INTTEGRATED MONITORING TOOLS IN
DIADEMA UNDERGROUND GAS STORAGE – ARGENTINA

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1.- ABSTRACT

The Diadema field is located 40 km northwest of the city of Comodoro Rivadavia on the northern flank of the San Jorge basin, Argentina. The field hosts several gas-bearing and oil-bearing horizons. One of the reservoirs in the Diadema field is the Banco Verde horizon, pertaining to the Cretaceous-Tertiary Salamanca Formation. Dry gas was produced from the Banco Verde horizon from 1950 to 2000. During that period of time, reservoir pressure dropped from 26 bar to 5 bar upon completion of gas-bearing operations.

In 2001, Repsol YPF leased the gas-bearing blocks hosting the Banco Verde horizon from CAPSA. The aim of this project was to develop the first underground gas storage site in Argentina for winter consumption in Comodoro Rivadavia and eventually in other industrial cities in central Patagonia.

Gas stored in the reservoir in summer (from October to March) comes from the San Martín pipeline at 60 bar, and is injected into the reservoir once its pressure has dropped to 25 bar. In winter (from April to September) a gas compression and treatment plant is used during the withdrawal phase prior to gas transportation and distribution.

The Diadema field is formed by monoclines in hydraulically interconnected fault-blocks allowing storage gas to flow through permeable faults. This natural migration from the injection wells to the reservoir limits needs to be monitored during the injection cycle (summer) and the withdrawal cycle (winter) for an adequate reservoir gas recovery.

Consequently, measures were put in place from the beginning of operations at the Diadema field to secure reservoir and well imperviousness, with a focus on preventing gas leakages into other hydrocarbon-producing layers and overlying aquifers (Rio Chico and Patagonia Formations).

Thorough work was done to safeguard pre-existing facilities (wells and gas pipelines) used during gas-production operations for fifty years. Environmental baseline studies were undertaken for future monitoring and follow-up of key operation indicators.

Storage and monitoring operations required repairing existing wells and drilling new ones. Operations currently comprise 10 storage wells, 14 gas monitoring wells and 2 aquifer monitoring wells located in the gas storage area.

It should be noted that the lessor company at the Diadema field (CAPSA) operates numerous oil wells with dissolved gas from the Bajo Barreal Formation, underlying Banco Verde. In addition, the Public Utility Company of Chubut [Servicios Públicos de la Provincia del Chubut] feeds drinking water from the Patagonia Formation into the water grid in Comodoro Rivadavia.

The operational complexity derived from the impacts of storage gas monitoring operations upon the reservoir, and from the preservation of the surrounding environment, led to the adoption of several control measures from the beginning of storage operations. Water quality surveys were put in place, and the storage operations area was monitored. Originally, before the initiation of gas injection into the reservoir (Banco Verde), small amounts of hydrocarbons were detected in the Rio Chico and Patagonia Formations in this area.

Geochemical and isotopic determinations were performed to determine the source of dissolved gas in the aquifers, and to monitor the migration and mixture of native gas and injected gas in Banco Verde.

This paper shows the results of periodic monitoring at the Diadema field from the beginning of operations. Studies consisted of well surface pressure measurement, gas chromatography in company wells and neighboring wells, hydrocarbon detection in surface waters and aquifers, geochemical and isotopic determinations in gas and water, and chemical tracers in the reservoir.

The main conclusions are as follows:

There are hydraulic interconnections among "I", "O", and "Q" blocks. Gas migration in the storage site shows a north-east bound trend. There is interconnection and east-to-west gas migration in the "H" block. Conclusions are based on pressure measurement records from gas monitoring wells in the reservoir.

The injection of a chemical tracer in well I-161, subsequently detected in neighboring gas wells, proves that gas in the reservoir tends to flow towards the north-east of the storage site.

Annual environmental monitoring of ground and surface water, as well as geochemical and isotope determinations from samples taken in several campaigns, reveal no evidence of gas migration from the storage site to the overlying aquifers. This is indicative of an adequate hydraulic seal in the reservoir.
The isotopic fingerprint of gas samples from different sources is indicative of thermogenic gases associated with oil and gas fields. By combining gas isotope composition and molecular ratios, different gas sources were clearly identified. The isotope composition of stored gas has varied with time due to the mixing of native gas and stored gas. Geochemical and isotopic determinations in adjacent blocks enabled the detection of gas pertaining to the UGS, playing a key role in claims to neighbor operators which had received gas from the storage and lead to the subsequent operational normalization.

I. Reservoir Location and Geology

I.1. Location

The Diadema field is located 40 km northwest of the city of Comodoro Rivadavia, on the Northern flank of San Jorge Basin.

![LOCATION](image)

Diadema has been a natural gas producing field supplying the city of Comodoro Rivadavia for more than sixty years, since the 30s until its depletion at the end of the 90s.

