Monitoring Plan for a Cyclic Steam Stimulation (CSS) Pilot Test in Orinoco Oil Belt, Venezuela

Repsol Technology Center (CTR), Madrid
PEA 2016 – Aberdeen, Scotland, UK
1. What is Pilot Test? Why monitoring it?
2. Monitoring Indicators (Parameters)
3. Monitoring Tools / Technologies
4. Simulation Studies
5. Monitoring Plan
What is Pilot Test?
Why Monitoring it?
Definition, Key questions and Objectives

Definition
Pilot Test is a scaled down version of the commercial full field implementation of an EOR process

Key questions
What are uncertainties (required results)
When are results needed

Objectives
To evaluate and reduce key uncertainties
Provide fruitful data to facilitate full field investment and operating decisions
Why Monitoring Pilot Test?

Pilot test performance must be understood and interpreted perfectly (uncertainty reduction)

**Monitoring:**
- Series of measurements which are done to evaluate the desired uncertainties (the only option to measure them)
- Combination of traditional and state-of-the-art technologies/tools or methods

**Monitoring indicators** (parameters) are covering all of uncertainties
Field Characteristics

Unconsolidated sandstone

1\textsuperscript{st} class reservoir!

\begin{align*}
\phi & \quad S_0 \\
\frac{k}{\phi} & \quad \frac{S_o}{\phi}
\end{align*}

Average reservoir properties (3 main geological units)

- Average porosity: 31-33%
- Aver. permeability: 2-4 D
- Initial $S_w$: 27-32%
- Net pay: 3-8 m
- Depth: 800-1000 m
- Viscosity: 8.4 °API
Challenges of Our CSS Pilot Test?

1. Deep reservoir: about 1 km depth
2. High pressure reservoir: about 1300 psi (90 bar)
3. Challenging steam saturation condition: HP and HT (limit of thermal applications)
4. Operational limit: thermal packers, casing stress, etc.
5. Highest specific steam injection rate (STBD/ft): from 2.2 up to 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure, bar (\text{psi})</td>
<td>100 (1476)</td>
</tr>
<tr>
<td>Temperature (^\circ\text{C}(^\circ\text{F}))</td>
<td>58 (137)</td>
</tr>
<tr>
<td>Oil viscosity @ RC (cP)</td>
<td>1376</td>
</tr>
</tbody>
</table>

**Pressure-Enthalpy Diagram**

- Initial average pressure
- After 30% reduction
- After 50% reduction

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CSS PILOT TEST DESIGN

- The CSS Pilot Test will be implemented only in Lower Unit
- For the CSS Pilot Test, there are available two wellpads
- Each wellpad has 10 horizontal wells, 5 wells in each side.
- Wellpads have different well length on their sides
- Well spacing is 300 m in both wellpads
- Two objectives: injectivity and type of insulation
Monitoring Indicators (Parameters)
Monitoring Indicators (Parameters) of CSS Pilot Test

Class 1
Directly evaluated in the field
1. Steam injectivity
2. Steam quality
3. Steam distribution
4. Corrosion
5. Water retention per cycle

Class 2
Critical for CSS economic assessment
1. Steam-oil-ratio (SOR)
2. Oil recovery factor
3. Stimulation factor
4. Diluent amount

Class 3
Other required parameters
1. Temperature
2. Pressure
3. Produced gas composition
4. Periodic sampling of produced liquids
5. Rate of produced fluids
6. Water salinity and sediments
7. Mineralogy
8. Steam pH

Cold production stage: foamy behavior of the oil
Monitoring Technologies/Tools or Methods
Monitoring Technologies

- Well Logging
- Core Sampling
- Observation Well
- Cross-well Seismic
- 4D Time-Lapse Seismic
- Steam quality Tools
- Fiber Optic Sensors
- Corrosion evaluation methods

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**Well Logging**

**Combination of:**
- *Compensated Neutron Log (CNL)*
- *Compensated Formation Density (FDC) Log* and
- *Gamma Ray (GR) Log*

1. Define oil, gas (steam), water zones and shale contents
2. Successfully used before in JOBO field
3. Run before start of CSS process (initial state)
4. Run during the injection stage of each cycle

