KEY TECHNICAL CONSIDERATIONS FOR SUCCESSFUL HYDRAULIC FRACTURING OF HPHT WELLS

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Most common HPHT definition –

*Pressure > 10,000 psi (690 bar)*
*Temperature > 300 °F (149 °C)*

Most tight gas developments onshore Europe are HPHT condition

- Berettyóújfalu (Beru)
- Varnhorn
- Goldenstedt
- Sohlingen
- Oythe
- HOD
Setting the Scene

- **Reservoir**
  - Depth – ~ 3700 - 4200 m TVD
  - Lithology – Tight Sandstone
  - Temperature – ~ 150 – 210 ºC
  - Reservoir Pressure – ~ 600 – 700 bar
  - Permeability –
  - Porosity –
  - Reservoir Fluids – Gas, sometimes with condensate
  - Contaminants – may contain CO$_2$, H$_2$S

- **Production**
  - Pre- Fracturing –
  - Post- Fracturing –
**HPHT Tight Gas: Hydraulic Fracturing**

![Production Increase Factor (PIF) vs. Length](image)

\[ F_{cd} = \frac{k_f w}{k x_f} \]

- \( K_f \): Prop Pack Perm
- \( W \): Fracture Width
- \( K \): Formation Perm
- \( X_f \): Frac Half Length

- Fracture Length \((X_f)\) is inversely proportional to formation perm \((k)\)

**Effective Wellbore Radius \(\sim 0.5 X_f\) \((F_{cd} > 10)\)**

**Low perm**

**Long Fracture & small width**

Avg. Prop. Conc. = 2 #/sq.ft.

Saih Rawl Database (Oman)
Challenges of HPHT Well Fracturing

- Materials designed for high/ultra temperature applications:
  - Fracturing fluids
  - Completions, and zonal isolation
  - Perf guns, Testing...etc

- Materials designed for high pressure / stress applications:
  - Proppants

- An integrated workflow based on reservoir characterization:
  - MEM: predicting the stress
  - Fracturing stage placement / zonal coverage (stress profile)

- Minimize surface treating pressure:
  - Optimized perforation strategy in high stress zones
  - Breakdown / Diagnostic injections
  - Fluids initiatives (low friction, high density..etc)
Solutions for High Temperature
HT Fracturing Fluids Requirement

- Place all proppant without screen-out
- Robust fluid design with location water, chem
- Maximize fracture half length

- Maintain leakoff control
- Delayed viscosity generation
- Maximized Clean-up/Conductivity

- Proppant Suspension @ BH Temperature
- Retained Viscosity at Pressure
- Shear–Rate Regimes

**Ease of Design**

**Fluid Efficiency**

**Stability**

*HPHT Reservoirs exacerbate BH challenges in fracturing, require unique, robust technological advances*
Desired Viscosity Profile

1. Low-intermediate viscosity in tubing
2. Complete crosslinking at high temperature (propagate frac, suspend proppant)
3. Sufficient fluid stability with time at high temperatures
4. Reduced fluid viscosity (break) after proppant is placed
### High / Ultra Temperature Fluids

<table>
<thead>
<tr>
<th>Temperature Ratings</th>
<th>300°F</th>
<th>325°F</th>
<th>350°F</th>
<th>375°F</th>
<th>400°F</th>
<th>425°F</th>
<th>450°F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>149°C</td>
<td>163°C</td>
<td>177°C</td>
<td>191°C</td>
<td>204°C</td>
<td>218°C</td>
<td>232°C</td>
</tr>
</tbody>
</table>

- **Borate Crosslinked Fluids**
  - Requires water introduction for formation cool down
  - Fluid at tip may not be able to grow in length
  - Low prop pack conductivity due to high gel loading

- **CMHPG Zirconium Crosslinked Fluids**
  - Performance of early version CMHPG fluid usually compromised for:
    - Shear –sensitivity
    - Crosslink too early / too late
  - Later generation CMHPG fluid:
    - Overcome shortage of earlier version
    - Most commonly applied in onshore Europe HT wells recent years
    - Stretched in ultra temp wells

- **Synthetic Guar Fluids**
  - Developed for ultra temperatures: 350 – 450 °F

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**ThermaFRAC**

**SAPPHIRE XF**
ThermaFRAC* Fluid (200 - 375 °F)

Crosslinking too early
- High-friction
- Shear degradation
- Screenout

Crosslinking too late
- Low viscosity
- Small fracture width
- Screenout

What is the temperature at the perforations?

