## Underground storage of natural gas and CO<sub>2</sub> in salt caverns in deep and ultra-deep water offshore Brazil

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**ABSTRACT:** With the application of new technologies for processing and interpreting seismic data, PETROBRAS, in recent years, has achieved great success in the discovery of giant oil fields underlying thick layers of rock salt. Due to the mechanical behavior of these rocks, subject to the creep phenomenon, it was developed a large research and development project in order to determine the creep properties of these rocks and the application of computational simulations to predict the behavior of deep wells during the drilling of these layers. If on one hand the salt layers, with thicknesses ranging from 2000 m to 5000 m, are a challenge in drilling activity, they can be considered in the logistic flow of gas and final destination of  $CO_2$ . The rock salt has negligible porosity when compared to other geomaterials, which guarantees excellent impermeability to most fluids and gases, even under high pressures. Another phenomenon associated with rock salt is the process of self-healing. Taking advantage of these physical-chemical and structural properties of rock salt, caverns opened by dissolution in salt domes have been used for storage of hydrocarbons and other products. Considering the large regional thicknesses and continuity of rock salt overlying the presalt reservoirs, PETROBRAS is studying the strategy and technical and economic feasibility for the use of underground storage of natural gas and  $CO_2$  in salt caverns. Despite being a technology already dominated worldwide is unprecedented, the offshore application in deep and ultra-deep water.

### Subject: Underground storage

Keywords: rock caverns, mine design, numerical modeling, stability analysis, oil reservoir

## 1 INTRODUCTION

The rock salt has negligible porosity when compared to other geomaterials, which ensures excellent sealing to most fluids and gases, even under high pressures. Rock salt is also subject to the phenomenon of visco-plastic creep deformation which develops in the time domain the relaxation of the deviatoric or shear stresses, to the condition of a steady-state equilibrium with constant creep strain rate and can tolerate high levels of strain without develop structural damage of its mineral skeleton.

This phenomenon can be observed in nature in the sedimentary layers intercepted by salt domes or other structures associated with the natural movement of salt. Another phenomenon associated with the salt rock is the process of self-healing, where cracks and faults are self-healed with time. Taking advantage of these physical-chemical and structural properties of rock salt, caverns developed by solution mining in salt domes have been used for storage of hydrocarbons and other products. Conventional underground salt mines are also used for final destination of radioactive material (nuclear waste).

Currently there are about 1600 caverns opened by solution mining in North America for this purpose and in approximately equal number in Europe. Among them the most important hydrocarbon underground storage is the "Strategic Petroleum Reserve, the largest strategic petroleum reserve in the world in the Gulf of Mexico, United States, where is stored 727 million barrels of crude oil in 60 caves open by solution mining, 600 m high and 60 m in diameter. Currently this project is being expanded to 1 billion barrels of oil.

Considering the great regional thickness and continuity of rock salt in the Santos Basin oil province in Brazil it is under study the strategy and technical and economical feasibility evaluation for the use of underground offshore caverns opened by solution mining, Figure 1.

The Santos Basin, offshore southeast Brazil, is one of the Brazilian basins that is receiving considerable industry attention nowadays, with the discovery of the giant oil fields known as Pre-Salt reservoirs.

The Pre-Salt reservoirs in Santos basin are located in water depth varying from 150 m up to 2200 m. To reach the Pre-Salt reservoirs located in deep water it is necessary to drill through 2000 m of salt rock, mainly halite, and in some places, tachyhydrite (CaCl<sub>2</sub>·2MgCl<sub>2</sub>·12H<sub>2</sub>O), and carnallite (KCl·MgCl<sub>2</sub>·6H<sub>2</sub>O) intercalations are found.

Despite being a technology already dominated worldwide is unprecedented its offshore application in deepwater and ultra-deep waters.



Figure 1. Offshore salt caverns opened by solution mining.

For storage of CH<sub>4</sub> (natural gas) production from the Santos Basin there are two strategies:

- Storage of Associated Natural Gas in order to ensure the production of oil.
- Storage of Natural Gas to meet the optimum relationship between production and demand.

In the case of  $CO_2$  the storage is considered as a possible CCS project.

## **2 CONSTITUTIVE EQUATION FOR SALT BEHAVIOR**

Due to its crystalline structure, salt rocks exhibit timedependent behavior when subjected to shear stress. The creep strain rate is influenced by the formation temperature, mineralogical composition, water content, presence of impurities, and the extent to which differential stresses are applied to the salt body. Chloride and sulphate salts containing water (bischofite, carnallite, kieserite and tachyhydrite) are the most mobile. Halite is relatively slow-moving, and anhydrite and the carbonates (calcite, dolomite) are essentially immobile (Costa et al. 2010).

