GAS INJECTION IN CUSIANA & CUPIAGUA FIELDS COLOMBIAN FOOTHILLS

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Preliminary Note on Intellectual Authorship

This brief presentation about gas injection experience in some fields of Colombian Foothills evidence teamwork, participation and interaction of several professionals for over 20 years (1994 - 2016), actively involving:

**Fluid Characterization:**

1. Raul Osorio Gallego - PVT and Fluids Characterization, Ecopetrol
2. Sheng-Tai Lee* - PVT Expert, British Petroleum
3. Professor Curtis H. Whitson - Consultant, Norwegian University of Science and Technology
4. Professor Ali Danesh* - Consultant, Heriot-Watt University
5. Professor Abbas Firoozabadi - Consultant, Yale University - RERI
6. Wilson Barrios - Former PVT Lab Leader, ICP

**Development Strategy and Operation:**

1. British Petroleum Company: BP Exploration Company Colombia - BP Energy Company Colombia
2. Equion Energía
3. Ecopetrol S.A

* R.I.P.
Outline

✓ General Information
✓ Data Acquired
✓ Wells, Lines & Gas Process Facilities
✓ Strategy
  • Gas Injection Optimization
  • Results
✓ Main Challenges - Lessons Learned
• Casanare, Colombia
• 175 Km northeast from Bogotá
• Foothills of Colombian Andes
General Information

- Three naturally fractured sandstone reservoirs (main + 2 secondary layers)
- Asymmetric tight anticline NE-SW elongated
- Commingled production / injection
- Average depth = 12500 ft / 13000 ft (TVDss)
- Structurally complex reservoirs:
  - Thrust faulting
  - Imbricate inverse faults
  - Minor intra reservoir faults
- Fluid system: volatile oil + rich condensate gas cap / rich condensate gas
- Average initial reservoir pressure: 5900 psia @ 12950 ft TVDss / 6500 psia @ 12950 ft TVDss
- Reservoir temperature: 240 - 300 °F
- Reservoir permeability: 0.1 - 300 mD
- Reservoir porosity: 2 - 12 %
- Early secondary recovery via lean gas miscible reinjection as main production mechanism
✓ Volatile oil + rich gas cap (170 - 200 STB/MMSCF)

✓ Relatively small near critical transition zone (≈ 100 ft)

✓ High compositional variation (150 - 700 stb/scf)

✓ Early crestal injection in main reservoir / late crestal injection in secondary reservoirs.

✓ 31 - 40 API, 0.4 - 0.5 cp @ reservoir conditions

✓ Very rich gas condensate (220 - 312 STB/MMSCF)

✓ Near critical fluid over 6000 ft. HC column

✓ Small compositional variation.

✓ Early crestal injection in main reservoir / late crestal injection in secondary reservoirs.

✓ 40 - 45 API, 0.2 - 0.5 cp @ reservoir conditions

✓ Unique fluid system in the world!
General Information - Fluid Systems

Maximum liquid recovery from gas cap and oil leg will be achievable through considerable gas reinjection and recycling. Process enhanced by:

CUSIANA

✓ Swelling due to gas solubility above MMP.

✓ High reservoir temperature and pressure will contribute to condensate revaporation below MMP.

✓ Partial pressure maintenance depending on areal gas injection distribution.

CUPIAGUA

✓ First contact miscibility above Psat. ①

✓ Below Psat, high reservoir temperature and pressure will contribute to condensate revaporation in contact with reinjected gas through multiple contacts. ②

✓ Partial pressure maintenance depending on areal gas injection distribution.
Main miscibility processes driven by gas/liquid mass transfer through swelling (above MMP) and revaporation (below MMP)

Some adaptations needed to better understand related processes (e.g. adapted backward multiple contact test for oil revaporation, Vogel and Yarborough - 1980).

* From: Phase Behavior - C. Whitson, M. Brulé
Data Acquired - Key PVT Testing
Multiple Contact Test in Cusiana

- Backward test better describes involved phenomena.

- MCT shows high efficiency at initial contacts.

- Process efficiency (≈60%) must be adjusted by sweep and areal efficiency to get maximum theoretical incremental volumes.