**Cement Bond Log (CBL) and/or Cement Evaluation Tools (CET):** Needs to be run before start of the process (it is proposed to have budget in order to repeat it after each injection cycle for confined well) to evaluate zonal/hydraulic isolation and prevent Surface Casing Vent Flow (SCVF) and/or Gas Migration (MG)
- **Cased-hole Log:** Wellbore integrity
- **Production/Injection Logging Tools (PLT/ILT):** as complementary to fiber-optic sensors, provides temperature and pressure data

**Note:** Application of the mentioned logging tools should be confirmed in HW during injection phase and in cased-hole vertical observation wells
Fiber-Optic Sensors (FOS)

- Pressure-Temperature combined Gauges (P/T Gauges)
- Array Temperature Sensors (ATS)
- High-Density-Array Temperature Sensors (LxATS)
- P/T plus ATS
- Flowmeters plus P/T Gauges
- Distributed Acoustic Sensing (DAS) System
- Distributed Temperature Sensing (DTS) System
LxATS Sensors - (FOS)

Calibrated temperature: 77 to 572°F / 25 to 300°C

Thermal Accuracy: ±0.9°F / ±0.5°C

Thermal Resolution: ±0.018°F / ±0.01°C

Extended Temp. range to 630°F / 330°C possible

Calibrated P range: Atm to 2000 psi / Atm to 138 Bar

Max. Non-Operating P: > 6000 psi / > 413 Bar

Pressure Accuracy: ±3 psi / ±0.2 Bar

Pressure Resolution: ≤ 0.1 psi / ≤ 0.007 Bar

Retreivable up to 15 times

Electromagnetic Inspection (EMI), hydrogen insensitive and safe in high T environments

Life time greater than 15 years
Compare LxATS, DTS & Thermocouples

LxATS (Frequency) vs. DTS (Amplitude)

- LxATS long-term reliability @ High T above 220°C
- LxATS react faster vs. DTS (per/sec vs. Average sampling)
- LxATS uses smaller amount of data
- LxATS includes optical PT

LxATS (Frequency) vs. Thermocouples

- LxATS greater spatial resolution
- LxATS increased accuracy & resolution
- LxATS includes optical PT

Redundancy: For each series of LxATS cable use of 4 Thermocouples are proposed
Observation Well (OBS)

- Widely used in pilot test and EOR evaluations
- At least two OBS is proposed (Middle and Toe) Should not be in the same side of the HW
- Simulation studies to define optimum location
- Fiber-optic sensors and cross-well seismic (recommended side-wall core sampling and well logging)
- Reservoir Saturation Tool (RST) logging
Cross-well Seismic Technology

- The same principle of Seismic but high detailed images
- Two or more vertical wellbores (not applicable for HWs)
- Vertical resolution: from 0.5 m to 100 m
- Depth of investigation: from few meters to 1 km
- Well separation: up to 2000 m (resolution??)
- Able to distinguish steam zone and fluid saturations for desired area (wide area coverage)
- It has to be done after each injection phase
4D TIME-LAPSE SEISMIC

- Wide range of reservoir coverage
- Distinguish phases (Steam and liquid)
- It is proposed to perform baseline seismic survey
- For better understanding in future evaluations
- It is recommended to have budget for at least three surveys (including the base line) along the pilot test
4D TIME-LAPSE SEISMIC
Advantages and Limitations

Key Strengths
1. Do not require permanent installation
2. Repeat survey can be done when necessary
3. Well adapted for evaluating the drainage areas and bypassed areas, after some time of oil production
4. Larger area coverage than well logging and observation wells

Key Limitations
1. Not continuous in time thus can miss the right moment to raise an alarm to make some operational decisions
2. Cost per Km² increases rapidly for small survey areas
3. Operationally not adequate for a monitoring frequency lower than a repeat once a year
4. Accuracy of time-lapse observations can be limited by variations in the near surface conditions due to seasonal changes
Steam quality Measurement at Well head
Neutron Densitometer

- Thermal neutron (Gamma) transmission principle
- Large mass attenuation of thermal neutrons in liquid water
- Mounted on the outside of the pipe
- Weakly attenuated by pipe wall material
- Measure steam quality @ wellhead
- Portable, non-intrusive and safe for field use
- Combine with Flow nozzle provide mass flow rate too
- The availability in market should be checked
Redundant Steam quality Methods
After generator

