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Hydraulic Fracturing of Horizontal Wells
- Realizing the Paradigm Shift that has been 30 years in Development

Dr. C. Mark Pearson
Liberty Resources LLC
Key Technologies

Horizontal Wells and Hydraulic Fracturing both stand as separate technologies that have had a significant impact on the petroleum industry and our ability to develop hydrocarbon resources. The combination of the two technologies have resulted in an industry revolution:

- 24000 references to Horizontal Well Fracturing in the SPE/One Petro Database
- Over 60% of US drilling activity is drilling horizontal wells
- In 2011, Pressure Pumping Services became the largest single business segment in the Oilfield Services arena.
Outline

- Early Studies and Fracturing of Horizontal Wells
- Current Multi-Stage Completion Designs:
  - Cemented Vs Uncemented Liner / Casing
  - “Plug and Perf” Vs “Sliding Sleeve”
- Bakken Shale – Central Basin Development
- Current Developments / Changes in Completion Practices
- Conclusions
Horizontal Well Drilling

• The first recorded horizontal well was in Texon, Texas in 1929 and another in the Franklin Heavy Oil Field, Pennsylvania in 1944.

• Short radius wells were tested by ARCO in 1979-1982 in the Empire Abo Field, New Mexico.

• Offshore platforms and remote land locations (e.g. Alaska) required the development of directional drilling technology:
  – Downhole motors
  – Measurement While Drilling
  – Steerable assemblies
  – Logging While Drilling

• First Medium Radius Horizontal Well was drilled in the Austin Chalk in May 1985 by ARCO – the John G. Hubbard #1 in Rockwall, Texas; a 1500ft lateral with a $20^\circ/100\text{ft}$ build rate.
Early Application of Horizontal Wells (1980’s)

- To handle reservoir issues in some developments that were already using deviated wells – gas coning problems, unconsolidated formations, thin sands development.
- Opportunity to more effectively develop naturally fractured reservoirs – e.g. the Austin Chalk.
- By the late-1980’s industry was already testing the opportunity to combine the technologies of horizontal drilling and hydraulic fracturing.
- Modern horizontal well drilling came of age at the end of the 1980’s:
  - 257 horizontal well permits issued in the USA in 1989.
  - Over 1000 permits in 1990.
  - API started tracking horizontal drilling in 1991.
Reservoir Contact from Fracturing – Vertical Well

Openhole completion: $8\frac{3}{4}''$ hole diameter * 50 ft = $115$ ft$^2$ of contact

Cased hole completion: 4 spf, with 2 ft. penetration beyond cement 200 perf tunnels, $\frac{1}{2}$ inch diameter = $52$ ft$^2$ of contact

Fracture Stimulated Completion: 500 ft half-length 2 wings * 2 faces * 500 ft * 50 ft = $100,000$ ft$^2$ of contact

Hydraulic Fracturing can increase reservoir contact in a vertical well by ~1,000 fold!
Reservoir Contact from Fracturing – Horizontal Well

Openhole completion: 6” hole diameter * 50 ft = 7850 ft² of contact

Cased hole completion: 1 spf, with 2 ft. penetration beyond cement
5000 perf tunnels, ½ inch diameter = 1310 ft² of contact

Fracture Stimulated Completion: 500 ft half-length
20 Stages * 2 wings * 2 faces * 500 ft * 50 ft = 2,000,000 ft² of contact

Horizontal Well Hydraulic Fracturing increases Reservoir Contact Area
>10,000 fold over a conventional vertical well!
The Resource Triangle

Source: Wood Mackenzie
1983 Gulf R&D Study on Horizontal Wells

- Significant potential for increasing production rates and EUR by fracture stimulating a horizontal well in a tight gas sand

- Completion Problems:
  - Casing Centralization
  - Cement Displacement

- Stimulation Issues:
  - Fracture Re-Orientaion
  - Fracture Extension / Growth
1980’s Completion Design

- Primary application to fractured carbonate reservoirs
- Acid stimulation – bull headed into the lateral with a similar design to a vertical well acid treatment using diverter stages in an attempt to maximize contact area
- Attempts to pump propped fracture treatments took a similar approach
Early Multi-Stage Hydraulic Fractured Well

Treatment Design:

- Pad
- 1 ppa
- 2 ppa
- 3 ppa
- 5 ppa
- 6 ppa
- Diverter

W M Schrock (26) #8 – Fractured July 7th 1987
Late 1980’s/90’s – Dan Field Redevelopment
Danish North Sea; SPE 25049 (1992)
1990’s – Emergence of Zonal Isolation Technology

