Role of Reservoir Temperature as a Favorable Factor for Application of In-Situ Combustion (Focus on Heavy Oil Reservoirs)

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Ashok Singhal, Premier Reservoir Engineering Services, Calgary
OUTLINE

- Introduction; spontaneous ignition

- Heavy Oil Field Cases
  - In-situ combustion (ISC) in oil reservoirs at low reservoir temperature
  - ISC in oil reservoirs at high reservoir temperature

- Conclusions
Messages to be taken home

The following advantages can be expected when applying ISC in reservoirs at high temperatures:

- Easy initiation of combustion; spontaneous ignition (SI).
- Generally, oxygen is fully consumed; minimal chances of premature O₂ break-through.
- Often, fully sustained process via propagation of ISC front of relatively moderate peak temperature. This helps protect bottom-hole equipment / cement at production wells.

Direct consequence: ISC is feasible in thick oil layers (meeting all conditions for spontaneous ignition).
Spontaneous Ignition (SI): Conditions

- Either original reservoir temperature ($T_R$) higher than 60-70 $^\circ$C or a very reactive oil, if $T_R < 60-70 \, ^\circ\text{C}$.

- For HPAI applied commercially in Williston Basin for very light oil recovery by ISC, both conditions ($T_R > 90 \, ^\circ\text{C}$ and very reactive oil) are met.

- SI is very important not only for simplification of ignition operation but also for making the process more stable (avoiding prematurely oxygen break-through) with much less or no damage to production wells.

- SI can work and hence favorable conditions for application of ISC can exist after steam flooding ($T_R > 80-90 \, ^\circ\text{C}$); ISC as a steam drive follow up process.
### Summary of 10 spontaneous ignition operations

**Strange, 1964 – with add-ons**

<table>
<thead>
<tr>
<th>Project</th>
<th>Depth (m)</th>
<th>Pay thickness (m)</th>
<th>Crude specific gravity</th>
<th>Original reservoir temperature $T_r$ (°C)</th>
<th>Average injection conditions until ignition</th>
<th>Ignition delay (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gross</td>
<td>Net</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Belridge, California <em>General Petroleum</em></td>
<td>210</td>
<td>11</td>
<td>10</td>
<td>0.980</td>
<td>30.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Midway Sunset, California <em>Mobil</em> Moco Sand</td>
<td>720</td>
<td>160</td>
<td>≈ 40</td>
<td>0.969</td>
<td>51.7</td>
<td>6.6</td>
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<tr>
<td></td>
<td></td>
<td>115</td>
<td>70.5</td>
<td>0.977</td>
<td>29.4</td>
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<tr>
<td></td>
<td></td>
<td>150</td>
<td>66</td>
<td>0.972</td>
<td>45</td>
<td>1.1 during 120 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.7</td>
<td>12</td>
<td>0.985</td>
<td>60</td>
<td>8.2</td>
</tr>
<tr>
<td>California F</td>
<td>22.8</td>
<td>15.3</td>
<td>0.991</td>
<td>51.7</td>
<td></td>
<td>6.3</td>
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<tr>
<td></td>
<td></td>
<td>59.7</td>
<td>33</td>
<td>0.959</td>
<td>35</td>
<td>2.9</td>
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<tr>
<td></td>
<td></td>
<td>63</td>
<td>27</td>
<td>0.959</td>
<td>23.9</td>
<td>0.9</td>
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<tr>
<td></td>
<td></td>
<td>≈ 500</td>
<td>2 layers</td>
<td>0.980</td>
<td>39</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>8</td>
<td>6.5</td>
<td>0.960</td>
<td>70</td>
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<tr>
<td></td>
<td></td>
<td>800</td>
<td>6</td>
<td>4</td>
<td>0.920</td>
<td>54</td>
</tr>
</tbody>
</table>

Balol, India

Videle, Romania
Comments on spontaneous ignition (SI)

- Determination of the ignition time/delay ($t_{\text{ign}}$) very approximate; several reasons

- For reservoir temperatures around $30^0\text{C}$, $t_{\text{ign}}$ in range of 3-5 months – very expensive!