Early in the 1990's, creep constitutive laws based on deformation mechanisms, have been recommended by the international technical literature, to represent the intrinsic behavior of the evaporates (Munson et al. 1990).

The law that incorporates the deformation mechanisms for the evaporite rocks was developed by Munson et al. 1990 (Munson & Devries 1991). The constitutive equation based on Munson's creep law considers the following mechanisms: Dislocation Glide, Dislocation Climb and Undefined Mechanism. The largest contribution of either mechanism depends on the temperature conditions and differential stress to which the salt is submitted.

The constitutive equation corresponding to the creep law of double deformation mechanism is a simplification of the equation developed by Munson, and it considers the creep mechanisms Dislocation Glide and Undefined Mechanism.

The latter effect was recently identified as being creep in the contacts of the salt grains, provoked by the dissolution of the salt in function of the increase of its solubility under the high pressures that happen in the contacts among grains.



Figure 2. Final assembling of the testing apparatus and Hydraulic control system.

In this paper, halite is analyzed according to the elasto/visco-elastic behavior, adopting the Double Mechanism creep law, as shown in Equation 1:

$$\boldsymbol{\epsilon} = \boldsymbol{\epsilon}_{0} \cdot \left( \frac{\boldsymbol{\sigma}_{ef}}{\boldsymbol{\sigma}_{0}} \right)^{n} \cdot e^{\left( \frac{\boldsymbol{Q}}{\boldsymbol{R}\boldsymbol{T}_{0}} - \frac{\boldsymbol{Q}}{\boldsymbol{R}\boldsymbol{T}} \right)} \tag{1}$$

where  $\varepsilon = \text{strain}$  rate due to creep at the steady state condition;  $\varepsilon_0 = \text{reference}$  strain rate due to creep (in steady state);  $\varepsilon_{\text{ef}} = \text{creep}$  effective stress;  $\sigma_0 = \text{reference}$  effective stress; Q = activation energy (kcal/mol), Q = 12 kcal/mol (Costa et al. 1991); R = Universal gas constant (kcal/mol.K), R = 1.9858E-03; T<sub>0</sub> = reference temperature (K); and T = rock temperature (K).

## 2.1 Determination of the rock salt mechanical properties

The elastic constants, Young Modulus and Poisson ratio were obtained by measurements of compressional and shear velocity in the potash mine through the application of direct reflection seismic (Costa 1984) on the floor and on the pillar faces in the mine. These constants have been used for decades to design the room and pillar structures of the mine. The Dynamic Young Modulus can be obtained by using the elasticity theory, applying the Dynamic Poisson's Ratio of 0.36, which value has been used in several works related with the mechanical behavior of the salt in the potash mine of Taquari-Vassouras – Northeast of Brazil, determined, and presented in the international technical literature.

The creep tests were performed in specimens with a length/diameter ratio of 2 (ISRM Standards) in a Laboratory of Rock Mechanics and Rock Hydraulics from IPT – Institute for Technological Research of the State of São Paulo – Brazil (Costa et al. 2005).

### 2.2 Experimental Assembly

A laboratory with six independent creep test stations was built in IPT (Costa et al. 2005). Each station uses an automatic servo control system, keeping the confining pressure and the axial pressure constant during the test. Figure 2 illustrates one of the creep test stations in the IPT lab.

It is shown in Figure 3 a typical salt rock creep behavior. In these tests, tachyhydrite, carnallite and halite are submitted to a 10 MPa differential stress and 86°C temperature. With these test parameters, tachyhydrite creeps approximately 107 times



Figure 3. Salts creep test, 86°C,  $\Delta \sigma = 10$  MPa.



Figure 4. Steady-state creep strain rate  $\times$  differential stress for halite (Temperature 86°C).

faster than halite and 2.7 times faster than carnallite (Costa et al. 2005).

The double mechanism constitutive creep Equation 1 represents only the steady-state creep stage. The transient creep, for the conditions normally found in mining and oil well drilling, is fully dissipated in a short period of time and can be absorbed by the initial deformation predicted by the numerical models. To obtain the constants  $\varepsilon_0$ ,  $\sigma_0$  and n, it is necessary to establish the relation between the steady-state creep strain rate and the differential stress applied to the specimen for a specific temperature.

It is shown in Figure 4 the steady-state creep strain rate for different differential stresses, ranging from 6–20 MPa, in di-log scale.