**Total Dissolved Solids (TDS)**

1. Compare concentration of soluble solids in feedwater and liquid portion of generator output
2. Adding dilute acid to find concentration (Chemical titration-Phenolphthalein indicator)
3. Ratio of added acid for output water and feedwater (5 times more acid for output means 80% quality)
4. Very accurate and most widely used
5. Sampling is critical and important process (avoid sampling at bends, tees, elbows or pipe fittings)

**Orifice meter Technique**

1. Measures gas and liquid flowrates
2. No need to phase separator or sampling
3. Appropriate for very high quality
4. Comparable with other methods like TDS
5. Continuous and online measurements
6. It is an approximate and measurements should be done at least 10 min after the steady-state flow
Corrosion Evaluation Methods

1. **Gas Chromatograph**: $\text{H}_2\text{S}$ and $\text{CO}_2$ concentrations
2. **H$_2$S Dragger**: as complementary to Gas Chromatograph
3. **Metallic Coupons** weight loss, stress corrosion cracking, X-Ray diffraction of corrosion products and electronic microscopic analysis
4. **Remote Monitoring System** (*state-of-the-art*)

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**Production Stage**

**Injection Stage**

1. **Fresh feed water** (low impurities and scales)
2. **Steam pH of 9-11**: minimize the acidic and corrosive effect of steam and reduce quartz dissolution
Core Sampling

- Side-wall cores during drilling operations of HWs and OBS (simulation study)
- To investigate grain-size and the presence of swelling shale contents
- Post-mortem cores to supply overall stimulation factor and $S_{or}$ information
Simulation Studies

(T-P profile and Observation well location)
Simulation Studies Objectives

- A Sector of well-pad area selected
- Horizontal well lengths of 2200 ft and 4500 ft with Observation wells at middle point and toe
- Recommended Pilot Plan production and injection constraints
- Objectives:
  - Optimum placement of vertical observation wells
  - Performance of CSS pilot test and expected results
Grid Refinements (Discretization)

- Highly discretized cells along the HW, OBS wells and their Surrounding area
- Grid refinement
  - along wellbore horizontal section
  - around wellbore horizontal section
  - In the middle and toe section of the wellbore vertically to the top (OBS well locations)
Observation Well Location

Observation wells
Temperature - Pressure Profile

Vertical growth of steam zone at Observation well location 7 m away from HW

<table>
<thead>
<tr>
<th>Pressure, psi</th>
<th>Temperature, F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>4 m (18 ft)</td>
</tr>
<tr>
<td>1260</td>
<td>8 m (24 ft)</td>
</tr>
<tr>
<td>1240</td>
<td>16.5 m (54 ft)</td>
</tr>
</tbody>
</table>

- $t_{end 1^{st} \text{Inj}}$
- $t_{end 2^{nd} \text{Inj}}$
- $t_{end 3^{rd} \text{Inj}}$
Steam height evaluation

- Observation well location
- Lateral distance away from HW, (meter)

- Height of Steam, (m)

- Recommended
Schematic of the HW and Obs. Well

Horizontal Well

Observation Well

Top of the reservoir

16,5 m (54 ft)

10 m (32 ft)

7 meter away laterally

Zero (Same level)
T-time and P-time Profile
(lateral distances of 7 m away from HW)

Vertical distance above HW:
Zero (same level)
10 m (32 ft)
16.5 m (54 ft) top of reservoir

