring	Shallow, deep and ultra-deep water	4
15 Salt cavern gas waste confinement (abandonment) monitoring	Shallow, deep and ultra-deep water	2

Table 7
Flow and Process technology.

Aspects	Comments	TRL
1 Electrical system for subsea pumps	Shallow, deep and ultra-deep water for the construction of the salt cavern with high flow rate and high pressure	7
2 Gas injection in reservoir	Shallow, deep water and ultra-deep water with high pressure and high flow rate	6
3 Gas injection in salt caverns Onshore	onshore with high pressure and high flow rate	6
4 Gas injection for salt caverns in Shallow water	Shallow water with high pressure and high flow rate	7
5 Gas injection for salt caverns in Deep water	Deep and ultra-deep water	7
6 Rigid flow lines with special metallurgy for gas injection in salt caverns	Hydraulics design of rigid flow lines with special metallurgy for gas injection in salt caverns for Ultra deep Water	6
7 Lazy wave SCR	Hydraulics design of lazy wave Steel catenary riser with special metallurgy/clade for FPSO (Injection of gas stream with high content of CO_2 for Ultra deep water	6
8 Retrofit of pumps and compressors at the FPSO for gas injection in the salt caverns	Ultra-deep water	6
9 Control system at the FPSO for monitoring the gas injection in the salt cavern	Ultra-deep water	7
10 Pumps for olefins injection in Shallow water	Shallow water with blanket based on olefins synthetic fluid for cavern construction and operation	5
11 Pumps for olefins injection in Deep water	Deep and ultra-deep water	5
12 Salt cavern gas waste storage monitoring during operation	Ultra-deep water	7
13 Sea floor gas waste seepage monitoring	Shallow, deep and ultra-deep water	3
14 Salt cavern gas waste confinement (abandonment) monitoring	Shallow, deep and ultra-deep water	7
15 Thermo-dynamic properties for gas injection in the cavern and final confinement	cavern abandonment	6

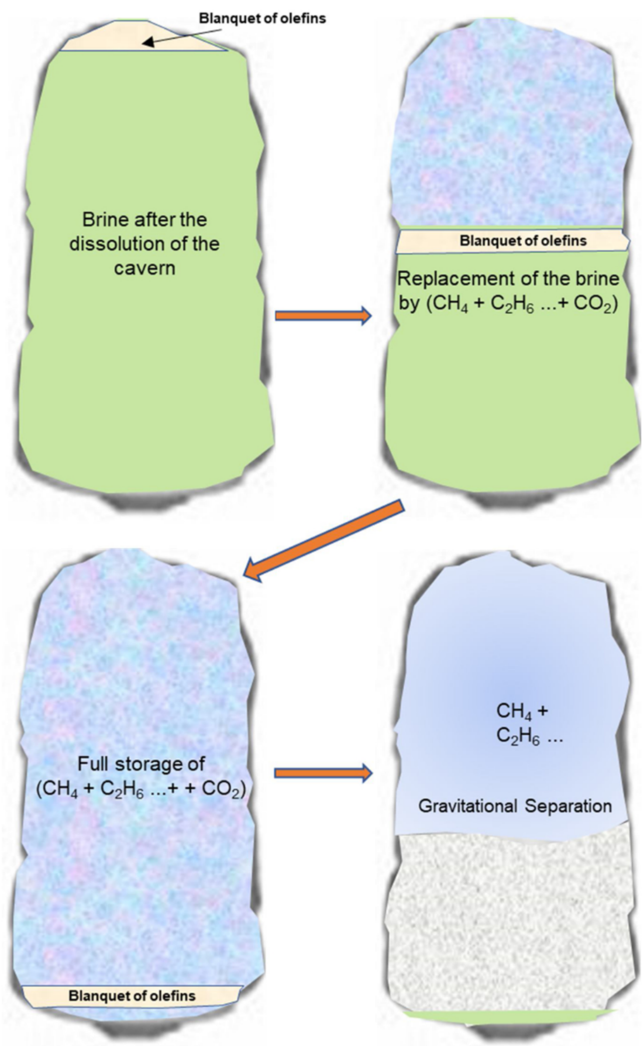


Fig. 6. Illustration of the process of gravitational separation of CO_2 and CH_4 inside the cavern.

Thus, for the temperature and pressure range in which the gas mixture is found, CO_2 enters in a liquid or supercritical state increasing its density and allowing gravitational separation of natural gas from CO_2 inside the cavern in which the highest density contaminant settles at the bottom of the cavern and the one with the lowest density settles at the top. It should be noted that cavern applications should always be under temperature and pressure conditions in which CO_2 is in liquid or supercritical state.

The cavern is periodically monitored for integrity control. The monitoring is conducted by digital pressure gauges installed in the Christmas tree that will detect the occurrence of pressure drop due to gas leakage.

After gravitational separation, natural gas from the top of the cavern is extracted by pressure difference between the pressure inside the cavern and the atmospheric pressure at the surface. The removal of CH_4 from the caverns must comply with the minimum pressure limit required so that CO_2 does not return to the gaseous state.

At the same time, CO_2 and other liquid or supercritical contaminating gases within the cavern are confined indefinitely, thus obtaining a definitive CO_2 capture and storage system (CCS).

4. Geomechanical design of the giant salt cavern (450m × 150m) - table 5, item 7 → TRL = 2

One of the most important aspects of the development of the technology is the construction and operation of the salt cavern in ultra-deep waters at a depth unprecedented worldwide. To analyze the TRL level of this aspect of the project is applied numerical simulators with extensive history of structural integrity analysis of salt rock underground excavations in Brazil (A.M. Costa et al., 2020; P.V.M. Costa et al., 2020a,b,c; A.M. Costa et al., 2019a,b,c; 2019; P.V.M. Costa et al., 2019; A.M. Costa et al., 2018a,b,c; P.V.M. Costa, 2018; P.V.M. Costa et al., 2017; P.V.M. Costa et al., 2015; A.M. Costa et al., 2015; P.V.M. Costa et al., 2014; A.M. Costa et al., 2014; A.M. Costa, 1999, 1997, 1995; A.M. Costa and de Melo, 1992). The analysis of the numerical simulations results is performed by COVES 2 (A.M. Costa, 1984), with over 40 years of experience on salt rock behavior. The results are presented below.