From the interpolation, in di-log scale, the values of  $\sigma_0$  and  $\varepsilon_0$  can be determined for the test temperature, 86°C:

 $(X;Y) = (9.91; 1.880E - 06) = (\sigma_0; \varepsilon_0) \rightarrow \sigma_0 = 9.91 \cong 10 \text{ MPa}.$ 



Figure 5. (a) Experimental panel D1 and (b) Finite element model of experimental room C1D1.

Therefore, the Constitutive Equation becomes:

 $\varepsilon = 1.880E - 06 (\sigma_{ef}/10)^n$ , in which:  $n = 3.36 \rightarrow \sigma_{ef} < \sigma_0$  and  $n = 7.55 \rightarrow \sigma_{ef} \ge \sigma_0$ .

The same procedure is used for carnallite and tachyhydrite to obtain the creep parameters.

# 2.3 Validation of the creep parameters and computer codes developed by Costa (1984)

As part of the rock mechanics studies, used to enable the mining of the lower sylvinite layer in the potash mine, an experimental panel, "D1" (Costa 1984) was designed and excavated in the lower sylvinite layer, overlying a layer of tachyhydrite 15 m thick. An experimental room, "C1D1", was excavated in this panel isolated from the effects of nearby excavations, with intensive use of field instrumentation, for back-analysis, allowing the calibration of the creep parameters. Figure 5 shows the layout of the mine and the location of the experimental panel D1 and the finite element model used in the simulations.

The experimental room C1D1 was designed and excavated with length of 95 m, divided in three sections. In each section a slab protection was left, with three different thickness, 3 m, 2 m and 1 m. The strategy is to evaluate the influence of the slab protection thickness of sylvinite in inhibiting the floor heave due to the creep of tachyhydrite. Among the various instruments installed in the room, this paper shows the comparison between the vertical closure measurements with those obtained by the numerical simulation.

The SIGMA (Poiate Jr et al. 2006) system is used for pre and post processing of the finite element model. The numerical simulations have been done through application of the finite element code ANVEC (Costa 1984). The ANVEC program is extensively applied in the behavior simulation of the underground excavations (Costa et al. 1991), considers the non-linear physical elasto/visco-elastic phenomenon, with constitutive law of double mechanism of deformation by creep. The program has shown excellent stability and convergence to predict the creep phenomenon in conditions of high temperature levels and high differential stresses and the procedure of simulating the behavior of the well with time as a function of the bit progress, through the technique of



Figure 6. Comparison between closure measurements and numerical simulation, sylvinite slap protection 2.5 m thick.

automatic mesh rezoning. This constituted in a differential advantage of the program providing valuable inputs for the drilling operation (Costa et al. 2010).

Figures 6 shows the comparison between the closure measured in the experimental gallery in different locations along its axis for different thickness of the sylvinite slab protection. Each plot shows the closure predicted by numerical simulation with and without the initial deformation after excavation, which normally is lost in the field. In these numerical models it is used the creep parameters obtained in the laboratory creep tests.

The constitutive creep equation and creep parameters were also validated by comparison with closure measurements by caliper in an experimental directional well drilled in an oil field in the same evaporitic basin of the potash reserve in the state of Sergipe. Again very good fit was obtained between both results, numerical and caliper measurements.

## 3 LOCATION SELECTION OF THE OFFSHORE SALT CAVERNS

In the process of selecting potential areas for the development of salt caverns by solution mining salt domes were 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. 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 it was selected a cluster of salt domes 10 km away from one of



Figure 7. Isopaque maps of the salt domes and vertical position of the salt caverns.



Figure 8. Offshore Salt caverns developed by two wells.

the major presalt oil fields in Santos Basin. Figure 7 shows the isopaque map of the salt domes and the vertical position of the caverns in relation to the top of the salt dome selected.

## 4 SOLUTION MINING PROCESS OF THE SALT CAVERNS

The development of the salt caverns by solution mining follows a well know worldwide methodology. In the case of the offshore salt caverns to be developed in Santos Basin it is planned to use sea water in the dissolution process. The sea water will be collected from a submerged pump installed closed to the well (Raw Water Injection).

Two methods can be used. In the first one the injection of the sea water and the returned of the brine will be done through the same well. In the second one two wells are used. One well will be used for injection of the sea water and the second will be used for the return of the brine. Using the method with two wells it is possible to increase the rate of injection and having a much faster development of the salt caverns.

Figure 8 shows a salt cavern developed by the second method. Completed the development of the caverns begins the process of the replacement of brine by  $CH_4$  at high pressures. The limits of pressure to be used for injection of  $CH_4$  are calculated based on the geomechanical and structural studies to ensure the stability of the caverns.