Vertical distance above HW:
Zero (same level)
10 m (32 ft)
16.5 m (54 ft) top of reservoir
Monitoring Plan
# Class 1: Indicators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement tool / Technique</th>
<th>Frequency</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steam Quality (X_s)</strong></td>
<td>@ Wellhead: Neutron densitometer&lt;br&gt;After generator: TDS and/or Orifice method&lt;br&gt;@ Bottom-hole: using wellbore model simulator to history match T &amp; P at sand face</td>
<td>Daily, Periodically or daily</td>
<td>Heat loss management and economic evaluation</td>
</tr>
<tr>
<td><strong>Steam Injectivity</strong></td>
<td>Steam injection rate and pressure at wellhead</td>
<td>Daily</td>
<td>Reservoir injectivity, swelling effect of shale contents</td>
</tr>
<tr>
<td><strong>Steam Distribution</strong></td>
<td>T-P profile from fiber-optic sensors along the HW and OBS wells and cross-well seismic data</td>
<td>Daily in case of FO sensors, At the end of each injection phase for cross-well seismic</td>
<td>Steam zone extension, vertical and horizontal sweep efficiency</td>
</tr>
<tr>
<td><strong>Water retention per cycle</strong></td>
<td>Material balance</td>
<td>End of each cycle</td>
<td>Change in wettability, relative permeability hysteresis</td>
</tr>
<tr>
<td><strong>Corrosion evaluation</strong></td>
<td>@ Inj. Phase: keep steam pH 9-11 by adding caustic materials&lt;br&gt;@ Prod. Phase: Metallic coupons: weight loss, stress corrosion cracking, X-Ray diffraction of corrosion products and electronic microscopic analysis Possibly: Remote corrosion monitoring system</td>
<td>Daily, Per Cycle, Real time</td>
<td>Safety of personnel, facilities and process</td>
</tr>
</tbody>
</table>
### Class 2: Indicators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement tool / Technique</th>
<th>Frequency</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inc. SOR</td>
<td>Calculation: ( q_s / q_{oinc} )</td>
<td>Daily</td>
<td>Economy of the process, Energy management</td>
</tr>
<tr>
<td>Oil recovery factor ((R_F))</td>
<td>Calculation: Net ( N_p / N_{STOIP} )</td>
<td>End of each cycle and end of the process</td>
<td>Economy of the process</td>
</tr>
<tr>
<td>Stimulation factor</td>
<td>Calculation: ( q_{ohot} / q_{ocold} )</td>
<td>End of each cycle and end of process</td>
<td>Economy evaluation</td>
</tr>
<tr>
<td>Diluent amount</td>
<td>Material Balance</td>
<td>Daily</td>
<td>Economy evaluation</td>
</tr>
<tr>
<td>Parameter</td>
<td>Measurement type</td>
<td>Frequency</td>
<td>Relevance</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>-------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Temperature and Pressure</td>
<td>Fiber-optic sensors / thermocouples</td>
<td>Daily</td>
<td>Heat management and energy balance</td>
</tr>
<tr>
<td>Produced gases composition</td>
<td>Gas chromatography and H₂S Dragger</td>
<td>Daily</td>
<td>Corrosion, safety and Steam distillation effects</td>
</tr>
<tr>
<td>Oil, Gas, Water and Steam production rate</td>
<td>Appropriate flow meters at surface</td>
<td>Monthly</td>
<td>Material balance calculations</td>
</tr>
<tr>
<td>Produced Oil composition and characteristics</td>
<td>Sampling of produced liquids</td>
<td>Periodic</td>
<td>Density, viscosity and composition,</td>
</tr>
<tr>
<td>Water salinity and Sediments</td>
<td>Surface facility and Laboratory analysis</td>
<td>From six months before start of first steam injection period: monthly measurements From one month before start of first steam injection period: weekly measurements and The last week measurement should be done on the last day before steam injection. However, during the hot production phase the plan is different and sampling is done in the following way: for first week of hot production daily measurement, from second week to the fourth week, weekly measurement and then monthly sampling. It is repeated for the other cycles too.</td>
<td>Presence of mobile water, thief or high permeable zone and sand production rate</td>
</tr>
<tr>
<td>Steam pH</td>
<td>pH meter at well head or after generator</td>
<td>Daily during injection phase</td>
<td>Corrosion evaluation</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Side-wall coring, mud cuttings, well logging</td>
<td>During and after well drilling operations (HW and Observation wells)</td>
<td>Shale contents</td>
</tr>
</tbody>
</table>
Final Remarks

A pilot test can be **successful** or **unsuccessful** depending on the applied technology or reservoir conditions. However, a pilot test will be **conclusive** or **non-conclusive** depending on the appropriate execution of an all-inclusive monitoring plan.

Cost reduction, related to the partial execution of monitoring plan, would be a big risk leading to a non-conclusive pilot test (waste of time and money).
THANK YOU