4.1. Site selection

In the process of selecting potential areas for the development of salt

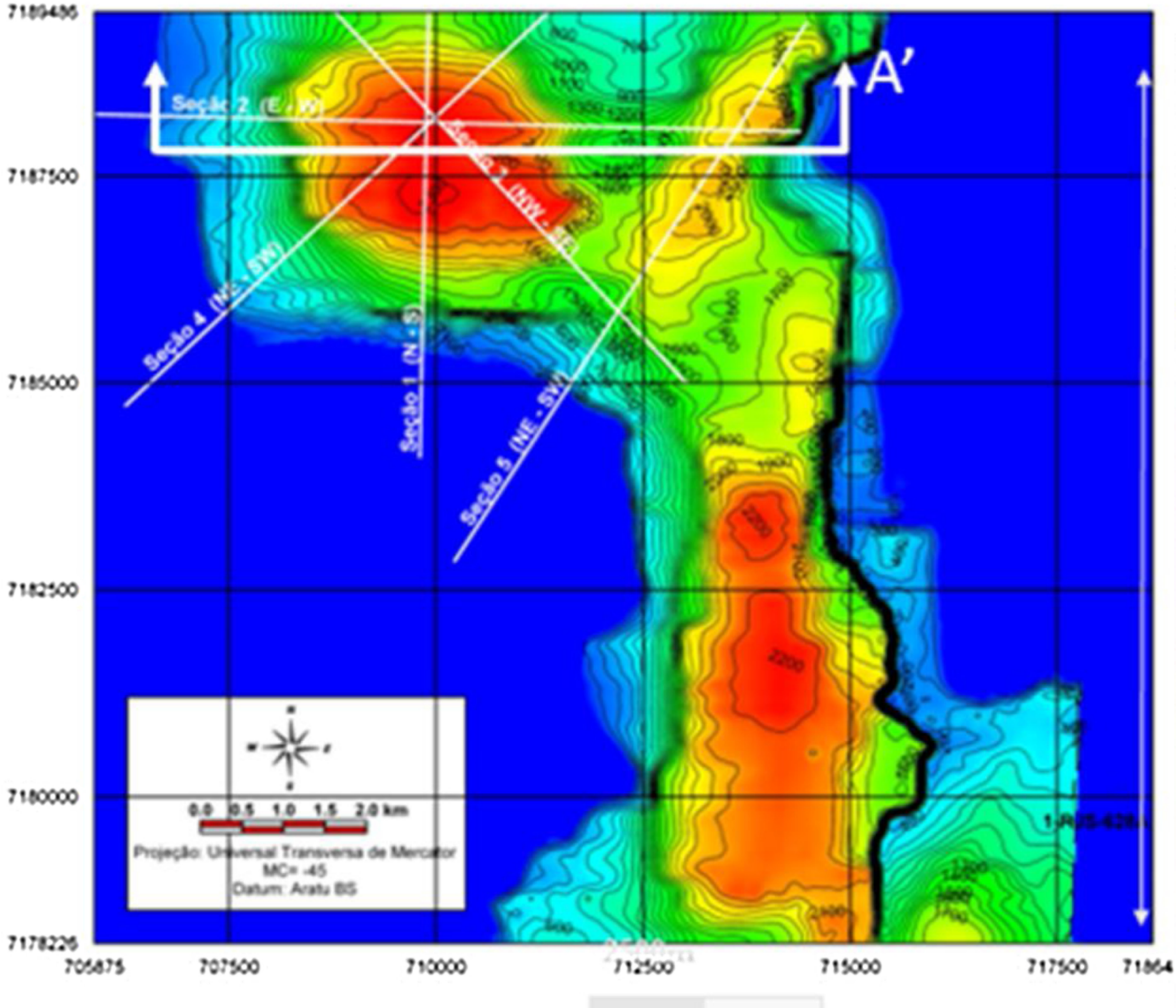


Fig. 7. Salt cavern location (A.M. Costa et al., 2011).

caverns by solution mining, salt domes are selected in order to minimize the presence of interbedded non-soluble rock layers like shale and anhydrite and also to avoid the more soluble salts, carnallite and tachyhydrite as much as possible. In addition, some other criteria were established, such as the maximum depth from the top of the rock salt dome and the distance of the salt domes in relation to the oil fields.

Based on interpretation of 3D seismic and 2D seismic, a cluster of salt domes 10 km away from one of the major pre-salt oil fields in

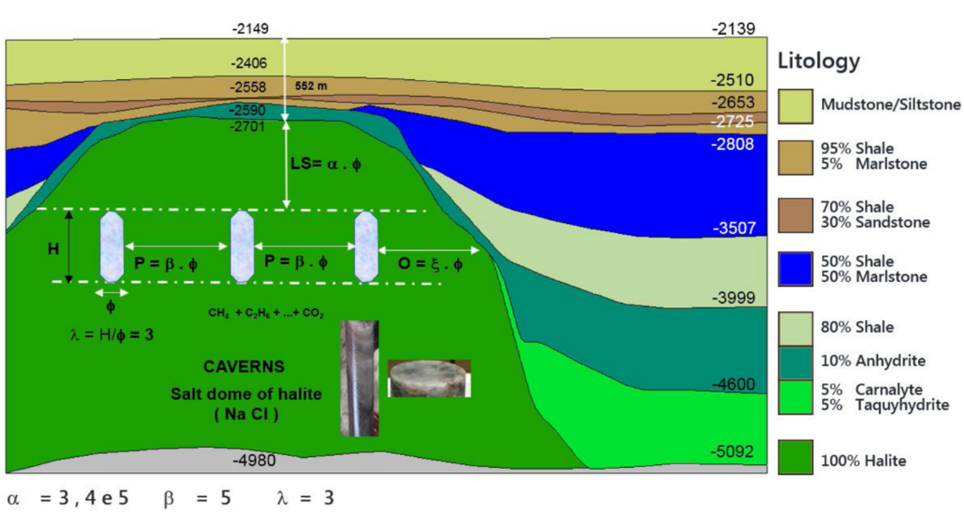
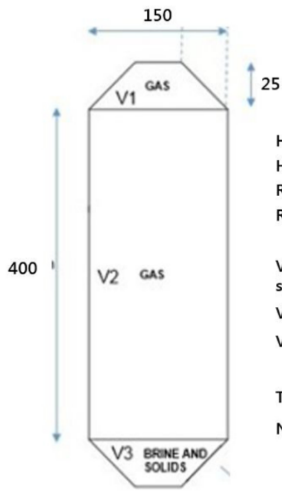


Fig. 8. Parametric variables α, β, and λ studied.



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

Fig. 9. Geometrical volume of the cavern (P.V.M. Costa et al., 2017).

Santos Basin was selected (A.M. Costa et al., 2011).

Fig. 7 shows the vertical seismic section crossing a salt rock deposit that was selected for the location of the first experimental and pilot caverns to be built in ultra-deep water for CCS of the pre-salt reservoirs.

4.2. Parametric variables and basic data

For the geomechanical design of the cavern it is necessary to make a parametric study changing the variables as indicated in Fig. 8 (Table 5 - items 19, 20 and 21→ TRL = 7).

Due to the large volume of salt dome selected, the distance between the caverns was calculated in order to eliminate the group effect so that the redistribution of stresses induced by the dissolution of one cavern will not influence the stability of the neighbor cavern in the cluster. In this condition the simulation of the structural behavior of the caverns is being conducted by the application of axisymmetric structural models. Due to the large size of the salt dome it is possible to construct giant salt caverns, A.M. Costa et al. (2018a) recently presented a very elegant procedure to design giant salt caverns in shallow water. In terms of the geomechanical analysis, there is no difference in the simulations and criteria used in the design of caverns of any size (P.V.M. Costa, 2018).

For evaluating the salt caverns stability, some basic data based on the authors' experience were adopted (P.V.M. Costa, 2018), Fig. 8 (Table 5 - items 19, 20 and 21 → TRL = 7):

- Specific weight of the sedimentary rock → 22.56 kN/m^3;
- Specific weight of the rock salt → 21 kN/m^3;
- Slab protection of rock salt at the top of the cavern → α x φ = 750 m;
- Minimum distance between caverns to avoid interference → β x φ (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 → $\lambda = h/\varphi = 3$;
- Shape → cylindrical;
- Size and shape of cavern→ = 450m × 150m;
- Initial state of stress at the top of the cavern → $\sigma_0 = 2139 \cdot 10 + 550 \cdot 22.56 + 750 \cdot 21 = 21{,}390 + 12{,}408 + 15{,}750 = 49{,}548$ kPa;