# 5 GEOMECHANICAL PROJECT OF THE SALT CAVERNS

Due to the large volume of salt dome selected, the distance between the caverns was calculated in order to eliminate the



Figure 9. Lithologic section used as the geomechanical model of simulation.

group effect. 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.

The evaluation of the structural behavior of the salt caverns is conducted by applying the finite element method by simulations in the time domain using the computer code ANVEC developed by Costa (1984).

On the geological section, resulting from the interpretation of 3D seismic data, is generated the axisymmetric structural model, which represents the three-dimensional behavior of an isolated cavern. For discretization of the rock mass by finite elements is used a total of 13,812 isoparametric quadratic 8 nodes elements and 42,017 nodal points. Figure 9 shows the lithologic section used as the structural geomechanical model and Figure 10 shows the finite element mesh used in the simulation.

### 5.1 Simulation premises

In the evaluation of the salt caverns stability are adopted some assumptions based on the experience of the authors, Costa (1984):

- Maximum Pressure of CH<sub>4</sub> ranged from 80% to 90% of the effective initial stress at the top of the cavern (Pmax);
- Minimum Pressure of CH<sub>4</sub> ranged from 30% to 50% of the initial effective stress at the top of the cavern (Pmin);
- Range of Natural Gas pressure inside the cavern: [50%  $\sigma_0 = 19,227.50 \text{ kPa} \le P \le [34,609.50 \text{ kPa} = 90\% \sigma_0];$
- Slab protection at the top of the cavern = 200 m;
- Minimum distance between caverns to avoid interference -5 diameters between axis;
- Temperature of the sea bed =  $4^{\circ}$ C;
- Geothermal gradient in sedimentary rock =  $30^{\circ}$ C/1000 m;
- Geothermal gradient in rock salt =  $12^{\circ}C/1000$  m;
- Geographical dimensions of caves:
- Cavern sizing: The size and shape characteristics of the caverns have been defined with the aim of having the largest volume of gas CH<sub>4</sub> for maximizing the safety.



Figure 10. Finite element mesh.

Table 1. Compression rate of natural gas inside the caverns.

	CH <sub>4</sub> -100%	CH <sub>4</sub> -100%	CH <sub>4</sub> -100%	CH <sub>4</sub> -100%
P (kgf/cm <sup>2</sup> )	115	192	308	346
T (oC)	44	44	44	44
Razão (Sm <sup>3</sup> /m <sup>3</sup> )	112,9	188,8	278,2	301,1

For estimating the geometric volume of the caverns 300 meters high and 100 meters in diameter it is considered a geometric shape approximated by an vertical ellipsoid of revolution, Figure 9. The total geometric volume of the cavern is 1,963,495 m<sup>3</sup>. Compression rate of natural gas inside the caverns for the maximum and minimum pressure is shown in Table 1.

- Volume of natural gas at the maximum pressure:  $301.1 \times 1,963,495 = 591,208,344.5 \text{ m}^3$ .
- Volume of natural gas at the minimum pressure:  $188.8 \times 1,963,495 = 370,707,856.0 \text{ m}^3$ .
- Net volume of natural gas: 591,208,344.5 370,707,856 = 220,500,488.5 m<sup>3</sup>.

### 5.2 Simulation results

Considering the cavern to operate as a contingency for gas storage, to ensure the production of oil in the event of stopping the flow of gas, it must be kept in most of the time at minimum pressure. It is considered one contingency per year, with pressure going from the minimum value for the maximum value in a period of 30 days during filling and 30 days from the maximum to the minimum during discharge. The cavern will be at the minimum pressure for a period of 300 days per year. Figure 11 shows the evolution with time of the vertical and horizontal displacements of the cavern wall at the minimum pressure in 30 years of operation.

Figure 12 shows the evolution with time of the effective stress in the wall of the cavern in 30 years of operation at the minimum pressure.



Figure 11. Evolution of cavern closure with time at the minimum pressure.



Figure 12. Effective stress distribution in t = 30 years-Internal pressure =  $50\% \sigma_0$ .



Figure 13. Effective creep strain distribution in t = 30 years, at the minimum pressure.



Figure 14. Caverns pattern in the salt dome.

Figure 13 shows the effective creep strain at the wall of the cavern after 30 years of operation at the minimum pressure.

Finally, Figure 14 shows the caverns pattern that is possible to be built in the salt dome chosen.

## 6 CONCLUSIONS

Based on these results the caverns will be stable in 30 years of operation at the minimum pressure of 50% of the initial stress at the top of the caverns.

Considering 12 caverns in the salt dome it is possible to store a net volume of natural gas of 2.7 billion m<sup>3</sup> at the minimum pressure of 19,227 kPa.

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