PROJECT 34 – CCS IN OFFSHORE SALT CAVERNS

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Research Centre for Gas Innovation
cleaner energy for a sustainable future

Workshop – RCGI - CO2 Abatement Program
University of São Paulo, Brazil
21-22 August 2018
Introduction

- CO₂ found pre-salt reservoirs - Earth’s mantle origin, migrating to pre-salt reservoirs through geological faults;
- **Today** ⇒ Disposal of gas with high content of CO₂ in the reservoirs (EOR);
  - Continuous increase of CO₂ content levels and RGO inside the reservoir
  ⇒ Potential closure of production wells over time;

- Technological solution under study – **Offshore Salt Cavern Carbon Capture and Storage (CCS)** solution
  - Other technological solutions – Not for large volumes of produced gas;
  - Saline aquifers characteristics in pre-salt region – Suggest unfeasibility;

- Mature technology – Salt underground caverns;

- Premises
  - Salt caverns for storage of gas with high content of CO₂;
  - Gas stream from existing FPSO;
  - Maximize existing FPSO infrastructure (plant, lines, pumps, compressors, umbilical, power);
  - Maximize disposal volume, keeping high safety standards;
Project planning – Activities

State of Art
Strategic Developments Salt Cavern CCS (Carbon Capture and Storage) Project

Parametric Evaluation Cavern Basic Design High CO2 content

Experimental/ Pilot Cavern Full Scale Basic Design High CO2 Content

D1-D2 Decision Gate – Shell Executive Decision
Shell future investments
6 to 9 months

Basic Design Report 2/28/2019

7/31/2018

SHELL FPSO SCENARIO

Field profile:
- Field profile;
- Cavern operation;
- Cavern construction;
- Subsea operation;
- Well design;
- Subsea design;
- Topside profile;

Subsea design:
- Water depth: 2140 m
- FPSO distance: 7 km
- Umbilical (catenary): Presalt pattern
- Xtree: Presalt pattern
- BOP: No
- Wellhead: Presalt pattern
- Riser (4" e 6") (LW): Presalt pattern
- Flowline rigid / flexible (4" e 6") : Presalt pattern
- Pump injection flowrate: 300 a 400 m3/h
- Injection pump ΔP: 78 a 110 bar

Field profile:
- FPSO capacity: 150000 bbl/d
- Average RGO (Gas to oil ratio): 220
- Average % CO2: 20
- Water Depth: 2140 m
- Injection gas composition (%CO2): 90%
- Gas discharge flow rate (FPSO’s plant): 1,500 MM/d
- Gas discharge temperature (FPSO’s plant): 40°C
- Gas discharge pressure (FPSO’s plant): 250 bar
- Pressão de injeção d’água (FPSO’s plant): 250 bar
- Temperatura Injeção de água (FPSO’s plant): 60°C
- Water injection pressure (FPSO’s plant): 550 bar
- Water injection temperature (FPSO’s plant): 61°C
- Reservoir pressure: 550 bar
- Reservoir temperature: 61°C
- Reservoir fluid composition
- Power FPSO plant: 100 MW (25 spare)
Project planning – Activities

- Geomechanical well design
- Leaching (Brine) simulation process
- Geomechanical structural cavern design
- Flow and Process Engineering
- Subsea & Marine Engineering
- Health, Safety, Environment (HSE)
- Legal and regulation analysis
- Logistics
- Risk Analysis & Diagnosis
- Fluidmechanical CFD (Support)

- Well design, leaching procedure and cavern design – **Well advanced**;
- Plant processing systems, equipments, risers, flowlines, umbilicals – **Under development** Participation manufacturers;
- Definition subsea production layout & FPSO
- Environmental license issues and aspects;
- Survey with sector stakeholders & Competent authority of licensing;
- Technical meetings - IBAMA, RCGI and SHELL – Joint identification and evaluation, criteria for environmental licensing experimental salt cavern;
- Regulation/supervision for licensing (assisted operation alternative);
Project planning – Activities