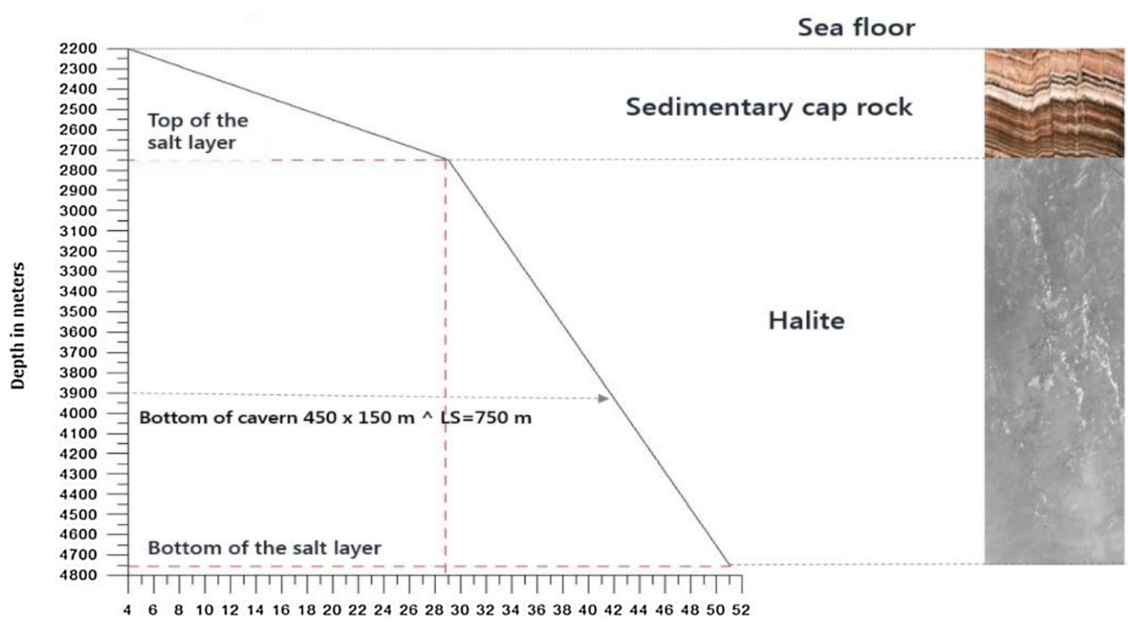


Fig. 10. Temperature profile at the location where the cluster of caverns will be constructed.

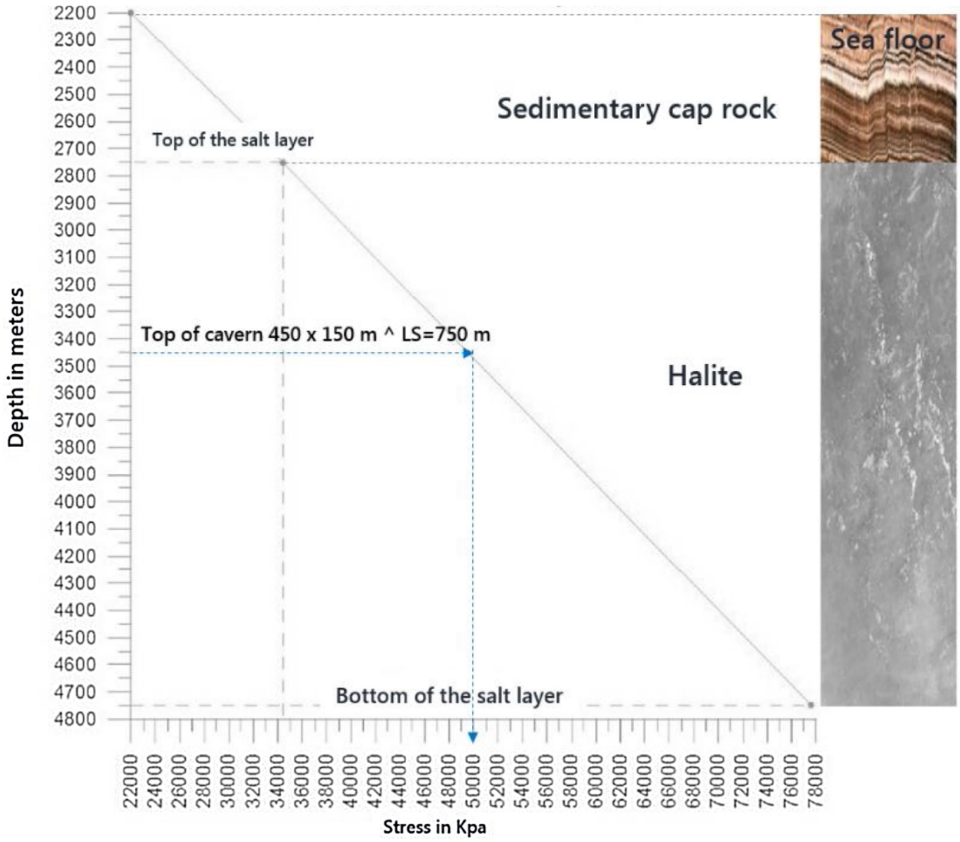


Fig. 11. Lithostatic stress gradient at the location of the cluster of caverns.

- 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 geometrical volume of the cavern is indicated in Fig. 9.

Fig. 10 shows the temperature profile as a function of depth at the location where the caverns will be constructed while Fig. 11 shows the lithostatic stress gradient used in the structural geomechanical simulation.

The creep strain rate of the halite 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. 12 shows the structural geomechanical model used in the simulation by COVES 2 computer code (A.M. Costa, 1984) (Table 5, item 21 → TRL = 7). On the structural geomechanical model is generated the finite element mesh.

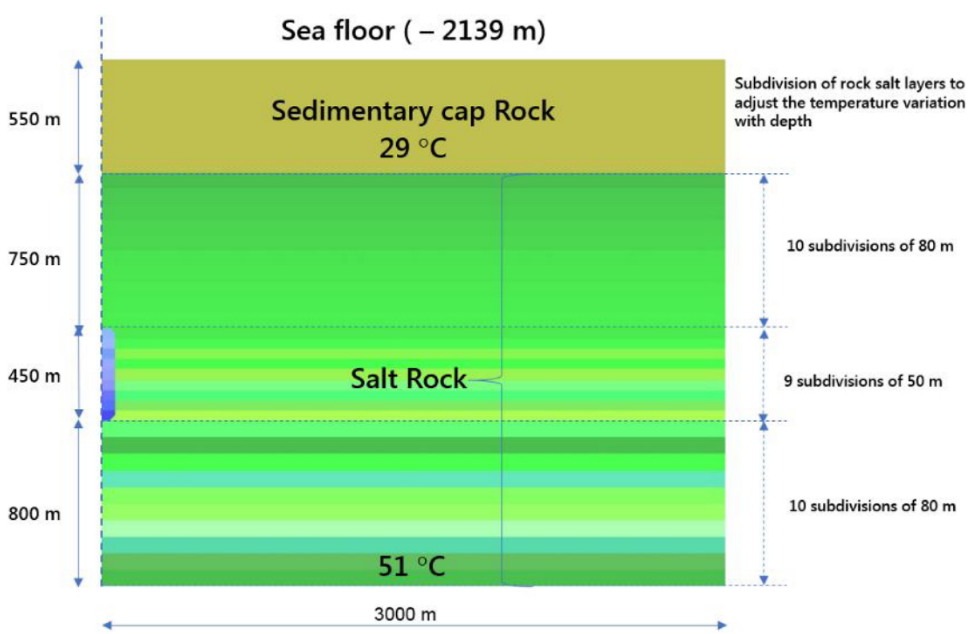


Fig. 12. Geomechanical structural model of a CCS salt cavern in ultra-deep water.

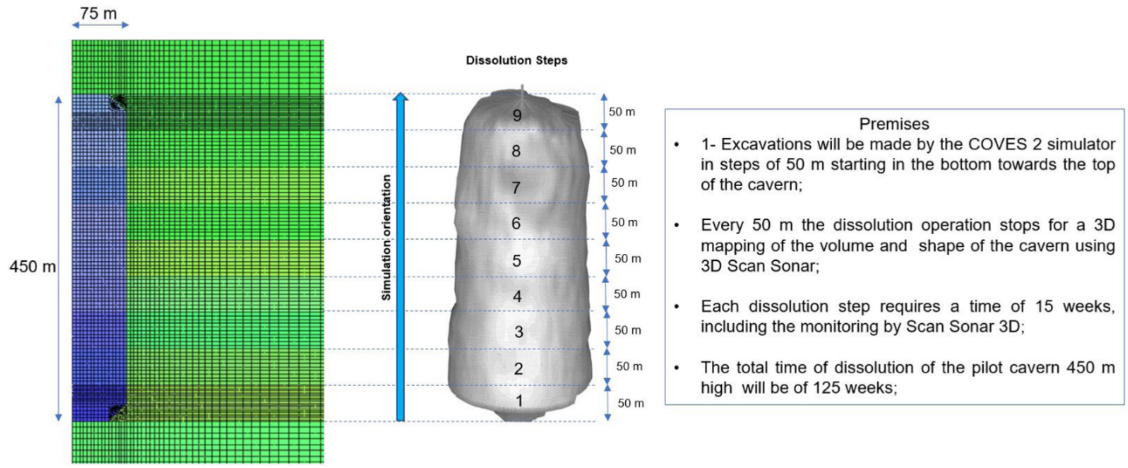


Fig. 13. Excavation steps of 50 m of the model.