- Between $30^0\text{C}$ and $60-70^0\text{C}$ SI may be possible if the oil-rock system is very reactive to oxidation. In these situations, ISC pilot should still test SI first. Later on, an enhanced SI (with linseed oil, for instance) may be tested if ISC was found feasible.
Our statistical comparison
(for BHT related behavior of production wells)

- Two cases of low temperature reservoirs: more than 40 years of commercial ISC with No. of production wells >90

- Four cases of high temperature reservoirs: more than 20 years of commercial ISC with No. of production wells in the range of 34-75
Field cases of ISC commercial application in heavy oil reservoirs *at low temperature* (ongoing projects)

- Suplacu de Barcau, Romania – line drive operation
- Bellevue, Louisiana, USA – pattern operation
- Other minor projects (not analyzed here)
## Suplacu and Bellevue Commercial ISC Processes: Main Reservoir Properties

<table>
<thead>
<tr>
<th>Field, Company, Country</th>
<th>Formation</th>
<th>Reserv Temp $^\circ$ C</th>
<th>Depth ft</th>
<th>Gross pay ft</th>
<th>Oil viscosity mPa.s</th>
<th>Permeability mD</th>
<th>Res. Pressure Initial / @ start of ISC (psi)</th>
<th>OOIP MMbbl</th>
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<tbody>
<tr>
<td>Suplacu de Barcau (SB), Petrom, Romania</td>
<td>Sand*</td>
<td>18-20</td>
<td>115-720</td>
<td>27-290</td>
<td>2,000</td>
<td>5,000-7,000*</td>
<td>140/80</td>
<td>310</td>
</tr>
<tr>
<td>Bellevue, BSOC, Louisiana, USA</td>
<td>Sand-Stone</td>
<td>23</td>
<td>400</td>
<td>70/30**</td>
<td>676</td>
<td>650</td>
<td>- / 40</td>
<td>4.6/10.6</td>
</tr>
</tbody>
</table>

* Unconsolidated sand  
** Two layers: Lower and Upper ; a layer of lime of 5.5 m between them
Suplacu de Barcau Field

Position of the in-situ combustion front as of July 2004 (longer than 10 km)

Note: strong ignition (gas burner or electrical heater)

Injection wells (111)

Burnt out area
Suplacu de Barcau and Bellevue ISC Projects: Scale of Application

Suplacu de Barcau: Dry combustion in a line drive, for a very shallow reservoir; pre-heating by CSS

<table>
<thead>
<tr>
<th>Field</th>
<th>Start of commerc. operation</th>
<th>Inj. press. (psi)</th>
<th>No. of inj. wells</th>
<th>No. of prod. wells</th>
<th>Daily oil prod. by ISC (Bbl/day)</th>
<th>Observations</th>
</tr>
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<tbody>
<tr>
<td>Suplacu de Barcau</td>
<td>1971</td>
<td>150-200</td>
<td>111*</td>
<td>736*</td>
<td>9000**</td>
<td>Very well instrumented</td>
</tr>
<tr>
<td>Bellevue</td>
<td>1970</td>
<td>60</td>
<td>15</td>
<td>90</td>
<td>300</td>
<td></td>
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</table>

* At any time, there are also 24 production wells under cyclic steam stimulation (CSS)
** It includes the contribution of CSS, estimated at 18% of the daily oil production
Typical Bottom Hole Temperature (BHT) Profile

Date: September 9th, 1971
Oil rate: 1.2 m³/day
Gas rate: 14,200 sm³/day

Temperature profile of the well 486 Suplacu de Barcau

Note 1: Thousands of BHT profiles have been recorded
Note 2: Peak temperature is located at the top of formation (segregated ISC)
Suplacu: Essential Results/Problems

Results

- Ultimate oil recovery: >50%
- AOR in the range of 6,000 to 18,000 scf/bbl (1070 to 3200sm³/m³), increasing in time
- At the low inj. pressure., even AOR of 18,000 scf/bbl is economic

Operational Aspects

- Burning out of some producers; 15% of producers replaced with new wells
- Hot well work-over challenges; special killing fluid developed
Bellevue Field, Louisiana. The zones operated by in-situ combustion by different companies. BSOC=Bayou State Oil Company
Bellevue Commercial ISC Process: Reservoir Properties

(A very low pressure ISC project conducted in patterns)

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* Unconsolidated sand

** Two layers: Lower and Upper; a layer of lime of 5.5 m between them
Bellevue Field. West-East cross-section through the Wyche Lease of BSOC, operated by in-situ combustion

Legend

Perforated
Very small well spacing
2-3 acres/pattern; 16 patterns
Bellevue ISC Project: Scale of Application

Two layers operated simultaneously and separately in pattern configuration

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<th>Field</th>
<th>Start of commerce operation</th>
<th>Inj. press. psi</th>
<th>No. of inj. wells</th>
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<td>9000</td>
<td></td>
</tr>
<tr>
<td>Bellevue</td>
<td>1970</td>
<td>60</td>
<td>15</td>
<td>90</td>
<td>300</td>
<td>Operated as a family business</td>
</tr>
</tbody>
</table>

