Guidelines for the Selection of a Waterflood Deoxygenation Strategy

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Recommended Strategy for Deepwater Waterflood Deoxygenation:

• Design for full chemical oxygen scavenger as a base case
  - Provide sufficient residence time for scavenger reaction
    • may require a retention vessel
    • required dose depends on temperature, mixing and scavenger concentration
    • w/o sulfate membranes: use catalyzed scavenger & provide 3 minutes to react
    • w/ sulfate membranes, can’t use catalyst so provide 5 minutes to react
  - Select appropriate metallurgy for poor scavenging & MIC control
  - Provide sufficient storage for 10 days

• Add mechanical deoxygenation in order to reduce OPEX
  - Required dose for chemical may be excessive in cold water
  - For Basis of Economics:
    • use historical / real uptime data (see below)
    • use real operating costs including Minox catalyst and other chemical costs
Historical Involvement in Compact Deoxygenation:

Seaject - Extensive field trials

- Developed initially by Norsk Process Inc. in 1980's
  - Initial funding / interest by Conoco
- 1990 Shell testing on shore
- 1990 One week pilot field test on Cognac
- 1992/1993 One year Bullwinkle field trial in parallel train
  - review report - many problems, excessive downtime
- 1994 - 2001 Shell Ram-Powell waterflood - Seaject on-line
  - many problems, excessive downtime
  - relying on chemical oxygen scavenger
  - extensive well tubing corrosion
- 1998 Axsia Serck Baker acquires Seaject
- 2001 Shell selects Seaject for Bonga
- 2001 Shell decommissions Seaject on Ram-Powell
Historical Involvement in Compact Deoxygenation:

2001 / 2002 Pivotal Years:

- SeaJect selected for Bonga & GA approved for construction
  - But operations raise strong objections
- Mars WF approved assuming compact deoxygenation
  - GA, weight & space constrained
- Shell acquires Enterprise, inc Bijupira-Salema
  - Minox selected by Modec / Alliance Engineering, designed by Minox
- Shell & BP (Mars partner) share their experience:
  - BP initial good experience with Minox
  - Minox selected for several more BP waterfloods
  - Not much industry experience available regarding Minox

Shell selects Minox for both Mars and Bonga
WF DeOx System – Common to all 3 DW WF:

- Overall nitrogen / seawater flow is counter-current
- Local nitrogen / seawater flow is co-current
  - nitrogen / seawater mixing in static mixers
- High efficiency from:
  - small bubble size (high surface area, short gas diffusion length)
  - 2-stage counter-current process
Shell Brazil Bijupira-Salema water injection performance

Water injection rate (cubes / day)