Assumptions

- **Cavern Construction**
  - Pure halite;
  - Discarding brine at sea;
  - No geological faults;
  - Olefins injected by the FPSO via ring line (diesel flush)

- **Subsea**
  - Same Xtree for both construction and operation;
  - Installations/facilities, vessels and standard pre-salt procedures;
  - Presumed space riser balcony for installation lines;
  - Power available FPSO for submerged pump/equipments;

- **Topsides**
  - Olefins injected using the chemical injection system (diesel flush system);

- **Cavern Operation**
  - Natural gas at 90% CO2;
  - PDG installed in downhole water injection pipe (P and T);

- **HSE / Risks / Legislation**
  - No restrictions on the disposal of brine subsea;
  - Qualitative risk matrix used by Shell EIA RIMA of the field of Lula as reference;

- **Logistics**
  - Drilling ship at disposal for construction of caverns;

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### Parametric Design

- **Flow Rate**
  - $Q_1 \text{ m}^3/\text{h}$
  - $Q_2 \text{ m}^3/\text{h}$
  - $Q_3 \text{ m}^3/\text{h}$

- **Well Entrance**
  - $T_1 ^\circ \text{C}$
  - $T_2 ^\circ \text{C}$
  - $T_3 ^\circ \text{C}$

- **Well Diameter**
  - $D_1$
  - $D_2$

- **Cavern Height**
  - $H_1 \text{ m}$
  - $H_2 \text{ m}$
  - $H_3 \text{ m}$
  - $H_4 \text{ m}$

- **Height difference between well pipes**
  - $hT_1 \text{ m}$
  - $hT_2 \text{ m}$
## Project planning – Activities

### Schedule

<table>
<thead>
<tr>
<th>PLANNED ACTIVITIES</th>
<th>Dependency (Y/N)</th>
<th>Activity Number</th>
<th>Type of dependency</th>
<th>Month</th>
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<tbody>
<tr>
<td>1. State of the Art Report Elaboration</td>
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<td>2. Solution mining process simulation</td>
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<td>2.1 - Dissolution factor experimental analysis</td>
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<td>2.2 - Parametric analysis for selected cases</td>
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<td>2.3 - Pipe wipe problem</td>
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<td>3. Fluidmechanical project of pilot cavern - CFD</td>
<td>Y 2 Finish-Finish</td>
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<td>3.1 Physical Modeling - Evaluation define pattern interface during Gas / Brine substitution process</td>
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<td>3.2 Brine substitution</td>
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<td>3.2.1 Geometry, grid modeling/analysis &amp; convergence</td>
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<td>3.2.2 Simulations &amp; Analysis</td>
<td>Y 4.1.1 Finish-Start</td>
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<td>3.2.3 Load functions of internal pressures inside the caverns</td>
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<td>3.3 Gas filing analyses (High content CO2)</td>
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<td>3.3.1 Alienation numerical grid model, convergence</td>
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<td>3.3.2 Simulations &amp; Analysis</td>
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<td>3.3.3 Load functions of internal pressures inside the caverns</td>
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<td>4. Flow and Process Engineering</td>
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<td>4.1 Flow assessment - Based on models available in publications/references + Experimental test</td>
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<tr>
<td>4.1.1 Flow assessment - Substitution phase - Gas / CO2 rich stream / Brine</td>
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<td>4.1.2 Flow assessment - Salt cavern final filling process - Gas / CO2 rich stream</td>
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<td>4.2 Assessment of solubility of CO2 rich stream in brine</td>
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<td>4.3 Conception subsea raw sea water injection system</td>
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<td>5. Subsea &amp; Marine Engineering</td>
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<td>5.1 Graphical and electronic model development</td>
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<td>5.1.1 3D graphical representation of the salt cavern construction</td>
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<td>5.1.2 Subsea arrangement for construction and operation of salt caverns</td>
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<td>5.2 Data collection</td>
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<td>5.2.1 Riser</td>
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<td>5.2.2 Flowline</td>
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<td>5.2.3 Umbilicals</td>
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<td>5.2.4 Xtree</td>
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<td>5.2.5 Mudline water injection pump</td>
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<td>5.3 Monitoring - cavern construction/operational process/abandonment</td>
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<td>6. Logistics</td>
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<td>6.1 Salt cavern project scheduling</td>
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<td>6.1.1 Problem definition (Well construction, solution mining, subsea arrangement, gas separation and confinement)</td>
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<td>6.1.2 Process description &amp; mapping, including resources, materials and duration</td>
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<td>6.1.3 Project modelling (precedence diagram, network representation) &amp; Model implementation</td>
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<td>6.4 Computational experiments</td>
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<td>6.5 Landscape screening</td>
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<td>7. Health, Safety, Environment (HSE) and Legislation</td>
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<td>7.1 Team engagement/interviews and learnings</td>
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<td>7.1.1 External stakeholder engagement strategy definition and kick-off</td>
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<td>7.2 Scoping</td>
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<td>7.2.1 Environmental study requirements for licensing</td>
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<td>7.2.2 Legal requirements for licensing</td>
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<td>8. Risk Analysis &amp; Diagnosis</td>
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<td>8.1 Cavern Construction APRI</td>
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<td>8.2 Well design APRI</td>
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<td>8.3 Subsea Design APRI</td>
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<td>8.4 Topside APRI</td>
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<td>8.5 Cavern Operation APRI</td>
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<td>8.6 Subsea Operation APRI</td>
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<td>8.7 HSE/Legislation/Assumption APRI</td>
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<td>8.8 Logistics APRI</td>
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<td>9. Phase wrap-up workshop</td>
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**RESEARCH CENTRE FOR GAS INNOVATION**
Cavern design