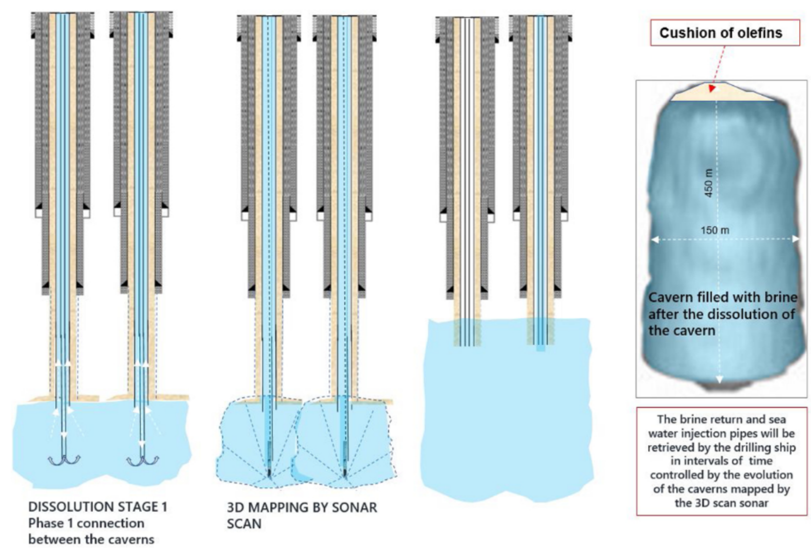


Fig. 14. Dissolution process of the giant salt cavern.

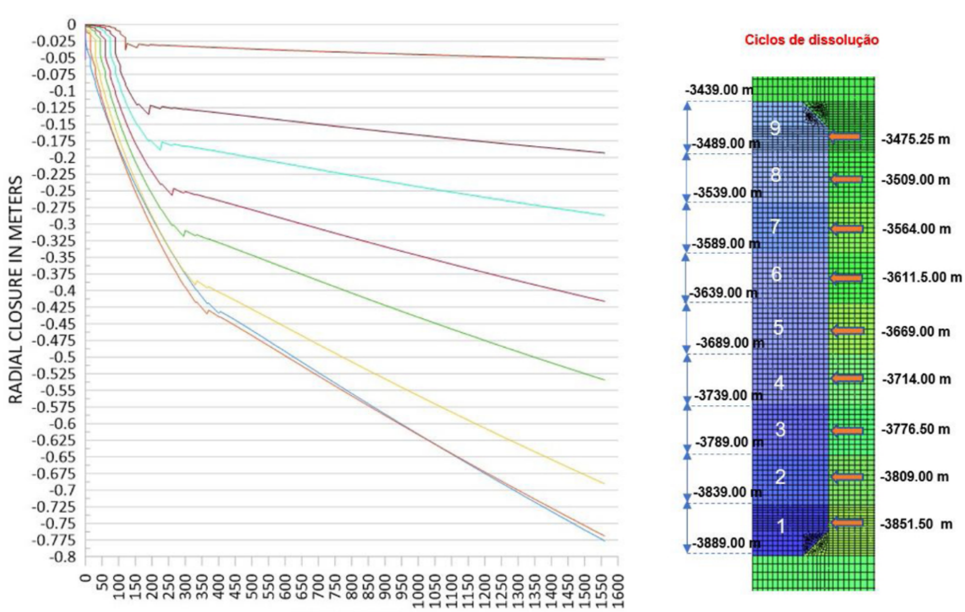


Fig. 15. Evolution with time of perimeter radial closure of the cavern in different vertical positions of the giant cavern 450m × 150m.

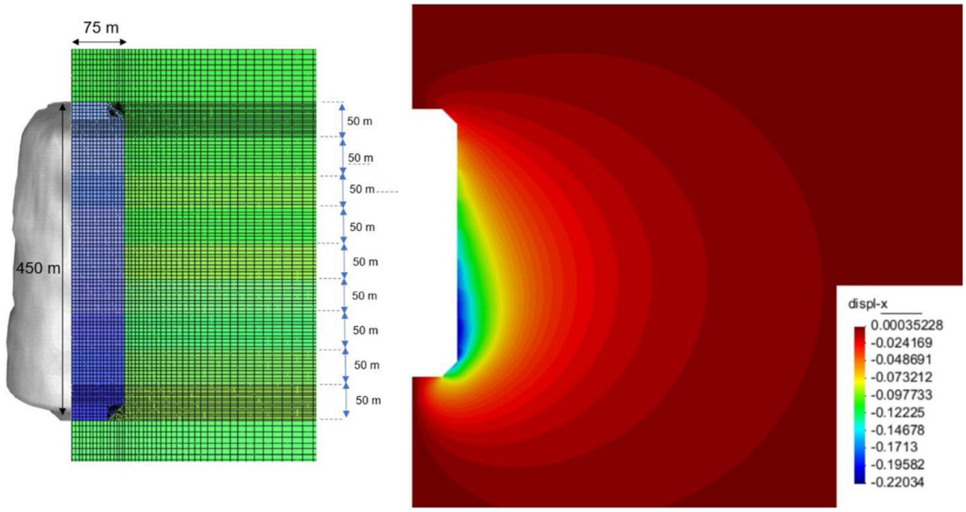


Fig. 16. Isosurface of the radial closure at the time = 120 weeks.

4.3. Simulation results (table 5, item 21 → TRL = 7)

During the cavern leaching process, it is normal engineering practice to assess the growth and shape of the cavern every 30 m or 50 m, upwards, from the bottom to the top. If the cavern growth deviates from the original design, which may compromise its stability, in these intervals it is possible to maneuver the water injection and brine return tubes to allow the correction of the cavern geometry (P.V.M. Costa, 2018; A.M. Costa and de Melo, 1992). Following this procedure COVES 2 simulates the excavation by leaching of the cavern in 9 steps of 50 m each, from bottom to top of the cavern. Fig. 13 shows the 9 excavation steps of 50 m that was simulated by COVES 2.

For efficient simulation of the stepwise excavation of the cavern, 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 is assumed the application of two wells to do the dissolution, using an injection flow rate of 140 000 barrels of seawater per day. The time to excavate each step of 50 m is approximately 15 weeks. Every 15 weeks the cavern will 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 is reanalyzed by the structural geomechanical simulation. For the prediction of the dissolution time the SALGAS computer code was used (Saberiam, 1984).

Fig. 14 shows how the dissolution of the giant cavern will be done (Table 5-item4→TRL = 2). 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 and becomes only one giant cavern in the process of dissolution. During the process, the caverns are monitored by scan sonar 3D in each cavern.

COVES 2 simulates the real excavation of the cavern, step by step, in a non-linear viscoelastic basis with time, excavating the elements included in each section of 50 m, keeping the global structural equilibrium of the full model. In the excavation process, pressure of brine is decreased to induce equilibrium with the sea water column of 2139 m.

Fig. 15 shows the evolution with time of the radial displacements of the cavern perimeter (points in Fig. 15 at right). Each curve starts at a different time when the excavation reaches that position. Is also possible to see the effect of gas injection inside the cavern. The excavation starts from the bottom up to the top and the injection from the top – down to the bottom of the cavern.