Once the potential of this field for conversion to underground gas storage was identified, several geological and geophysical studies were made and the integrity of the existing facilities and wells was evaluated with the goal to determine the feasibility of turning the field into the first gas reservoir in Argentina.

I.2. Geology

The gas producing horizon par excellence is “Banco Verde” belonging to the Hansen Member of the Cretaceous-Tertiary Salamanca Formation, located at an average of 650 meters depth below wellhead (Table 1). Banco Verde is made up of glauconitic sandstones of 10-20 meters variable thickness, deposited in an estuarine environment of marine transgression and covered by clays deposited on a coastal lagoon environment. The porosity of this horizon is 25-30%, while its permeability reaches more than 1.0 Darcy. There are sandy pelites from a conchoidal fracture informally known as “Fragmentosa” at its base and an area made up of dark pelites of 20 m thickness approximately called “Banco Negro” at its roof.
<table>
<thead>
<tr>
<th>LITHOSTRATIGRAPHIC UNITS</th>
<th>Thickness (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOWER PALEOCENE (Danian)</td>
<td></td>
</tr>
<tr>
<td>SALAMANCA FORMATION</td>
<td></td>
</tr>
<tr>
<td>Hansen Member</td>
<td></td>
</tr>
<tr>
<td>BANCO NEGRO</td>
<td>20</td>
</tr>
<tr>
<td>BANCO VERDE</td>
<td>20</td>
</tr>
<tr>
<td>FRAGMENTOSA</td>
<td>130 140</td>
</tr>
<tr>
<td>Bustamante Member</td>
<td></td>
</tr>
<tr>
<td>GLAUCONITIC</td>
<td>10-30</td>
</tr>
<tr>
<td>LIGNITIFEROUS</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1. Diadema’s Simplified Stratigraphy.

Picture 1. Banco Verde Outcrop. The yellow lines indicate roof and base between Banco Negro and Fragmentosa, respectively

Banco Verde in the study area constitutes an ancient depleted gas reservoir with an original 26 Bar pressure.

Banco Verde is structurally divided into blocks caused by direct faults with an east-western and northeast-southwestern strike with up to 40 meters throw, as seen in the structural map (Figure 2).
The reservoir used for gas storage operations is crossed by direct faults which are permeable to the injected gas flow as observed in the Structural Cross-Section (Figure 3).

The seal rock is made up of sandy levels belonging to the base of Rio Chico Formation, as seen in the Schematic Cross-Section (Figure 4).

Figure 4 shows that Banco Verde´s overlying aquifer levels provides an approximate 60 Bar pressure hydrostatic column that constitutes a blocking system for a potential leakage of gas stored in the reservoir having a maximum working pressure of 26 Bar.
II. Facilities and General Characteristics of Gas Storage

Gas storage is associated to the trunk gas transportation system (TGS S.A.) and to gas distribution (Camuzzi Gas del Sur S.A.), through a 10-12” diameter and 7.1 km length gas pipeline operating at a maximum pressure of 60 Bar.

For gas injection into the reservoir there are 10 wells with their respective metering systems for a 120,000 m3/day flow per well approximately, at a maximum regulated pressure of 25 Bar.

Regarding reservoir gas withdrawal, the maximum flow reached is 1,200,000 m3/day during winter season for which there are three (3) engine-driven compressors operating at a 10-15 Bar suction pressure and at a 60 Bar discharge pressure, consistent with Camuzzi Gas del Sur S.A.’s distribution gas pipeline operative pressure.

Reservoir withdrawal gas conditioning is made by a dehydration system with Tryethilene Glycol (TEG) so as to comply with gas marketing specifications required by the National Gas Regulatory Body (Ente Nacional Regulador del Gas - ENARGAS).

III. Gas Storage Operation

*Pre-Operative Studies and Gas Injection*

Before beginning gas injection tests, campaigns with electronic probes were made to measure bottom-hole static pressure (static gradient analysis), to know the existing pressure and to identify gas-water contact in the reservoir.

At the beginning of gas injection into the reservoir the dynamic pressure was recorded for each injection well during a period of at least 4 days, providing records with relevant information to adjust the reservoir parameters required for the development of the numerical simulation model.

Because of the low residual pressure at reservoir at the beginning of storage operation, great volumes of gas were injected to reach a reservoir pressure consistent with the anticipated operation conditions.

Gas injection into the reservoir began in 2001 using two existing wells, which were conditioned and used during a pilot test in 1992. Afterwards other three existing wells were conditioned for gas injection and two
wells were drilled for this purpose in 2002 so as to increase the injection capacity and to provide an adequate withdrawal volume during winter.

With the current gas volume in the reservoir, a reserve was achieved to comply with storage operative requirements.

Diadema Storage Operative cycles consist of an injection period of 7 months approximately, from October to March and a production period of 4-5 months approximately, between May and September of each year.