Bypass Minox –
Using full chemical scavenger instead
Dramatic Uptime Improvement

Voidage Replacement (cubes / day)
Mars topsides performance

Minox: 40% average downtime
<table>
<thead>
<tr>
<th>Project</th>
<th>Company</th>
<th>Mark</th>
<th>Date Installed</th>
<th>Capacity kBWPD</th>
<th>Working Effectively</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snorre</td>
<td>Saga</td>
<td></td>
<td>1991</td>
<td>375</td>
<td></td>
<td>Minox unit very successful here - single stage, using the catalyst reactor. Static mixer &amp; stripping tower contactor / separator.</td>
</tr>
<tr>
<td>Foinaven</td>
<td>BP Mark 1</td>
<td>1995</td>
<td>165</td>
<td></td>
<td>Y</td>
<td>76% injection against target - single stage, using the catalyst reactor. Static mixer &amp; stripping tower contactor / separator.</td>
</tr>
<tr>
<td>Schiehallion</td>
<td>BP Mark 1</td>
<td>1996</td>
<td>280</td>
<td></td>
<td>N</td>
<td>76% injection against target - single stage, using the catalyst reactor. Static mixer &amp; stripping tower contactor / separator.</td>
</tr>
<tr>
<td>Vigdis (Snorre)</td>
<td>Saga</td>
<td>1996</td>
<td>136</td>
<td></td>
<td></td>
<td>Conversions of fuel gas stripping tower</td>
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<tr>
<td>Masa</td>
<td>Petronas</td>
<td>1998</td>
<td>25</td>
<td></td>
<td></td>
<td>Conversion of fuel gas stripping tower</td>
</tr>
<tr>
<td>Siri</td>
<td>Statoil</td>
<td>1998</td>
<td>81.5</td>
<td></td>
<td></td>
<td>Conversion of fuel gas stripping tower</td>
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<tr>
<td>Staffjord</td>
<td>Statoil</td>
<td>1998</td>
<td>790</td>
<td></td>
<td></td>
<td>Conversion of fuel gas stripping tower</td>
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<tr>
<td>Gabon</td>
<td>Marathon</td>
<td>1999</td>
<td>45</td>
<td></td>
<td>-</td>
<td>Not installed</td>
</tr>
<tr>
<td>Pogo 1 (Thailand)</td>
<td>Chevron</td>
<td>1999</td>
<td>20</td>
<td></td>
<td>N</td>
<td>Not operating</td>
</tr>
<tr>
<td>Pogo 3 (Thailand)</td>
<td>Chevron</td>
<td>1999</td>
<td>40</td>
<td></td>
<td>N</td>
<td>Not operating</td>
</tr>
<tr>
<td>Glitne (FPSO)</td>
<td>Statoil PGS</td>
<td>2000</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pogo 2 (Thailand)</td>
<td>Chevron</td>
<td>2000</td>
<td>20</td>
<td></td>
<td>N</td>
<td>Not operating</td>
</tr>
<tr>
<td>ValHall</td>
<td>BP Two stage</td>
<td>2000</td>
<td>220</td>
<td></td>
<td>N</td>
<td>Fixed by NATCo</td>
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<tr>
<td>Halfdan</td>
<td>Maersk</td>
<td>2001</td>
<td>220</td>
<td></td>
<td>Y</td>
<td>Fixed by NATCo</td>
</tr>
<tr>
<td>Heidrun</td>
<td>Statoil</td>
<td>2001</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bijupira Salema</td>
<td>Shell Mark 3</td>
<td>2002</td>
<td>100</td>
<td></td>
<td>N</td>
<td>Minox currently by-passed. Relying on oxygen scavenger.</td>
</tr>
<tr>
<td>Mars</td>
<td>Shell Mark 2</td>
<td>2003</td>
<td>94</td>
<td></td>
<td>Y</td>
<td>Shell design</td>
</tr>
<tr>
<td>Balam GOM</td>
<td>Pemex</td>
<td>2005</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clair</td>
<td>BP Two stage</td>
<td>2005</td>
<td>100</td>
<td></td>
<td>Y</td>
<td>Requires 80 kbps. T. Marsh note of 29/6 says best achievable through Minox is 35 kbps.</td>
</tr>
<tr>
<td>Holstein</td>
<td>BP Mark 3</td>
<td>2005</td>
<td>100</td>
<td></td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>P 18 (Brazil)</td>
<td>Petrobras</td>
<td>2005</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thunderhorse GOM</td>
<td>BP Two stage</td>
<td>2005</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bonga</td>
<td>Shell Mark 3</td>
<td>2005</td>
<td>400</td>
<td></td>
<td>N</td>
<td>Minox in permanent bypass due to blower bearing problems. Relying on Oxy Scavenger injection.</td>
</tr>
<tr>
<td>Agbami (W. Africa)</td>
<td>Chevron</td>
<td>2006</td>
<td>450</td>
<td></td>
<td>-</td>
<td>Under installation 10/06</td>
</tr>
<tr>
<td>Atlantis GOM</td>
<td>BP Two stage</td>
<td>2006</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ursa (future)</td>
<td>Shell Mark 2</td>
<td>2008</td>
<td>-</td>
<td></td>
<td></td>
<td>Shell design with large vessels, internals and scrubbers (SRM: cannot inject de-foamer)</td>
</tr>
</tbody>
</table>
Problems w/
Mars
Bijupira-Salema
Bonga

- Salt deposits
- Vessels full of foam
- Catalyst fouling / short catalyst life
- Compressor fouling / high maintenance
Almost all conventional HC G/L systems have scrubbers U/S of compressors, yet this system has:
- No scrubbers
- Limited coalescing filters
- No membrane filters

### Carry-Over & Carry-Under:

<table>
<thead>
<tr>
<th>Residence Time (sec)</th>
<th>cfm/sq ft</th>
<th>cm/hour/sq m</th>
</tr>
</thead>
<tbody>
<tr>
<td>WF1</td>
<td>19</td>
<td>382</td>
</tr>
<tr>
<td>WF2</td>
<td>25</td>
<td>288</td>
</tr>
<tr>
<td>WF3</td>
<td>30</td>
<td>257</td>
</tr>
<tr>
<td>WF4</td>
<td>91</td>
<td>143</td>
</tr>
<tr>
<td>Auger HP Vert Sep</td>
<td>6</td>
<td>110</td>
</tr>
</tbody>
</table>

Gas flux: cubic feet per minute
cross-sectional area: sq ft
droplet entrainment

carry-under
note variation
Minox Separator Vessel Sizing
Should Account for Foam Height

Vessel Design should include Foam Height:

\[ H_V = H_O + H_F + H_G \]

- \( H_O \) = height of oil section (retention time = 1 minute)
- \( H_F \) = height of foam section
- \( H_G \) = height of gas section (Shell spec)

\[ H_F = \frac{V_F}{A_V} \]

\[ V_F = k_1 k_F E_F F_O \]

