Snorre In-depth water diversion

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Outline

• Introduction
• Numerical simulation of the two-well silica pilot
• Execution of the silica plot
• Results
• Conclusions
In-depth water diversion – Sodium silicate

Goal: Establish flow restrictions in flooded areas to improve lateral and vertical reservoir sweep

• Silicate
  • Low temp – Flows like water
  • Reservoir temp - Gelling

• Dynamic gelling:
  • 2008-2009: Lab: > 25 bar
  • 2011: Single well test: 80-120 bar

• Intolerant to seawater (need preflush)
Sodium Silicate

- paper industrie, adhesive/lamination
- soil remediation/soil solidification
- binding material for foundry
- Coatings
Snorre field

- Fluvial sand deposits
- Permeability: 0.1 – 4 D
- Initial Reservoir Pressure: 383 bar
- Reservoir Temperature: 90 °C
- Production start: 1992 with water injection
- WAG injection from 1996 in parts of the field
Pilot area

Thief zone challenge

Initial injection water front speed: approx. 6 m/d (2002-2003)
Water tracer injection (2008)
Tracer front speed: 9-11 m/d
EOR Modeling

Reservoir cooling from water injection

- Initial reservoir temperature
  - ~95° C

- Reservoir cooling from water injection 2002-2013
  - ~9 mill Sm³ - 30° C

Jan 1st, 2002
Jan 1st, 2003
Jan 1st, 2004
Jan 1st, 2005
Jan 1st, 2006
Jan 1st, 2007
Jan 1st, 2008
Jan 1st, 2009
Jan 1st, 2010
Jan 1st, 2011
Jan 1st, 2012
Jan 1st, 2013
EOR Modeling

Temperature simulations

- Reservoir temperature is still observed in the producer.
- Temperature is matching slightly better for the wide thief zone.

Narrow thief zone

Wide thief zone

July 2013
EOR Modeling

Simulations: Placement of in-depth restriction

Reduced permeability if
- \( T > 70^\circ C \)
- Silicate concentration > 1%

Restarts and a script is used for dynamically enforcing the permeability reduction.
Modeling of the response

Simulated response from in-depth diversion

Many sensitivities performed – Study uncertainties and risks
Tracer response

Reference case

Wide thief zone

Narrow thief zone
Mezzanine deck
Fresh water plant – Generators
Acid storage
Mixing equipment
HP-pumps – Control cabin
Silicate refill

Accommodation
Life boat
Helicopter deck
Subsea water injection well – Modified vessel
Injected volumes

• 1.5 months Pre-flush: 113 500 m³
  – Concentrated KCl
  – Diluted with desalinated water

• 3 months Silicate injection: 240 000 m³
  – Concentrated Silicate
  – Diluted with desalinated water
  – pH adjustment with HCl
    (diluted from concentrated acid)

• 0.5 month Post-flush: 49 000 m³
  – Concentrated KCl
  – Diluted with desalinated water
Resupply of Silicate (batch 2)
From Anneleen Knutsen to Siri Knutsen

Vessel capacity: 50% of the concentrated Sodium Silicate
Offshore vessel-to-vessel re-supply
E-4 H - Falloff tests

- **Early data:** General same behaviour
- **Late data:** Increasing slope indicates reduced mobility far from the well

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**Pressure** vs **Time**

- **Before Silicate**
- **During Silicate**
- **After Silicate**
### Tracer injections - Pre-pilot:
- 25.02.2008 2-FBA (25 kg)
- 14.04.2012 4-FBA (25 kg)
- 14.04.2012 IFT-WT-60 (25 kg)

### Silicate pilot pumping sequence
- Preflush: 113,500 m³ KCl preflush injected (02.06.13-15.07.13)
- Silicate injection (4% silicate): 240,000 m³ Sodium Silicate injected (16.07.13-13.10.13)
- Postflush: 49,000 m³ KCl postflush – (13.10.13-27.10.13)

### Tracer injections – Silicate pilot:
- 02.06.2013 Start of **preflush injection**
- 08.06.2013 Tracer injections: 2,4,5-TFBA (25 kg) and 2,6-DFBA (125 kg)
- 06.07.2013 Tracer injection: IFE-WT-9 (25 kg)
- 15.07.2013 Started **Silicate injection**
- 13.10.2013 Started **postflush injection**
- 26.10.2013 Tracer injection: 3,4-DFBA (125 kg)  
  **No BT of post silicate tracers**
- 27.10.2013 Disconnection – **End of operation**
- 30.04.2014 Tracer injections: IFE-WT-15 (25 kg) and IFE-WT-41 (125 kg)  
  **No BT of post silicate tracers**
Comparison of tracer detections – 25 kg tracers
Tracer detection concentration versus cumulative injection