Note: Ignition ONLY with electrical heaters. O$_2$ utilization ~ 80%
Bellevue: Results/Problems

Results

- V. low inj. pressure: 400 kPa (60 psi)

- Ultimate oil recovery: close to 60%

- AOR: 2700 sm³/m³ (15,000 scf/bbl)

Operational Aspects

- Ignition operation important for whole performance; strong ignition necessary

- Burning out of some producers; 20% of producers replaced with new wells; improved placement of new production wells

- Successful operation of separate layers in the same stack even when high BHT are recorded.
Field cases of ISC application in heavy oil reservoirs at *high reservoir temperature*

- Midway Sunset, California, USA
- West Heidelberg, Mississippi, USA
- Balol, India
- Santhal, India

Note: First two projects- completed; last two projects - ongoing
General Comments

- These projects did not have special instrumentation for investigation of ISC (no observation wells or coring wells; very few systematical BHT profiles)

- However, during long periods of operation (20 - 30 years) a lot of experience gained

- All projects conducted in a line drive configuration: “crestal” injection in the first two and a peripheral advancing line drive in the last two projects.
# Large Scale Commercial ISC Projects in High Temperature Reservoirs

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<th>INJ. WELLS</th>
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<td>2,700</td>
<td>52</td>
<td>1,500</td>
<td>110</td>
<td>6/up</td>
<td>34</td>
<td>1600</td>
<td>6,700</td>
<td>800</td>
</tr>
<tr>
<td>West Heidelberg, Gulf/Chevron</td>
<td>11,300</td>
<td>105</td>
<td>85</td>
<td>6</td>
<td>3/up</td>
<td>14</td>
<td>800</td>
<td>11,200</td>
<td>5,000</td>
</tr>
<tr>
<td>Balol, ONGC*</td>
<td>3000</td>
<td>70</td>
<td>3000 - 8000</td>
<td>150-500</td>
<td>50 / up</td>
<td>75</td>
<td>4400</td>
<td>11,200</td>
<td>&gt;1500**</td>
</tr>
<tr>
<td>Santhial, ONGC*</td>
<td>3000</td>
<td>70</td>
<td>3000 - 5000</td>
<td>50-150</td>
<td>45 / up</td>
<td>105</td>
<td>4000</td>
<td>11,2000</td>
<td>&gt;1500 **</td>
</tr>
</tbody>
</table>

* Situation as of 2006 (A Turta, S. Chattopadhyay, 2007)
** Very strong edge water drive
Midway Sunset, Moco T Zone

An anticline with 6 oil layers; DIP 20-45 degrees

- bottom water for M6 layer and edge water aquifer for other layers
  - Oil visc=110 cP; SGOR=75 scf/bbl (13 sm³/m³)
  - Pay thickness: 39m/150m (hₑ/ₜₒₜ=0.26!);.
  - Res. temperature 52°C; Spont. Ign: tₐᵣₖ=17days
Midway Sunset (primary recovery by ISC)

- Crestal air injection; comingled air injectors in all six layers; 6 injectors/34 producers; average daily air injection per well: 30,000sm³/day (≈ 1 million scfd)

- Productive area: 150 acres (60ha); well spacing approx. 2ha/well
- Successful commercial project; O₂ utilization efficiency close to 100%

- Average AOR= 1300 sm³/m³ (among best worldwide). 32 years of operations (as of ’94, when oil recovery was 24%); estimated ultimate oil recovery 45%

Well Completions

- No problems reported for production wells. Perhaps, these were not thermally cemented.

- **Air injection wells:**
  - Cemented and perforated liner of API grade J55 pipe; with another smaller-diameter *liner inside*. This is necessary as the SI does not occur simultaneously in different layers of the stack.

- Some temperature increase in the perforations can be recorded even weeks or months after start of air injection. Tubing should be set up at top of perforation (just in case it is needed).
West Heidelberg Commercial Operation (1971-1990)

- At $T_{res}$ of 105°C spontaneous ignition was extremely rapid. Production response: 3 months since start of air inj. (primary oil recovery was 6% at the initiation of ISC).

- Expansions (air injection increase, new wells, etc) occurred in 1978 and 1982.

- After 20 years of operations, oil recovery was >30%; incremental oil (>24%) was obtained at an AOR of 1,800 sm³/m³ (10,200scf/bbl). Ultimate oil recovery estimated at 41%.