- Fully cemented liners
  - Separate perforated intervals
- Temporary Wellbore Plugs
  - Sand
  - Gel
- External Casing Packers:
  - Hydraulic inflated packer ran on the outside of the casing
  - Typically set with either drilling mud or cement.
Kuparuk: Use of Longitudinally Fractured Wells

![Graph showing recovery comparison of fractured and non-fractured horizontal wells over time.](image)

![Drill Site 3R Fault Map highlighting certain locations.](image)
Kuparuk: Use of Longitudinially Fractured Wells

![Graph showing cumulative oil production over time for 4 horizontal wells (red) and 8 offset wells (yellow). The red line represents an average of 4 horizontal wells, demonstrating significantly higher cumulative oil production compared to the yellow line for the average of 8 offset wells. The graph spans from 0 to 20 years, with cumulative oil production measured in billions of barrels (BO).](image-url)
Valhall Field Development
Norwegian North Sea; SPE 84392 (2003)
Valhall Field HFHW Development Results
Comparison of Acid and Proppant Fracturing

![Graph showing discounted cumulative production vs. production time for different treatments]

- **Acid - High (3 wells)**
- **Acid - Low (2 wells)**

**Discounted Cumulative Production (BO)**
- 7,000,000
- 6,000,000
- 5,000,000
- 4,000,000
- 3,000,000
- 2,000,000
- 1,000,000
- 0

**Production Time (years)**
- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
Late 1990’s – Horizontal Well Completion Options

1. Openhole “barefoot” completion – no stimulation or single stage acid

2. Uncemented slotted or pre-perforated liner with a single stage acid or frac treatment (with or without diverting materials).

3. Cemented liner / casing – multi-stage perforating with gel or solid plugs allowing multi-stage fracturing
Late 1990’s – Composite Plug Development

Wireline run below perforating tools

Standard equipment for 4-1/2” and 5-1/2” liners

Up to 12,500 psi differential pressure rating

Easily drilled out using either a workover rig or coiled tubing
Typical Gas Shale Cemented Liner Completion

- KISS principle of Completion Design (Keep It Simple Stupid)
- Use of “Plug and Perf” completion technique
- Multiple (10 to 15) Completion Stages per well
- Relatively large Slickwater stimulation treatments (200 to 500,000 lbs per stage)
Barnett Shale Horizontal Well Pilot

- 2.02 Average Uncemented
- 1.74 Average Cemented
- 0.84 Average Vertical
Mid-2000’s – Development of Swell Packer Technology

- Bonded element to standard casing / liner pipe; oil or water swellable:
  - Typically can withstand 5000 psi differential pressure

![Diagram of swell packer technology](image_url)
Uncemented Wellbore Schematic
Example 20 stage “Plug and Perf” Completion

- Application in liquid-rich fractured reservoirs
- Propped Fracture Stimulation is typically run across 15 to 35 completion stages working from the toe of the well to the heel.
Mid-2000’s: Ball Activated Sliding Sleeve Development
Sliding Sleeve Example
Uncemented Wellbore Schematic
Example 20 stage “Sliding Sleeve” Completion

• Application in liquid-rich fractured reservoirs

• Propped Fracture Stimulation is typically run across 10 to 40 completion stages working from the toe of the well to the heel.
Open Hole Multi-Stage Systems; SPE 135584 (2010)

Production of 3 wells with a cemented liner & plug and perf completion Vs. 13 wells in the same field with an openhole liner and sliding sleeves
## 2012 Current Multi-Zone Completion Techniques

<table>
<thead>
<tr>
<th>Plug and Perf</th>
<th>Vs.</th>
<th>Sliding Sleeve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cemented or uncemented</td>
<td></td>
<td>Uncemented</td>
</tr>
<tr>
<td>Unlimited # of zones</td>
<td></td>
<td>Typically limited to ~20 stages (repeater port technology increases this)</td>
</tr>
<tr>
<td>Multiple perf clusters per stage</td>
<td></td>
<td>Typically 1 opening per stage (mutil-port technology is available)</td>
</tr>
<tr>
<td>Slickwater or Gelled Frac</td>
<td></td>
<td>Slickwater or Gelled Frac</td>
</tr>
<tr>
<td>Slow - Repetitive perforating and stimulation phases to each stage (3 to 5 hours per cycle)</td>
<td></td>
<td>Fast – timing is driven by the frac design (1–2 hours per cycle)</td>
</tr>
</tbody>
</table>