The evolution of gas injection and withdrawal cycles can be seen in Figure 5, with a strong increase of inventoried gas caused by a gradual increase of the storage area as a consequence of reservoir pressurization that was recorded in the monitoring wells most remote from gas injection area.

IV. Reservoir Monitoring and Aquifer Levels

IV.1. Reservoir

Control Wells

To monitor the gas bubble in the reservoir, the existing wells located in the operations area, within the storage zone and in neighboring blocks have been drilled and workovers made to allow a daily measurement wellbore static pressure evolution.

Since there are oil producing levels located underneath the gas reservoir and in order to monitor hydraulic system tightness, valves have been installed at the drive pipes of oil producing wells to detect methane gas and to collect samples as shown in the schematic cross-section (Figure 6).
Table 2 summarizes number and type of wells used for storage operations and controls.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>AIM</th>
<th>NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Injection / Withdrawal</td>
<td>Banco Verde</td>
<td>10</td>
</tr>
<tr>
<td>Gas Bubble Monitoring</td>
<td>Banco Verde</td>
<td>13</td>
</tr>
<tr>
<td>Gas Levels Monitoring</td>
<td>Rio Chico Fm</td>
<td>1</td>
</tr>
<tr>
<td>Aquifer Levels Monitoring</td>
<td>Patagonia Fm</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>26</strong></td>
</tr>
</tbody>
</table>

Field check and verification of underground storage wellbore pressures is a fundamental task for safety. To this aim various probes strategically located within the field were conditioned (Figure 6) allowing daily measurement of gas reservoir pressures (tubing) and explosive mixture between tubing and casing in oil producing wells.

In Figure 7 the location of the different types of wells and the preferential directions of gas movements within the reservoir are shown.
Daily records of pressure and volume of injected and withdrawal gas from the reservoir are entered in a chart like the one in Figure 8 showing the evolution of different parameters for each well.

Within the framework of controls performed in Diadema, Rio Chico Fm is monitored through well I-162, with the special feature of being a gas horizon which has been essayed to determine gas quality and production potential.

In this regard the original pressure of 24.7 Bar Ab was reduced to 3.0 Bar Ab after one week of production and was maintained uniform until the present even though gas has been injected and withdrawn from Banco Verde (underlying), during more than four cycles (Figure 9).

In view of pressure drop after production tests gas level is of little extension.
Based on well I-162 pressure evolution in time, it can be concluded that the gas reservoir formed by Banco Verde, located some 60 meters below Rio Chico Fm is not hydraulically connected to that gas horizon providing a proof of Diadema storage tightness.

**Chemical Tracers**

On October 2006 the first studies related to chemical tracer injections were made to have information on reservoir gas displacement.
- To evaluate areal distribution of chemical tracers in the reservoir and gas transit time through the reservoir.
- To obtain gas flow preferential directions in the reservoir.

For this activity well I-160 located at the northwestern part of Block "I", was selected as an injection well and other 14 as monitoring wells.

The essay consisted in the injection of a perfluorcarbonated chemical tracer that is stable in natural gas mixtures and compatible with the environment and subsequent gas sampling of wells close to the injection well so as to determine the presence of the injected tracer. Detection levels of these compounds are on the order of ppb.

Tracer injection was made in the storage injection phase. During the first 6 months after injection from October 2006 to March 2007 the tracer was not recorded in monitoring wells. When storage production began it was possible to detect the tracer as from May 2007 reaching only 4 monitoring wells in Block I (I-160, I-161, I-12 and I-22).

This implies that tracer and therefore gas movement was radial from the injection well. At an equivalent gas production of wells I-12, 22 and 161, tracer concentration in well I-12 was more than double that of other wells. This demonstrates a preferential E-NE migration direction in the reservoir, which agrees with flow preferential properties of the reservoir and with findings made with other monitoring techniques. Tracer concentration in wells reached its peak and then dropped rapidly without producing sufficient information to determine gas flow velocity and to clearly ensure what was the preferential flow direction.

**Conventional Geochemistry**

Since 2001 until the present gas sampling and chromatographic analysis campaigns have been annually performed in relation to oil exploitation of underlying levels to the gas reservoir and of different types of well and pipeline gas. The goal was to have comparative values over time, to have an additional tool to detect well leakage and to establish a possible interaction among different geological horizons.
Injected and withdrawn gas chromatographies are shown to be very similar in the following chart indicating that at present reservoir extracted gas does not suffer a significant variation in relation to the injected gas, as a consequence of gas mixtures made along many operative cycles.