Cusiana backward MCT results
Two different test configurations in order to completely understand revaporation phenomena:

- Series 1: pressure depletion + constant volume (not common).
- Series 2: constant pressure + constant volume.
Injected Gas

- Injected gas corresponds to dehydrated separator gas
- Other gases used for sensitivity purposes
- No N2 or CO2 available for economically feasible EOR application

*Results from compositional numerical simulation model
Wells, Lines & Gas Process Facilities

General Gas Process Facilities

- Due to commingled production and injection, completions must be designed for easy GSO/WSO, PLT/ILT etc.
- Easily converted depending on pad facilities availability.
- Maximum flexibility pipes to optimize gas injection strategy.
- Modular design will allow special adaptability to production/injection evolution and availability. Optimization function:

Production – Injection = Flare & Consumption

**Production – Injection = Flare & Consumption + LPG/NGL + Gas Sales**

**KEY POINT:** The overall architecture was designed taking into account long-term vision to guarantee the change of strategy: STAGE I ➔ STAGE II, avoiding extremely expensive future modifications.
Strategy

1. Crestal reinjection for gas cap expansion + flank / middle flank oil production.

2. Flank reinjection + middle flank recycling wells closed.

3. Flank producer wells converted to injectors + Middle flank producer wells reactivation + gas cap blowdown.
# Gas Injection Optimization - Surveillance Data

<table>
<thead>
<tr>
<th>SURVEILLANCE ALTERNATIVE</th>
<th>DIAGNOSED ISSUES</th>
<th>SUBSEQUENT ACTIVITY</th>
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<tr>
<td>WT</td>
<td>Gas recycling</td>
<td>GSO / Foams</td>
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<tr>
<td>Real Time WHT / WHP / inj rates</td>
<td>Lifting problems</td>
<td>CTGL / AutoGL / WSO</td>
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<td>PLT / ILT Tracers</td>
<td>Crossflow</td>
<td>WSO / partial isolation</td>
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<td>Unefficient gas injection conformance</td>
<td>Foams / sand plugs / DH choke</td>
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<td>Injectivity problems</td>
<td>Hydraulic fracturing / Gas dispersible CHS / TTRD</td>
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<td>Compartmentalization</td>
<td>Numerical and analytical model updating</td>
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<td>Flow barriers</td>
<td>History match tuning</td>
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<td>Low / High transmissibility zones</td>
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<td>PBU / PFO / Static</td>
<td>Skin damage</td>
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## Diagram

![Diagram showing data analysis and model updating](image.png)

**Log-Log Plot**

- Cs: 0.17 bb/psi
- K: 3.04 md
- Kt: 815 md-ft
- S: 20.52
- P*: 3537 psia

**Semi-Log Plot**

- Pressure data from different models and times.

**Timeline**

- 29/03/2002
- 28/04/2002
- 28/05/2002
- 27/06/2002
- 27/07/2002
Gas Injection Optimization - Analysis & Diagnosis

- Recycling pattern identification
- Real GOR vs depletion GOR (or yield)
- GOR as process tracer
Gas Injection Optimization

Asphaltene + recycling + conformance = inefficiency.
The development of the fields has been carried out in two stages:

**STAGE I**
- Development focused on early secondary oil recovery
- Drilling campaign + Crestal lean-gas injection
- Crestal lean-gas injection optimization + gas sales start-up
- Lean-gas injection at flank and mid-flank + Gas inj at secondary Fm

**STAGE II**
- Development focused on gas recovery
- Higher Gas sales + LPG/NGL generation
- Blowdown

**FLUID EXPANSION**
- Miscible Lean Gas Reinjection
- Multiple Contact Revaporation
Strategy Results

Cusiana

Cupiagua
Main Challenges - Lessons Learned (Stage I)

- For Cusiana and Cupiagua fields, fluid system detailed understanding and their response to miscible gas reinjection implies understanding of over 70% of total process, hence the importance of a correct PVT test design and EoS calibration.

- A good process understanding, associated efficiencies, heterogeneities and reservoirs dimension, makes it possible to identify areas in which optimal recovery can be reached. Prioritization strategies if required.

- A rigorous monitoring strategy based on identifying deviations from theoretical behavior allows for optimization measures even at early stages.

- A complete field development plan containing detailed strategies for each production stage will lead to optimal wells, flow lines and processing facilities design focused on cover most of the assets life. This way, investments can be efficiently apply reducing mid or late term additional CAPEX utilization.