It is expected that the filling of each 50 m of the cavern will expend 30 weeks. So, after the cavern is finished at the time of 270 weeks the

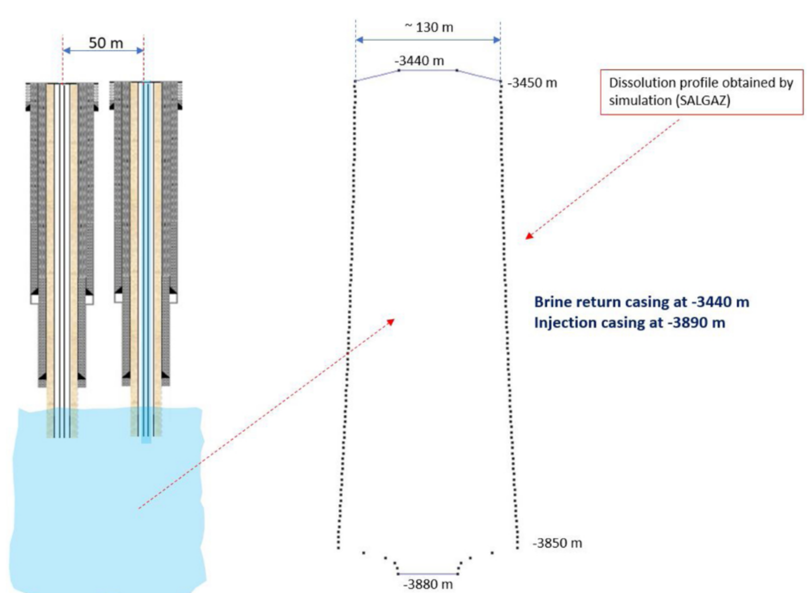


Fig. 17. Dissolution of the cavern 450m × 150m keeping fixed the position of the injection and brine return casing.

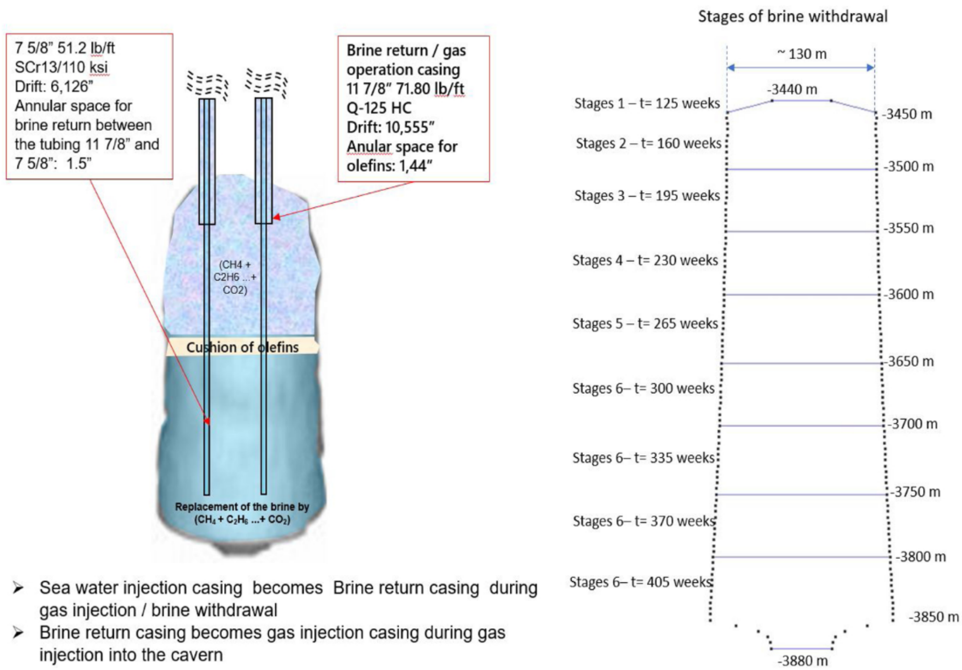


Fig. 18. Stages of replacement of brine by gas with high content of CO_2.

gas pressure will reach the bottom changing the creep closure velocity of that section of the cavern. The iso-surfaces of the horizontal or radial displacements is shown in Figs. 16 at the time = 120 weeks.

The maximum radial displacement at the perimeter of the cavern, at the time = 120 weeks, is only 220 mm, because the halite is cold, only 42 °C and mainly due to the high hydrostatic pressure added by the water column of 2140 m, which corresponds an additional of 21.4 MPa or ~ 214 bar. Keeping the position of the brine return casing at the top of the cavern −3440 m and the injection casing at the bottom of the cavern – 3890 m, at the same period of days 840 days or 125 weeks, it is possible to reach the cavern with 450 m of height and 150 m in diameter, as shown in Fig. 17.

The gas with high CO_2 content is injected after 125 days, from the top to the bottom of the cavern replacing the brine with time. The gas produced in the FPSOs that is not reinject in the reservoir is filtered in the membrane equipment at the process plant. The cleaned gas, with maximum grade of 3% of CO_2 is compressed through a gas pipeline to shore. The remaining gas, now with high content of CO_2 will be re-injected in the reservoir for EOR and part of this contaminated gas with CO_2 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 the top to the bottom, as shown in Fig. 18 This Figure presents units used in oil & gas industry; convention: 7 5/8″ = 2.15 m, 11 7/8″ = 3.375 m, 51.2 lb/ft = 747.21 N/m, 51.2 lb/ft = 1047.84 N/m.

For the geomechanical simulation, a time of 280 weeks to completely fill the cavern and replace the brine was assumed. At the time equal to 405 weeks the gas reaches the bottom of the cavern. 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 pay attention that

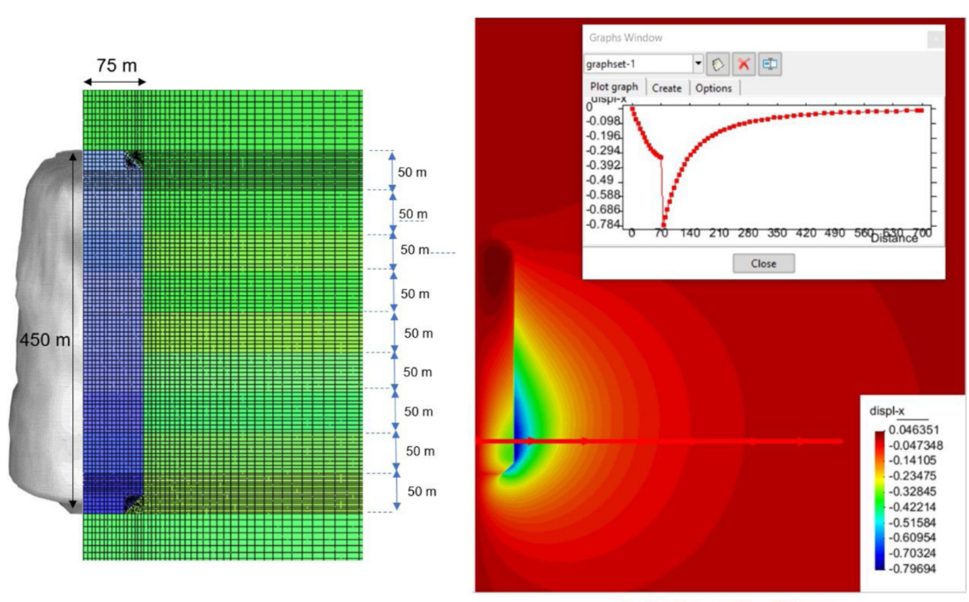


Fig. 19. Isosurface of the radial closure at time equal to 30 years.