Shear Tolerance

Controllable Viscosity

Retained Perm

Viscosity Development

Earlier
CMHPG

Borate Fluid

Time
SAPPHIRE XF* Fluid (350 - 450°F)

**Polymer**
- Synthetic polymer for HT applications

**Crosslinker & Delay**
- HT crosslinker component
- Combined approach of chemical & temperature delay

**Surfactants**
- Surfactants acting as flow back aids to minimize risk of water block

**pH Buffer**
- Ensuring fast polymer hydration for high pump rate

**Temperature stabilizer**
- Chemical stabilization of polymer for high temperature application

**Breaker**
- Active breaker & encapsulated breaker for controlled viscosity reduction
SAPPHIRE XF* Fluid (350 - 450°F)

**SAPPHIRE XF 148 @ 450 degF [232 degC]**

![Graph showing viscosity and temperature over time](chart)

**Broken Gel Viscosity measured at 75degF (after 10 hr Shut-in)**

![Graph showing viscosity vs. shear rate](chart)

<table>
<thead>
<tr>
<th>Temperature degF</th>
<th>Fluid Description</th>
<th>Proppant</th>
<th>Breaker [lbf/1000 galUS]</th>
<th>Retained Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>SAPPHIRE XF48</td>
<td>20/40 Carbo HSP</td>
<td>10 (J481) + 10 (J490)</td>
<td>40%</td>
</tr>
<tr>
<td>350</td>
<td>SAPPHIRE XF48</td>
<td>20/40 Carbo HSP</td>
<td>10 (J481) + 10 (J490)</td>
<td>30%</td>
</tr>
<tr>
<td>325</td>
<td>SAPPHIRE XF40</td>
<td>40/70 sand</td>
<td>5 (J481) + 5 (J490)</td>
<td>59%</td>
</tr>
<tr>
<td>300</td>
<td>SAPPHIRE XF35</td>
<td>20/40 Carbo HSP</td>
<td>5 (J481) + 5 (J490)</td>
<td>56%</td>
</tr>
</tbody>
</table>

Test conditions: 5000 psi, 2 lb/ft²
SAPPHIRE XF* Fluid (350 - 450°F)

- 3 jobs in USA
- 60 BPM up to 5 PPA @ 300°F
- Per job ~ 4000 bbl fluid
- Per job ~ 192,000 lb Proppant

- 2 jobs in India
- 20 BPM up to 8 PPA @ 357°F & 395°F
- Per stage ~ 2000 bbl fluid
- Per stage ~ 170,000 lb Proppant

Planning for BP in Jordan
Solutions for High Pressure
Reservoir-Centric Integrated Workflow

- Integrated workflow supports seismic-to-simulation modeling
- Hydraulic Fracturing permanently alters the reservoir

Integrated workflow includes:

- Structure Lithology
- Staging & Perforating
- Geomechanical Model
- Microseismic Mapping
- Automated Gridding
- Reservoir Simulation

Complex Hydraulic Fracture Models
Tight Gas Sand Fracturing Design

- Where to initiate frac?
- Staging/zonal coverage?