- \( k_1 \) = constant
- \( k_F \) = Foam Height Geometry Factor (dimensionless)
- \( E_F \) = intrinsic Foam to Oil ratio (ft\(^3\) foam/BPM)
- \( F_O \) = oil flow rate (BPM)

Deuel, Walsh: Deoxygenation Guidance
Seawater / Nitrogen Foam Height Design Curves:

<table>
<thead>
<tr>
<th>Foaminess Index (cu ft / BPM)</th>
<th>Bonga</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel ID (ft)</td>
<td>8.43</td>
</tr>
<tr>
<td>Liquid flux rate (BPM / sq ft)</td>
<td>1.9</td>
</tr>
<tr>
<td>Foam height (ft)</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Foam height as a function of vessel ID and foaminess index for the UPWF Minox separators:
Minox System. Possible Upgrades shown in red

- Nitrogen
- Inst Air
- Atm. Vent
- Backup Antifoam Injection
- From Fine Filters
- Drain
- FCV, FIC?
- Scrubber on catalyst inlet?
- Scrubber on compressor suction?
- Check valve or SDV?
- Spre compressor?
- Gas oxygen analyzer?
- Gas oxygen analyzer?
- High Capacity O₂ scav linked to bypass
- To Injection Pumps
- Replace LCV’s for control/isolation
- Outlet LCV here or at PCV3200 as Mars?
- Nitrogen Backup
- MEOH Injection
- Antifoam Injection
- Backup

Deuel, Walsh: Deoxygenation Guidance
WF2 Complex Oxygen Control Response

Separator Level control converted to direct control
Added a FIC / FCV upstream of the 1st stage separator
Changed the instrument gas pressure regulator to a FIC / FCV

Waterflood Feed Pumps

Strainers

Cartridge Filters

Air Makeup

Deuel, Walsh: Deoxygenation Guidance
Level / Flow Control for the DeOx / High Pressure Pump system

**WF1-problems**

- Operating experience: frequent trips on startup of HP pumps
- PIT instead of a FIT – sensitive dP / Q relation but too nonlinear

**WF2-successful**

- Operating experience: no trips on startup of pump systems
- LIC / LCV tied to overflow / discharge line – effective for rapid flow control / response
- Flow sensor tied to overflow / discharge line – effective over broad range of startup & normal operating conditions
Third-Party Review:
- sealing and salt deposition problems in the nitrogen blowers
- inability of the system to respond automatically to flow or temperature changes
- high degree of operator intervention required
- lack of engineering and service capability within Minox Technology
- In addition to the above, doubts remain about the capability of the separators to achieve adequate separation without making them substantially larger.

Holstein Upgrades:
The Minox unit for Holstein as delivered from Kvaerner Process Systems required instrumentation upgrades and de-bottlenecking. These upgrades included:
1. oxygen gas phase analyzers installed on inlet and outlet of the deoxidizer,
2. temperature indicators installed in the same locations as the gas phase oxygen analyzers,
3. methanol flow measurement and control,
4. instrument air flow measurement and control,
5. instrument air coalescing filters,
6. replacement of a Big Joe regulator to a PCV on second stage separator,
7. single 16” static mixer on separator inlets versus two mixers (10” and 12”) in parallel for turn down,
8. changed 50 hp to 60 hp blower driver,
9. increase deoxidizer catalyst bed volume,
10. installed methanol atomizing quill,
11. automated Minox inlet and by pass valves,
12. installed methanol and Instrument air mixing orifice,
13. made logic changes from sea water level to flow control
14. Tie-in of all Minox system input / output into the platform Honeywell DCS.
Opex Cost Considerations:

Scavenger: ppm rate depends on water T and source depth
- Holstein: 50 ppm (-650 feet from NSL)
- Bonga: 55 ppm (warm water)
- Brazil: 45 ppm (warm water)
- Mars: 80 ppm

Minox:
- MeOH polishing scavenger
defoamer
catalyst replacement cost

![Graph showing water rate vs. daily cost and annual cost with specific ppm values for different locations.]
Oxy scav is incompatible w/ hypo, which exposes D/ S piping to biofilm.

Org biocide is incompatible w/ oxy scav which causes an oxygen excursion when batch biocide is performed.

Thus, oxy scav must be nearly fully reacted before batch biocide addition. Also, a flush biocide treatment can be performed during S/ D.

Guidelines for Biomonitoring & Control should be followed.

There are other small but important design details that must be incorporated for long term integrity using chemical.

Global Category Management is working on this Guideline.
Other options:
  Stripping tower
  Vacuum tower
Even with these, break dependence on production uptime for power, gas, etc. need to switch to chemical to achieve waterflood uptime

However with chemical only systems, need to have high quality injection equipment plant uptime, sparing, automated flow control, alarm measurement, etc., Need residence time, and tanks

Weight space cost comparisons logistics storage uptime vs Brazil & Bonga uptime 95% +