**Estimated Usage:**
- 100% of Gas Shale Completions
- ~70% of Oil Shale Completions
- ~30% of Oil Shale Completions
Williston Basin Geological Cross-Section
Bakken Lithofacies

Deadwood Canyon Ranch #43-28H

Facies G
(10,077 – 10,077 feet)
(3,071.5 – 3,071.5 meters)

Facies E1, E2 & F
(10,077 – 10,084 feet)
(3,071.5 – 3,073.6 meters)

U. Bakken

Facies C1 & C2
(10,102 – 10,119 feet)
(3,079.1 – 3,084.3 meters)

M. Bakken

Facies A
(10,142 – 10,146 feet)
(3,091.3 – 3,092.5 meters)

L. Bakken

Facies D1 & D2
(10,084 – 10,102 feet)
(3,073.6 – 3,079.1 meters)

Facies B
(10,119 – 10,142 feet)
(3,084.3 – 3,091.3 meters)

Facies G
(10,146 – 10,192 feet)
(3,092.5 – 3,106.5 meters)

Simenson, 2010
Bakken Case Study: Structure & Development

1. Antelope Arch
2. Nesson & Billings Anticlines
3. Elm Coulee Field
4. Sanish / Parshall / Ross Fields
5. Central Basin
Central Basin Initial Well Results - 2006

Treatment Design:

- Pad
- 2 ppa
- 3 ppa
- 4 ppa
- 5 ppa
- Diverter

} x6

Calculated Average Monthly Oil Rate (BOPD)

Production Month

- Well #1
- Well #2
- Well #3
Central Basin Initial Well Results: 2006
Central Basin Initial Well Results: 2006 & 2008
Central Basin Company B Well Results: 2008

- 9 Stage Completions

Graph showing cumulative oil production over producing days for Well #6 and Well #7.
Central Basin Company B Well Results: 2008
Central Basin Company B Well Results: 2008-2010
Central Basin Company A and B Initial Well Results: 2008-2010
North Dakota Rig-Count and Production
North Dakota Rig-Count and Production

... and 3% Unemployment Statewide

source: https://www.dmr.nd.gov/oilgas/stats/historicaloilprodstats.pdf
Current Developments in Multi-Stage Horizontal Wells

- Further development of completion hardware
  - Repeater Ports
  - Multi-Entry Sleeves
  - Cemented Sleeves

- More / better measurement of what how much of the resource we are draining from each well

- A focus on pad developments:
  - Simultaneous operations
  - Simulfrac treatments
Pad Development – Horn River Basin, BC
SPE 140654 (2011)

Courtesy: Apache Corp.
Example MultiStage Microseismic Mapping at Horn River, BC
Marcellus Shale Mapped Fracture Treatments

SPE 145949 – Courtesy of Pinnacle Technologies

http://nwis.waterdata.usgs.gov/nwis/inventory
The Resource Triangle

Increased reservoir contact per well:

- **Vertical Wells with Hydraulic Fracturing**
- **Horizontal Wells with Multi-Stage Hydraulic Fracturing**
Conclusions

- Horizontal Drilling technology has been actively used for the past 30 years, but it is only in the last 5 to 10 years that we have seen the widespread application of multi-stage hydraulic fracturing of horizontal wells.

- The reservoir productivity gains from multi-stage hydraulic fracturing of horizontal wells is causing a revolution in our industry:
  - The number of horizontal rigs
  - The need for pumping services
  - The opportunity for economic exploitation of Unconventional Resources

- Today’s Completion Engineer has a variety of completion tools and techniques which can be applied to effectively stimulate horizontal wells.

- No one completion design fits all cases.
The Technology Doesn’t Always Work!!
Mississippian Lime Formation (OK) – 3 Stage Completion (2007)

- Event locations from all stages plot in the same general area
- Width: 1700 ft.
- Height: 500 ft.
What is the Reservoir Potential with an Optimal Stimulation?

- Bakken well with 3522 ft lateral
- Located on the Nesson Anticline
- Frac Design and Service provided by Mother Nature!!

Cum Prod = 1,284,231 bbls oil (July 2012)
Acknowledgements

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  – TAM International (Kendall Manning)
  – ex-UPRC personnel (Nathan Meehan, Santosh Verma)
  – Wood MacKenzie (Sid Sen)
Thank you !!!

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