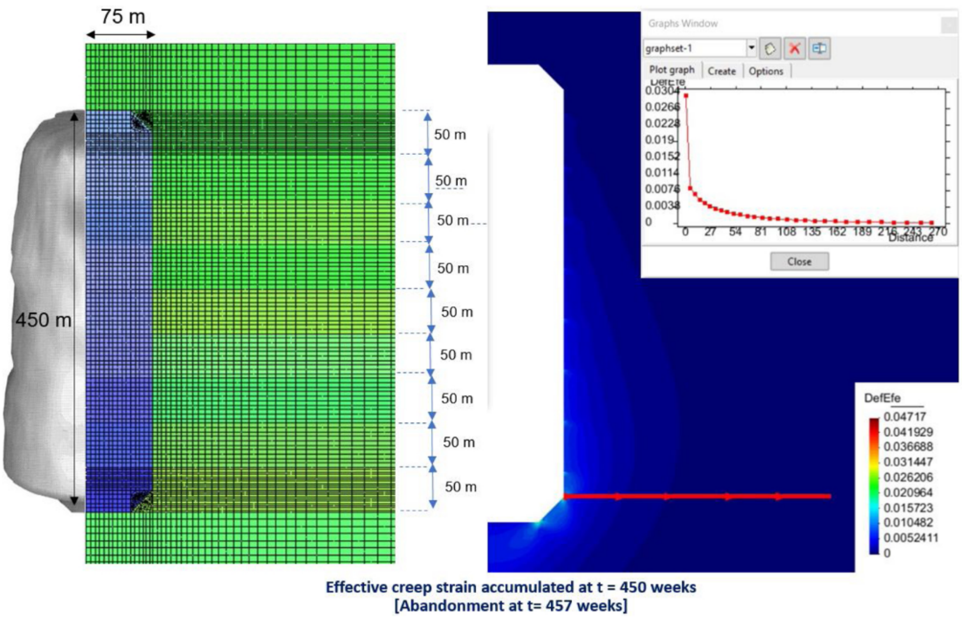


Fig. 20. Isosurface of the effective creep strain in t = 450 weeks.

during the injection time the nodal points used to monitor the simulated closure of the cavern with time, continue to increase due to the creep of the halite, but with a much smaller time closure rate.

It will take 52 weeks more to finish the filling of the cavern with gas at the pressure of 90 % of the lithostatic pressure. At the time equal to 457 weeks the Xtree is closed.

COVES 2 simulates over time the excavation, the replacement of the brine by the gas with high content of CO_2 and the final abandonment of the cavern. When the cavern is 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 is assumed that the cavern is filled with only CO_2, due to lack of data for mixtures of gases with varying compositions. Currently laboratory tests are geared to obtain 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 is used. Fig. 19 shows the distribution of the radial displacements after 30 years of abandonment of the cavern with CO_2.

The isosurfaces of displacements confirm the simulation results due to the immediate smooth distribution of deformation between the rock and CO_2 at the critical state inside the cavern. Just after the abandonment of the cavern by closing the wet Christmas tree, the deformation goes to a steady-state condition with small creep closure rate. The process of squeezing the gas inside cavern deaccelerate the creep closure of the cavern as expected, reaching a steady-state condition. In Fig. 17 is possible to understand the process of gas injection and gas squeezing with time. As the gas is injected from the top - down this causes a phenomenon of pushing the isosurface of higher displacements

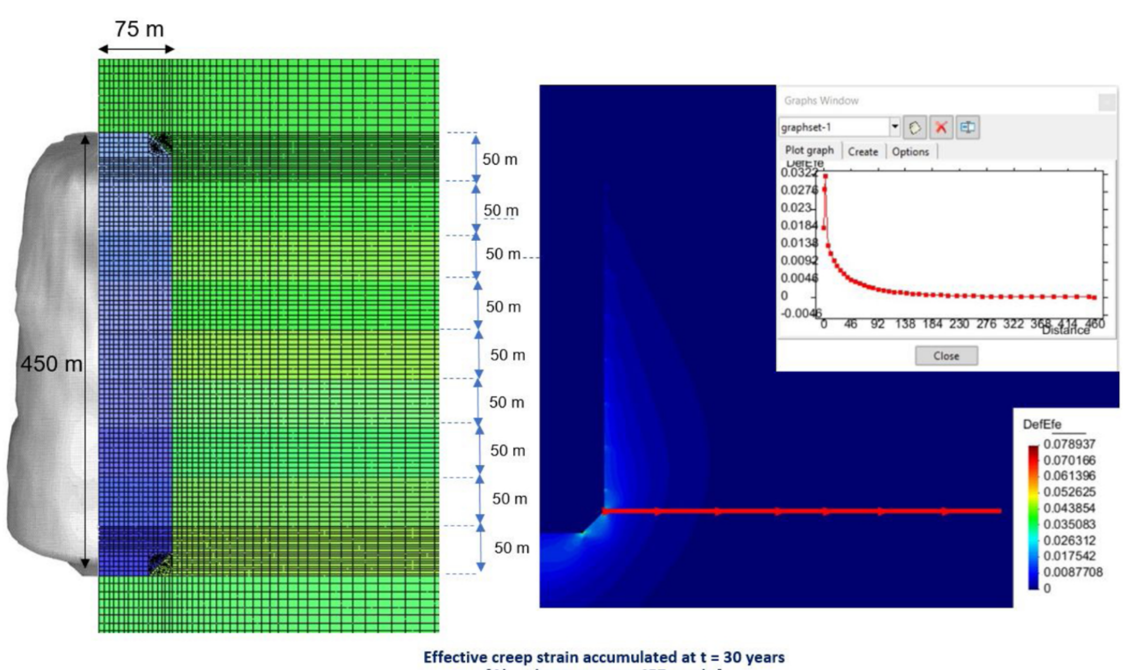


Fig. 21. Isosurface of the effective creep strain in t = 30 years.

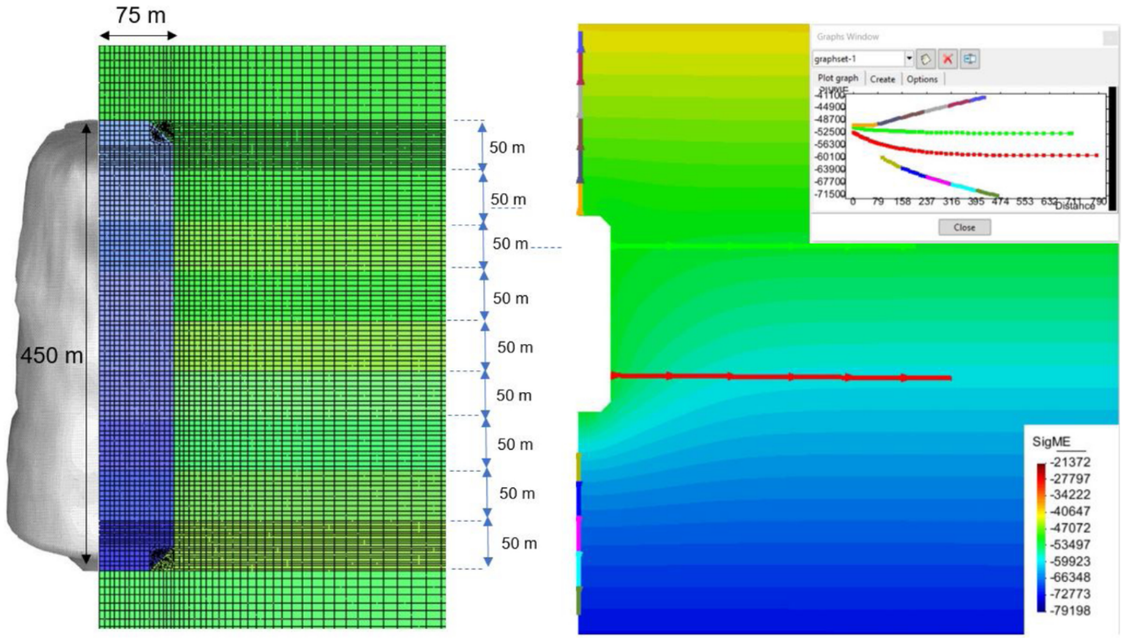


Fig. 22. Isosurface of the first invariant of stresses at t = 450 weeks.