![Graph showing tracer detection concentration versus cumulative injection]
Comparison of tracer detections – 25 kg tracers
Tracer detection concentration versus cumulative injection
Comparison of tracer detections – 125 kg tracers
Tracer detection concentration versus cumulative injection
P-15 Watercut from start of pilot injection
(Latest test, 28.04.2015)
Water cut – P-15

Blue solid: DG3 sim. – ref
Blue dashed: DG3 sim. - gelling
Red: Observed (from day rates)
Black diamonds: Observed (well tests)
Decline in "reservoir transmissibility" after start silicate injection
Monthly average injection rate in E-4AH
Conclusions – January 2015

• **Operation**
  - New concept of using shuttle tanker as operation platform for large scale chemical injection in subsea wells has proven operationally robust
  - Large scale logistic-operation and desalination of sea-water, mixing and injection successful

• **Permeability reduction**
  - A significant flow restriction is established deep into the reservoir (FO-tests)
  - No near wellbore damage in the injection well observed
  - No breakthrough of Silicate in the production well even with more than twice displacement volume injected as compared with previous tracer BT volumes

• **Sweep alteration**
  - Restriction will induce changes in flow pattern for injected water (tracer, H$_2$S)
  - None of the tracers after start of silica injection has been observed in the producers

• **EOR effect**
  - Trend in water cut changed from increasing to decreasing from April/May 2014
  - Stabilized oil production rate (Constrained by water injection)
2012 (DG3) – Snorre Field Pilot success criteria

Technical success criteria
• Successful large scale transportation, mixing and pumping of silicate. **Confirmed**
• Proved in-depth flow restriction and minor near wellbore damage. **Confirmed**
• Proved significant change in flow pattern. **Confirmed**

Economical success criteria
• Conclusive IOR-response (reduced water cut). **Confirmed**

Interpretation of IOR volume within 2015.
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  - ExxonMobil E&P Norway AS
  - Idemitsu Petroleum Norge AS
  - DEA Norge AS
  - Core Energy AS

- **Contractors**
  - IRIS
  - Knutsen NYK Offshore Tankers
  - Halliburton
  - BASF
  - SS7
Backup
Main risks

• **Main risk highlighted as main risks at DG3 decision:**
• Damage of injection well or production well. *Cleared*
• Handling of strong acids and high alkaline fluid. *Cleared*
• IOR response below detection limit. *Cleared*
Other risks

- **Other DG3 risks:**
  - Ambiguous time plan (Planned 7 months from DG3 to operation start) **Cleared**
    - Siri Knutsen installation/modification completed according to plan
  - Regulatory regime for the vessel (New concept) **Cleared**
    - Stimulation vessel regulations for Siri Knutsen (Not an installation)
  - 3” hose design/strength **Cleared**
    - Operation within comfortable margins for 3” hose
  - Silicate supply and quality (Extensive logistic operation) **Cleared**
    - Good silicate quality and cleanliness:
      - All conc. silicate filtered (5 micron abs.) on Siri Knutsen before dilution.
  - Up-scaling of mixing accuracy from lab scale to field scale **Cleared**
    - Good quality:
      - Gelling time on samples from injection resembled gelling time from lab.
      - All injected fluids filtered through 10 mikron filters
  - Damage of injection well: Near wellbore plugging of injection well **Cleared**
    - No near wellbore damage.
  - Damage of production well – Break through of unreacted silicate **Cleared**
    - No silicate break through after 100 % increase of displacement volume compared with pre-job tracer break through
  - IOR response below resolution **Cleared**
    - It seems like the IOR-response will be above resolution of response measurement
  - Breakthrough of cold injection water in the production well will increase the risk of failure **Cleared**
    - No reduction in temperature of produced water.
  - Well integrity problems in injector or producer may prevent the pilot operation or response measurement **Cleared**
    - No well integrity issues in injection well or production well.
  - Siri Knutsen operational limitations due to weather. **Cleared**
    - High regularity: 4-5 short disconnects due to weather limitations
  - Silicate re-supply: Off shore vessel to vessel silicate transfer (Both vessels on DP) **Cleared**
    - Successful vessel to vessel transfer
Ion analysis: H2S concentration P-15
(Latest measurement 28.04.2015)