- First project cycle studies
  - Basic geomechanical design of an experimental cavern;
    - Obtain parameters to be used definitive design salt caverns with central CO$_2$ disposal station;
    - Dissolution / mining process
  - Monitoring plan, to be applied in the construction, operation and abandonment phases of the caverns;
  - Basic geomechanical design of a giant cavern for assessing the technical feasibility of storing large volumes of CO$_2$;

- Parametric study of caverns with different sizes;
1. Topology data of the experimental cavern certified in the design:
   - Thickness of the safety halite slab protection: 1144 m;
   - Depth of the top of cavern: -3850 m;
   - Depth of the bottom of the cavern: -3898 m;
   - Diameter at the top: 14 m;
   - Diameter at the bottom: 20 m;
   - Height: 48 m;

2. Volume of the experimental cavern obtained by simulation: 11.000 m$^3$;
3. Volume of gas confined inside the cavern: 4.048.000 m$^3$;
4. Maximum Gas pressure expected after 2 years of abandonment: 52.460 kPa;
   Observation: The cavern develops very small deformation, so the squeeze of the gas by the closure of the salt rock is negligible;
5. Maximum gas pressure expected after 30 years of abandonment: 52.650 kPa;
Cavern design – leaching process

Evolution of the solution mining process

Schematic illustration of the brine/seawater flow inside the cavern

Dissolution profile of the experimental cavern

Daily salt production in tons

Daily salt dissolved in tons

Salt production in tons

Salt dissolved in tons

Time in days

Time in days
Experimental salt cavern – Monitoring

Monitoring of the gas pressure inside the cavern

Conventional permanent downhole gauge (PDG), of the oil industry, to measure pressure and temperature.