- Project is considered a great technical and economic success.
West Heidelberg. Structural map at top of Sand 4

(Huffmann et al. 1983)

≈24 ft (8m)

- Updip side: Salt intrusion
- Downdip side: Immobile tar belt
- No water production (10-15% water cut)
- There are 8 oil productive sands (Sand 1 to Sand 8), but ISC is applied only for Sand 4 and Sand 5

242 = Bottom hole temperature during ISC (°C)
West Heidelberg Field

- Depth=3,500m (the deepest ISC project of the world); DIP 5-15°

- Effective pay thickness 20m; oil viscosity = 6 cP at T_{res}

- Permeability = 85 mD

- Under-saturated oil. Pi=38MPa; BPP=6.5MPa. Current res. pressure=5 MPa

- Productive area: 352 acres (140 ha); Well spacing ≈ 22 acres/well (9 ha/well)

- ISC application: crestal injection; 3 injectors (2-air, 1-flue gas)/14 producers; 5 millions scf/day (140,000sm³/day) air injection (maximum). Injection pressure: 3,000 - 5,000 psi (20 to 35MPa)
West Heidelberg. Structural map at top of Sand 4, with BHT on the map

- BHT recorded (1971-1990)
  - April 1981: Well 5-5-2 – BHT>149 °C
  - February 1981: Well 5-12-1 - BHT=242 °C
  - March 1985: Well 5-11-3 - BHT=213 °C

- Maximum BHT recorded: 242 °C (467 °F)

- There are reports of explosions in compressor station and in air pipelines, but there are no reports of damaged production wells; some corrosion/abrasion was reported
Balol and Santhahl Reservoirs

Wet combustion in a peripheral line drive, strong edge (lateral) water-drive reservoirs

Start of commercial operations: 1997
Ongoing
Balol and Santhal

SANTHAL-BALOL-LANWA FIELD - SCHEMATIC MAP SHOWING THE LOCATION OF THE EXPERIMENTAL IN SITU COMBUSTION PATTERNS

LEGEND:
- OIL WATER CONTACT
- PINCHOUT LINE S-I
- PINCHOUT LINE S-II
- PINCHOUT LINE S-III
- 940m. ISO-BATH
- INJECTION WELL
- PRODUCTION WELL
- OBSERVATION WELL
- ABANDONED WELL

NOT AT SCALE
Large Scale Commercial ISC Projects in High Temperature Reservoirs. Balol and Santhal  
(Very strong edge water drive)

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<td>Santhal**, ONGC</td>
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</tr>
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* Situation as of 2006 (A. Turta, S. Chatopatayay, 2007)  
**Santhal reservoir has two layers

Note: Coal and carbonaceous material is present in the formations
Note: Santhal ISC Project had an almost similar oil production evolution.
Balol and Santhal Performance

- Total oxygen consumption; with effluent O₂ %=0 everywhere
- BHT lower than 200°C were recorded in production wells
- No production well was damaged in almost 20 years of operation
Balol & Santhal: Other Results

- Artificial ignition (gas burner) and spontaneous ignition used for ISC initiation.

- Ultimate oil recovery: 26-36%.

- AOR around 11,200 scf/bbl- (2000 sm³/m³).

- Stability w.r.t. air injection interruption is practically infinity.

- Challenges in operating separately two layers in the same stack.
Favorable conditions for ISC application?

- When $T_R < 60-70^\circ\text{C}$ we may still have favorable conditions; laboratory tests needed to ascertain.

- Minimal laboratory tests: Ramped Temperature Oxidation (RTO) or Pressurized Differential Scanning Calorimetry (PDSC), first to determine kinetics, and then a Combustion Tube (CT) test to confirm (or not) the favorable conditions.
Oxygen consumption during typical RTO test for heavy oils and light oils (Moore et al., 2008)

- Light oil ISC: $T_{\text{peak}} \sim 240\text{-}380^0\text{C}$
  - No damage to production wells reported during field tests

- Different heavy oils have very different RTO (or PDSC) curves

- Medium-heavy oils (viscosity 60 to 600cp) may have oxidation characteristics similar to light oils with lower expected $T_{\text{peak}}$; RTO (PDSC) tests can indicate this

Light oils have higher chemical reactivity
Conclusions

In case of high temperature reservoirs (HTR) we should have significantly more courage to consider in-situ combustion (ISC) as an EOR method, because:

- Initiation of ISC is simple
- Operation is not so complicated (more stable process, less O_2 break-through, etc.)
- Bottom-hole equipment at production wells may not experience very high temperature and there are few damage risks

Direct consequence: it also makes ISC applicable to very thick, multiple layer formations

Most efficient applications: HTR with a dip of at least 3-5 degrees and deploying peripheral line drive ISC.