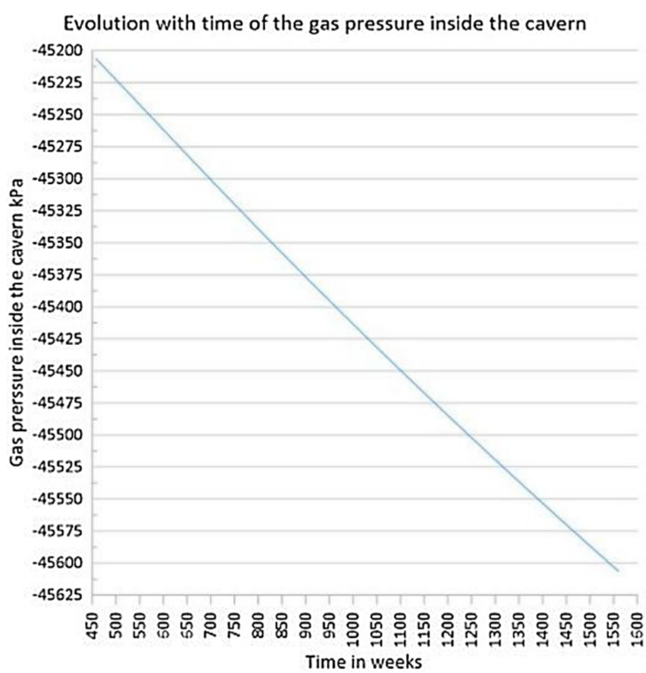


Fig. 23. Evolution with time of the gas pressure inside the cavern.

down, close to the bottom of the cavern, which is a perfect simulation of the phenomenon.

The process of scaling of the cavern wall starts when the creep strain reaches values ranging between 5% and 10 % in a conventional mining, without counter pressure. In this case study the maximum effective creep strain occurs only in the corner of the cavern wall, which will be smoothed over time. Fig. 20 and 21 show the isosurface of the effective creep strain at times 450 weeks and 30 years respectively, confirming that the cavern will be kept in a particularly good condition even after 30 years, with 22 years of abandonment.

The phenomenon of scaling of halite at the cavern wall is negligible which allows the use of this giant salt cavern for CCS storage in an abandonment pressure of ~45 MPa.

Another criterion that must be analyzed is the state of stresses of the cavern after abandonment. The cavern must always keep a reaction against the internal pressure through a closing tendency, always creating a compressive stress distribution in its surroundings, preventing the formation of micro-cracks or micro-fractures that may permeate gases to another formation or even to surface. Fig. 22 shows the isosurface of the first invariant of stresses $\{\sigma m = (\sigma 1 + \sigma 2 + \sigma 3)/3\}$ at t = 450 weeks, 7 weeks before the Xtree is closed. Close to the perimeter of the cavern the first invariant of stresses is ~52.5 MPa. The average internal pressure in the gas is 45.2 MPa, which is 20 % smaller than the first invariant of stresses at the perimeter of the cavern.

In the salt deposits of the Sergipe Basin, whose genesis of geological formation is the same as that of the Santos Basin, initial stress measurements were carried out "in-situ", using the hydraulic fracturing technique, (Poiate, 2012), verifying that the gradient of salt fracture varies from 1.20 to 1.7 times the overburden gradient. The minimum value obtained for the fracture gradient is used, with a good safety margin, as a safety factor for the maximum gas pressure inside the cavern. The evolution with time of the pressure of the gas inside the cavern is presented in Fig. 23. Due to the small bulk modulus of the gas, the increment of the pressure induced by the gas squeezing locked inside the cavern, by the creep closure deformation of the salt cavern is small. Fig. 24 shows the isosurface after 30 years. The pressure inside the cavern is ~ 45 MPa and in the boundary of the cavern wall ~52 MPa, at the bottom of the cavern. The cavern is protected by a compressive state of stresses eliminating the possibility of gas leakage over time.

During gas injection and abandonment, the cavern must be monitored using pressure and temperature gages. Is recommended to use the conventional PDG´s (Permanent Downhole Gage), adopted by the oil and gas industry (Table 5-item 17→TRL = 7). Based on the simulation results it is possible to locate the PDG´s inside the cavern. The PDG´s will be installed in the 7 5/8″ (2.15 m) casing as illustrated in Fig. 25.

To calculate the volume of gas that is possible to be confined inside the cavern is necessary to have the expansion coefficient of the gas with different grades of CO_2 for several state variables (temperature and pressure). For the state variables pressure of ~45 MPa and temperature 42 °C it is shown in Fig. 26 the estimation of the coefficient (Table 7, item 15 → TRL = 6). The curve was originally obtained for a gas with 90 % of CO_2 and temperature of 44 °C but is still a good approximation

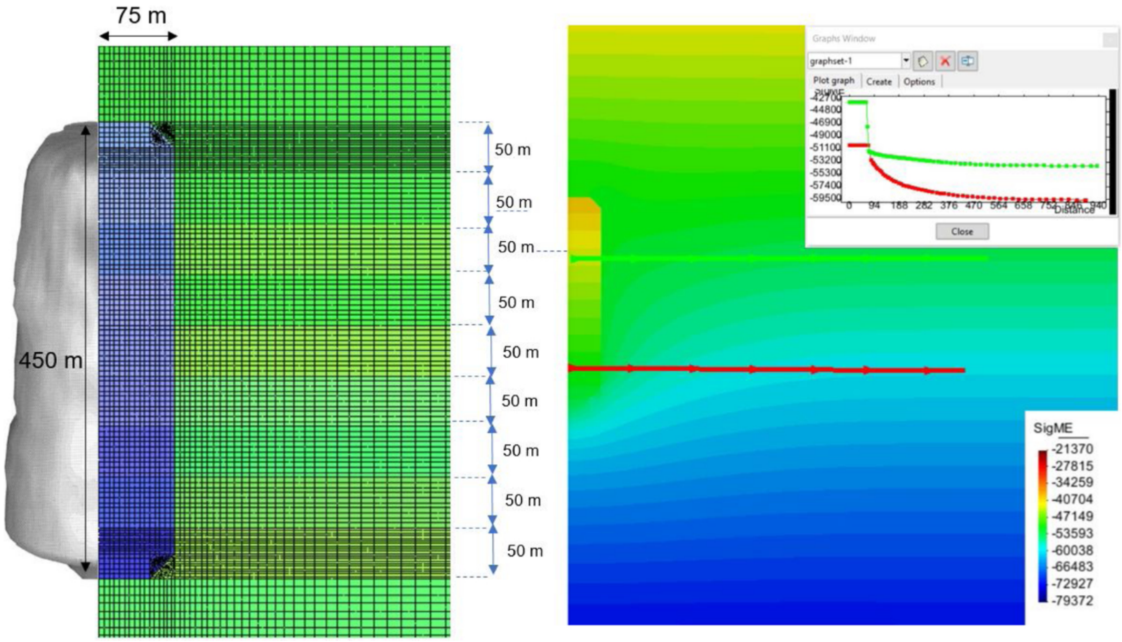


Fig. 24. Isosurface of the first invariant of stresses at t = 30 years.

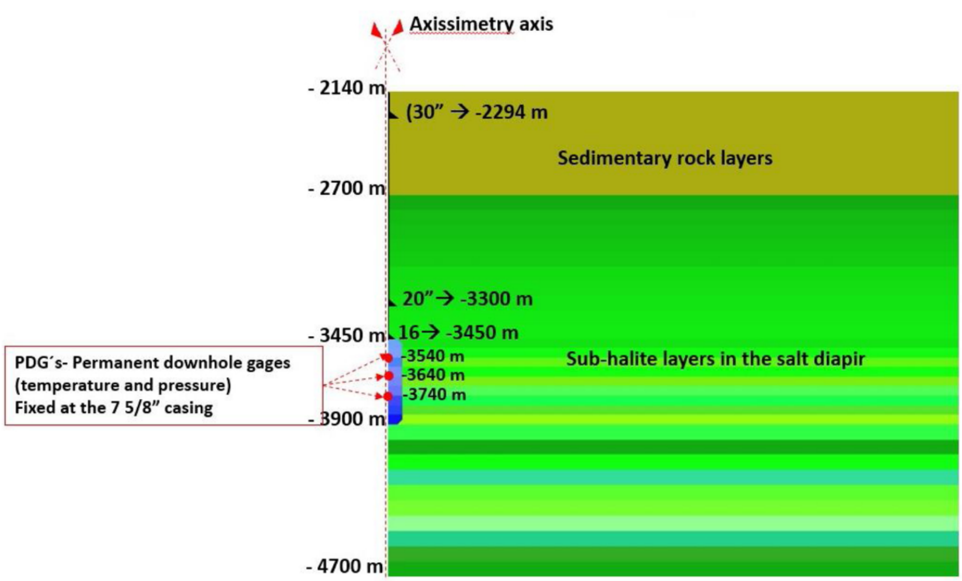


Fig. 25. Proposed location for the installation of the PDG´s inside the cavern.

until the laboratory tests under execution at the state university of São Paulo are concluded.