1. Data Integration / Zoning
2. Identify Pay Zone
3. Identify Frac Units
4. Staging & Perforations
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Treating Pressure

\[ P_{\text{suf}} = (P_{\text{BD}}) + P_{\text{frac}} - P_{\text{hyd}} + P_{\text{net}} + P_{\text{fric}} + P_{\text{nwb}} \]

- Breakdown Gradient = 1.2 psi/ft (0.27 bar/m)
- NWB Friction = 1000 psi (69 bar)
- Fluid Friction = 340 psi (23 bar) @ 8 BPM

\[ P_{\text{suf}} = P_{\text{BD}} - P_{\text{hyd}} + P_{\text{fric}} + P_{\text{nwb}} \]
\[ P_{\text{suf}} = 1080 \text{ bar} - 396 \text{ bar} + 23 \text{ bar} + 69 \text{ bar} \]
\[ P_{\text{suf}} = 776 \text{ bar} \]

- Frac Gradient = 1.0 psi/ft (0.23 bar/m)
- NWB Friction = 1500 psi (103 bar)
- Net Pressure = 1000 psi (69 bar)
- Fluid Friction = 1700 psi (117 bar) @ 30BPM

\[ P_{\text{suf}} = P_{\text{FRAC}} - P_{\text{hyd}} + P_{\text{fric}} + P_{\text{nwb}} + P_{\text{net}} \]
\[ P_{\text{suf}} = 920 \text{ bar} - 396 \text{ bar} + 117 \text{ bar} + 103 \text{ bar} + 69 \text{ bar} \]
\[ P_{\text{suf}} = 813 \text{ bar} \]
Achieving a Better NWB Connection

- Connection between wellbore and hydraulic fracturing (through perforations) are extremely important for:
  - Formation Breakdown
  - NWB friction – perforations / tortuosity

  → stress concentration
  → proppant admittance

- Basic perforation requirements:
  - Penetration: 4~6 in (~12 cm) into formation
  - Perf hole size: $9 \times D_{pr\_ave}$
  - 2 shots / BPM
  - 60° phasing

- Abrasive jetting has been applied in several HTHP wells onshore Europe to lower down breakdown pressure, perforation friction

![Graph showing treating pressure and skin rate with time]
Additional Technology
# Ultra High Strength Proppant Technology

## CARBO KRYPTO SPHERE
- Retains integrity at 20,000 psi closure
- Single mesh size product (any size)
- Twice baseline conductivity at 20,000 psi compared to typical HSP
- Spherical shape and smooth surface to significantly reduce erosion

## SAINT GOBAIN TITAN 3050
- Industry’s first beyond conventional
- Rated 20000, 25000, 30000 psi
- Available in 30/50 mesh

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**High-strength proppant**
Irregular size and shape with manufacturing imperfections.

**KRYPTOSPHERE**
Uniform size and shape with exceptional microstructure.

![Enhanced Mechanical Strength](image-url)
HiWay* Flow Channel Frac Technology

More Value with Less Resources Demanding

Reliable service, proven solution
- > 13,800 treatments (> 1,200 wells) in 16 countries
- Variety of formations (carbonate, sandstone, shale)
- Unprecedented proppant placement rate (99.9%)
  - ~ 700 screen-outs prevented to date

Significant impact on production
- >20% increase in tight formations

Significant reduction in logistics, safety risks and environmental footprint. Reductions in:
- Water and proppant consumption per job of 25% and 42%, respectively;
- > 540 million gallons of water and > 1.8 billion lbs of proppant saved so far;
- > 80,000 proppant and water hauling road journeys
- ~ 18 million lbs of CO2 emissions avoided

Paradigm shift in hydraulic fracturing technology
Conclusion

- Fracturing fluid technology developments facilitate the challenges of ultra-high-temperature reservoirs.

- Success of hydraulic fracturing in HTHP wells lies on the application of proper workflow, includes multi-discipline contributions:
  - Materials technology for HTHP application
  - Reservoir description and data integration
  - Proper staging to achieve optimum zonal coverage
  - Proper perf strategy to minimize treating pressure

- Based on well conditions, “out of box” additional technology may be tested to evaluate its applicability onshore Europe.
Thank Your & Discussions