- Gas pressure
- Counter pressure exerted by the salt rock

CH₄ + C₂H₆ + ... + CO₂

Brine

Synthetic fluid blanket

Evolution with time of the gas pressure inside the cavern

GAS PRESSURE IN KPa

1000 1500 2000 2500 3000 3500 4000 4500 5000 5500

5700 5650 5600 5550 5500 5450 5400 5350 5300 5250

5200 5150 5100 5050 5000 4950 4900 4850 4800 4750

4700 4650 4600 4550 4500 4450 4400 4350 4300 4250

4200 4150 4100 4050 4000 3950 3900 3850 3800 3750

3700 3650 3600 3550 3500 3450 3400 3350 3300 3250

3200 3150 3100 3050 3000 2950 2900 2850 2800 2750

2700 2650 2600 2550 2500 2450 2400 2350 2300 2250

2200 2150 2100 2050 2000 1950 1900 1850 1800 1750

1700 1650 1600 1550 1500 1450 1400 1350 1300 1250

1200 1150 1100 1050 1000 950 900 850 800 750

1000 1500 2000 2500 3000 3500 4000 4500 5000 5500

time in days
1. Dimensions of the pilot giant cavern certified by the geomechanical project:
   ✓ 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 m³;

2. Storage volume of gas stream with high content of CO₂ in one cavern: 3,840,000,000 Sm³;

3. Maximum Gas pressure expected after abandonment: 465 bar;

4. Based on the salt dome studied for CCS application, one cavern can store 4 billion Sm³ or 7.2 million tons of CO₂. 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 CO₂.
Flow Assessment

- Expected seawater temperature at well bottom hole
  - Two models implemented ⇒ Estimate effect seawater temperature at well bottom hole during dissolution:
  - Both indicated that seawater reaches well bottom hole at a temperature close to brine inlet, regardless of seawater temperature at wellhead

- Is erosion an issue?
  - Brine contains insolubles
    - DNVGL-RP-O501 (managing sand production and erosion);
  - During dissolution
    - Brine flows through annular space between outer pipe and inner pipe
  - During brine substitution by gas
    - Brine flows through inner pipe

2 years of brine substitution (conservative)
Depending on the flowrate and concentration, erosion could be an issue
Logistics

- **Global Development Strategy**
  - Plan construction several caverns associated to existing oil & gas wells and new projects;
  - Plan = $f$ (amount available resources; prioritization issues; location/size; sharing cavern with more than one FPSO);
    - Limited resources and conflicting decisions;
  - Optimization approach = PROPOSED;
  - Main phases:
    - 1) Elaboration different scenarios concerning Santos Basin development;
    - 2) Mathematical modelling;
    - 3) Optimization.
  - Output:
    - 1) Location; 2) Size; 3) When to build; 4) Connections between FPSOs and salt caverns.
Risk Analysis

- **Methodology**
  - Development of Preliminary Risk Analysis (APRI, in Portuguese), identifying hazard events, causes, and consequences;
  - Evaluation of events’ frequency and consequences’ severity;
  - Qualitative Risk assessment according to SHELL standards;
  - Barriers identification;
    - Establishment of mitigation plan

- **Scope:**
  - Cavern well construction APRI
  - Well design APRI
  - Subsea Design APRI
  - Topside APRI
  - Cavern Operation APRI
  - Subsea Operation APRI
  - HSE / Legislation / Assumptions APRI
  - Logistic APRI
HSSE & Regulation – Project 42

• **Contribution project 42**
  
  – 1. **Screening**
    • 1.1. Definition of the type of licensing by Project 42 staff (all team);
      - 2 months – August and September;
    • 1.2. Discussion about type licensing with participation of IBAMA and Project 34;
      - 1 month – September;
  
  – 2. **Scoping**
    • 2.1. Scope of the Environmental Study (analysis of alternatives, risk assessment, impact analysis and PBA (mitigating measures):
      Definition scope Environmental Study required for licensing (EIA team)
      - 5 months – November to March;
    • 2.2. Discussion about the scope with participation of IBAMA and Project 34
      - 5 months - November to March.

  – **Deliverables**
    • March
    • Understanding about the screening step of salt cavern project licensing;
    • Draft of the Term of Reference of the Environmental Study.
THANK YOU

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