With the interpolation of the expansion curve and using the gas pressure inside the cavern is possible to calculate the CCS volume of the cavern, Fig. 27.

5. Conclusions

In the research carried out no offshore operations of natural gas or other hydrocarbons storage in salt caverns were identified, in shallow water or deep water. The TRL for the overall design of a salt cavern for natural gas storage with CO_2 is equal to 2 (Table 5-item 9→TRL 2).

Well is the critical element of an underground storage system of natural gas in salt caverns, being responsible for accidents and complications related to gas leaks. In the construction of the wells the weak link of the process is the quality of the cement, whose chemical formulation and method of execution lead to the success or loss of the storage system (Table 4-item 6→TRL = 3).

There are no operations of CO_2 confinement in salt caverns. There are only studies about the CO_2 interaction with salt rock, determination of CO2 thermodynamic state variables, CO_2 phase diagrams, compressibility Isothermal curves, and geomechanical analysis of CO_2 storage in salt caverns. Besides the Salt rock is always considered to be the best geomaterial for the storage of hydrocarbons and CCS, the use for storage of CO_2 has not yet taken off according to the ratio between the volume of CO_2 emission and the maximum volume of storage normally practiced with natural gas (Table 5-item 14→TRL = 2).

Dimensions of the pilot giant cavern certified by the geomechanical TRA (Table 5-item 21→TRL = 7):

- 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;

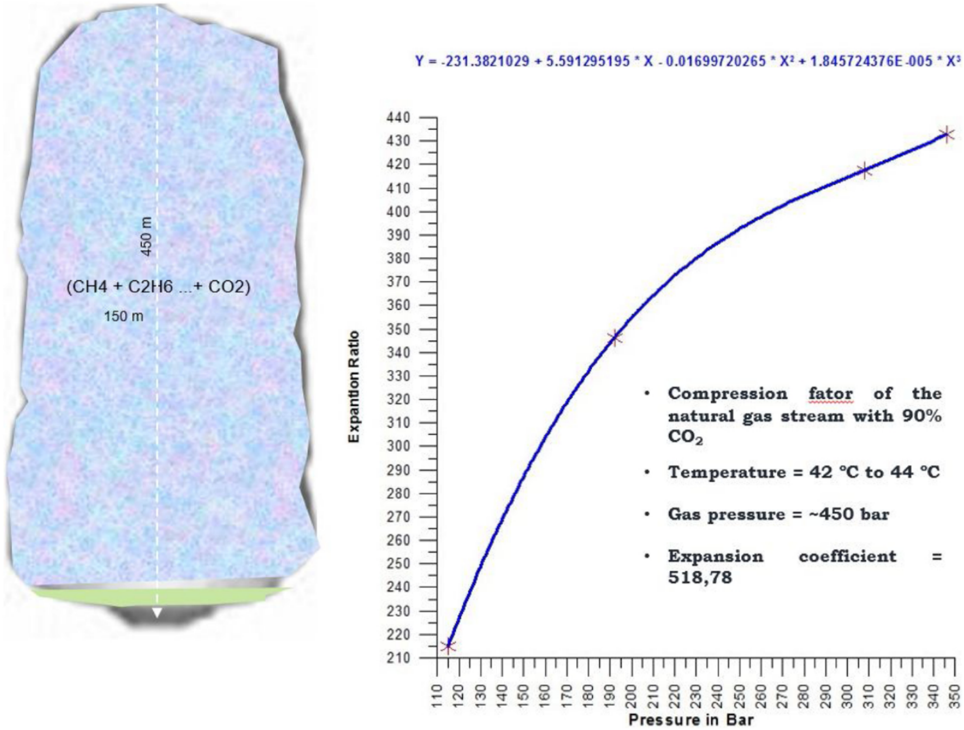


Fig. 26. Expansion coefficient of gas stream with 90 % of CO_2 at the temperature of 44 °C and gas pressure of 450 bar = 45 MPa (P.V.M. Costa et al., 2014; A.M. Costa et al., 2014).

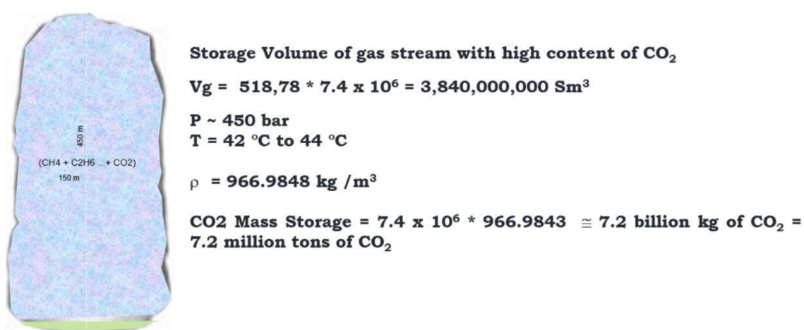


Fig. 27. Volume of CCS inside the cavern 450 m by 150 m (450 bar = 45 MPa).

- 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;
- Storage volume of gas stream with high content of CO_2 in one cavern: 3,840,000,000 Sm^3;
- Maximum Gas pressure expected after abandonment: 465 bar = 46.5 MPa.

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, 5 times the diameter of one cavern, the salt dome can accommodate the construction of 15 caverns, thus providing the confinement of approximately 108 million tons of CO_2.

In the projects of researched hydrocarbon storage systems, "Taylor Made" simulators are used for application in Geomechanics projects. The Geomechanical project of the offshore caverns is conducted with computer simulation support, adopting the family of simulators (COVES), developed by (A.M. Costa, 1984), with over 40 years of successful applications in hundreds of excavation projects and drilling wells in salt rock (A.M. Costa et al., 2020; P.V.M. Costa et al., 2020a,b,c; A.M. Costa et al., 2019a,b,c; P.V.M. Costa et al., 2019; A.M. Costa et al., 2018a,b,c; P.V.M. Costa, 2018; P.V.M. Costa et al., 2017; P.V.M. Costa et al., 2015; A.M. Costa et al., 2015; P.V.M. Costa et al., 2014; A.M. Costa et al., 2014; A.M. Costa, 1999, 1997, 1995; A.M. Costa and de Melo, 1992) (Table 5- items 19, 20 and 21 → TRL = 7).

The application of the Technology Readiness Assessment method allowed to identify the most critical items that are necessary to a real implementation of confinement and separation of large volume of CO2 from natural gas in ultradeep offshore salt caverns. It is crucial to large-scale high innovative projects as presented here. Based on the found TRLs, the authors recommend initially to build an experimental cavern in the site to obtain safe parameters for the future real cavern.

CRediT authorship contribution statement

Mariana Barbero Ribeiro Goulart: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - original draft, Visualization, Supervision. **Pedro Vassalo Maia da Costa:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - original draft, Visualization, Supervision. **Alvaro Maia da Costa:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision. **Antonio C.O. Miranda:** Validation, Writing - review & editing. **Andre Bergsten Mendes:** Validation, Supervision. **Nelson F.F. Ebecken:** Validation, Supervision. **Julio R. Meneghini:** Validation, Supervision, Project administration. **Kazuo Nishimoto:** Validation, Supervision, Project administration. **Gustavo R.S. Assi:** Validation, Supervision, Project administration.

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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