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Storage Gas</th>
<th>Native Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Injection</td>
<td>Withdrawal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>% Molar</td>
<td>% Molar</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>1.56</td>
<td>1.70</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>0.93</td>
<td>0.78</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>91.13</td>
<td>91.06</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>4.57</td>
<td>4.45</td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td>1.05</td>
<td>1.15</td>
</tr>
<tr>
<td>i-Butane</td>
<td>C₄H₁₀</td>
<td>0.26</td>
<td>0.30</td>
</tr>
<tr>
<td>n-Butane</td>
<td>nC₄H₁₀</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>i-Pentane</td>
<td>IC₅H₁₀</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>nC₅H₁₂</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>Hexane</td>
<td>C₆H₁₄</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Heptane</td>
<td>C₇H₁₆</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Octane</td>
<td>C₈H₁₈</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Nonane</td>
<td>C₉H₂₀</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Table 3. Chromatographic Analysis of Storage and Native Gas

IV. 2. Aquifers

The existence of aquifer levels located above gas reservoir (Banco Verde) entails the need to monitor daily key parameters for the early detection of hydrocarbons that could affect them.

To do this a hydrogeological survey was made (Figures 10 and 11) and three wells were drilled, two directed towards Patagonia Formation and one to Rio Chico Formation on which daily checking are made on explosive mixture and wellbore pressures.

Since 2001 samples of spring water and aquifers (Figure 10) were taken every year to monitor them and to verify that reservoir gas injection–withdrawal operations do not entail a severe environmental impact.

Figure 10. Monitoring Wells Location in Aquifers and Spring Waters (Patagonia Fm)
As an example, in Figure 11 the results of Total Dissolved Solids (mg/l) essay in Patagonia Fm, corresponding to the 2008 campaign are shown.

It should be pointed out that after several annual sampling no impact due to gas storage activities is recorded.

The following set of essays is performed on collected samples of water:

a.- Physical-Chemical Parameters.

- Anions: Chlorides (Cl), Sulphates (SO4), Carbonates (CO3), Bicarbonates (HCO3)
- Cations: Sodium (Na), Calcium (Ca), Magnesium (Mg), Total Iron (Fe)
- Salinity, pH, T° in situ, conductivity.
- Total Alkalinity
- TDS (Total Dissolved Solids)

b.- Hydrocarbons and By-Products

- Total Hydrocarbons (HCT)
- Volatile Organic Compounds (VOC’s), Polynuclear Aromatic Hydrocarbons (PHA) and Benzene, Toluene, Ethyl Benzene, Xylene (BTEX).

c.- Heavy Metals

d.- Stable Isotopes

To complement the essays determinations of isotope composition of production water and spring water were made.

The main results show that water coming from Patagonia Fm wells corresponding to the Myburg area present isotope compositions similar to other water in Patagonia Fm in the area. Production water is similar to the formation water in the area. At sampling moment there is no evidence of production water contribution from Banco Verde to Patagonia Fm.
In summary no anomalies are detected in the parameters analyzed.

IV.3. Isotope Studies of Gas Hydrocarbons in Reservoirs and Aquifers.

Five gas and water sampling and essaying campaigns were made in the area of Diadema storage including samples of Patagonia and Rio Chico Formations, underlying the gas reservoir (Banco Verde). Figure 12 shows sampling points of gas and water wells. The goal is:

- To determine the origin of hydrocarbons present at different geological levels of operative and environmental interest.
- To monitor the evolution of gas mixture proportions between native gas and reservoir stored gas.

For this reason isotope compositions of methane and CO2 and molar composition of gas hydrocarbons were used. The charts used allowed to characterize different components such as:

a) The original gas present in Banco Verde
b) The injected gas
c) The gas present in the Rio Chico Formation

Figure 12 (Location of Sampling Points – Isotopic Analysis)

Figure 13 (C1/CO2 vs $\delta^{13}$C of CO2 correlation) shows the ASGN field (in red), differentiated from the original gas field (in blue) and neighboring fields gas (in black). The arrow indicates the straight line of potential mixture. Figure 14 shows the same fields but in this case using $\delta^{13}$C of CH4 vs $\delta^{13}$C F CO2. In Figure 15 two components are shown: storage (red) and original gas (blue). Summarizing the results obtained it can be concluded that it was possible to identify the original component, injection gas, gas present in the Rio Chico Formation and gas corresponding to aquifers. It was also be possible to recognize the introduction of storage gas to neighboring non isolated producing wells, which has produced relevant claims.
CONCLUSIONS

The monitoring of Diadema storage is focused on the control of pressure evolution in observation wells and on the use of chemical tracers and geochemical-isotope analysis with which the following was determined:

- The main directions of gas bubble movements in the reservoir.
- The influence of gas injection in oil producing wells, not adequately isolated from Banco Verde.
- Non impact of gas storage on overlying aquifer levels.

On the other side since the beginning of gas storage in 2001 the quality of overlying aquifer and springs has been monitored every year confirming the results obtained with the above mentioned method.

ACKNOWLEDGMENTS

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REFERENCES