SPE-194345

Trends in the North American Frac Industry: Invention through the Shale Revolution

Updated w/ DJ Basin Focus

Leen Weijers, Chris Wright, and Mike Mayerhofer; Liberty Oilfield Services
Mark Pearson, Larry Griffin and Paul Weddle; Liberty Resources
Conventional vs Shale Frac’ing

• 1947 – present

• Higher permeability sand – **Moving the hydrocarbon molecule to the frac**

• Vertical wells, mostly single stages

• Focus on conductivity

![Diagram showing sand and shale layers with pressure and temperature conditions](image-url)
Dawn of the Shale Revolution

“The Frac that Changed Everything”

• Persistence, ingenuity & luck
• Thin fluids; Almost no proppant
• Multi-directional networks
  • Interaction w/ natural fracs
  • Massive network from single stage in vertical well: 4,000 x 1,000 ft
• Proof: Killed offset wells and had “eyes” to see what happened “down there”

From: SPE 77441 & 90051 (2001)
Conventional vs Shale Frac’ing

- 1947 – present
- Higher permeability sand – **Moving the hydrocarbon molecule to the frac**
- Vertical wells, mostly single stages
- Focus on conductivity

- ~2000 – present
- Low permeability shale – **Bringing the frac to the hydrocarbon molecule**
- Multi-stage horizontal wells
- Focus on complexity – “2 miles of plumbing”
Increase in Fractivity through the Shale Revolution

![Graph showing the increase in HHP through the years, with annotations indicating a 10x increase to approximately 20 million and a 2 million increase.](image-url)
Increase in Fractivity through the Shale Revolution

Stage Count – 20x

- 25,000

- 500,000
Increase in Fractivity through the Shale Revolution

Prop Mass – 40x

~5 billion

~200 billion

Graph showing propellant mass in billions from 1990 to 2020.
“Big Picture” Liquid-Rich Frac Trends

- Stage count stabilizing and declining in some basins
- Lateral lengths catching up to Williston
- Rates keep increasing
“Big Picture” Liquid-Rich Frac Trends

- Stage count stabilizing and declining in some basins
- Lateral lengths catching up to Williston
- Rates keep increasing
- Rockies basins have stabilized fluid volume and proppant mass at ~1,000 lbs/ft
- Texas basins approaching ~2,000 lbs/ft
Shale Revolution Frac Trends

- Larger fracture network
  - Horizontal wells
  - Longer laterals
    - Increase in proppant mass
    - Increase in fluid volume
- Denser fracture distribution
  - Higher stage count
  - Higher pump rate
  - Changes in perf clustering
- Cost-sensitive
  - Fewer additives
  - Local proppant

Further increase if basin swaps to local proppant?
Poll

Text to: 22333

Leenweijers113
Where Will the DJ Sand Train Stop (in Proppant Mass per Lateral Foot)?

- 500 lbs/ft Northern White Sand: 10%
- 1,000 lbs/ft Northern White Sand: 2%
- 2,000 lbs/ft Northern White Sand: 2%
- 1,000 lbs/ft Regional Sand: 35%
- 2,000 lbs/ft Regional Sand: 47%
- >3,000 lbs/ft Regional Sand: 6%
Shale Revolution Frac Trends

• Larger fracture network
  • Horizontal wells
  • Longer laterals
  • Increase in proppant mass
  • Increase in fluid volume

• Denser fracture distribution
  • Higher stage count
  • Higher pump rate
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Slightly decreasing stage intensity
Shale Revolution Frac Trends

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Williston Basin

- Increasing clusters/stage
- Stable perfs/stage
- Increasing rate/perf
- Increasing rate/ft/stage
First Sand Ramp Cluster Efficiency (RA prop tracers):

- Non XLE Avg. = 59%
- Non XLE Avg. = 85%*
  *With Solid Particle Diverter (SPE 184828)
- XLE = 85% Initial PCE
- XLE = 93%* Final PCE
  *No other diversion

XLE ΔPperf Trials:

- 2,000 psi – 4,000 psi
- End of Stage Step Down Analysis

 Courtesy: SPE-189880 – Weddle et al.
Multi-well calibration of $N_p$ has resulted in a 75% holes open design assumption:

- Max rate before SDT impacts the number of holes initially open.
- Intra-stage $S_{H_{min}}$ variability impacts % of holes open.
- Calibration of $N_p$ gives ability to consistently achieve desired pump rate.

\[
\Delta P_p = P_{pf} = \frac{0.2369 \rho Q^2}{D_p^4 N_p^2 C_D^2}
\]

Where:
- $\Delta P_{perf}$ = Total perforation friction, psi
- $Q$ = Total Flow Rate, BPM/perf
- $D_p$ = Diameter of perforation, in.
- $C_D$ = Perforation coefficient
- $\rho$ = Fluid density, lbs/gal
- $N_p$ = Number of open perforations

Step Down Analysis:
The Step Rate Test performed pre- & post-proppant
- SPE 62549 L. Weijers, C.A.Wright...et al)
Shale Revolution Frac Trends

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DJ Basin

- Increasing clusters/stage
- Stable perfs/stage
- Stable rate/ft/stage
Shale Revolution Frac Trends

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Williston Basin

Critical mass for HVFR

Reduction in gel loading and use
Shale Revolution Frac Trends

- Larger fracture network
  - Horizontal wells
  - Longer laterals
  - Increase in proppant mass
  - Increase in fluid volume

- Denser fracture distribution
  - Higher stage count
  - Higher pump rate
  - Changes in perf clustering

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DJ Basin

Discontinuation of gel for some operators

Slight reduction in gel use and increase in FR use?
Shale Revolution Frac Trends

- Larger fracture network
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  - Increase in proppant mass
  - Increase in fluid volume
- Denser fracture distribution
  - Higher stage count
  - Higher pump rate
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Delaware Basin

- 20/40 mesh out
- 40/70 mesh generating traction
- 100 mesh increasing fast
Shale Revolution Frac Trends

- Larger fracture network
  - Horizontal wells
  - Longer laterals
  - Increase in proppant mass
  - Increase in fluid volume
- Denser fracture distribution
  - Higher stage count
  - Higher pump rate
  - Changes in perf clustering
- Cost-sensitive
  - Fewer additives
  - Local proppant

**DJ Basin**

- 20/40 down but not out
- 40/70 mesh favorite, but VERY operator specific preferences
- 100 mesh mostly absent
But What Drives Production? Trends
Multiple Linear Regression: Codell

RMSE as % of Mean Response = 31%
## What Drives Production - Statistics (Codell Example)

<table>
<thead>
<tr>
<th>Variable</th>
<th>MLR</th>
<th>PB MLR</th>
<th>ACE</th>
<th>GAM</th>
<th>MARS</th>
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<tr>
<td>AdjustedWC365Day</td>
<td>31%</td>
<td>30%</td>
<td>18%</td>
<td>38%</td>
<td>20%</td>
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<td>PropMassPerLateralLength</td>
<td>28%</td>
<td>27%</td>
<td>21%</td>
<td>27%</td>
<td>14%</td>
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<tr>
<td>GOR365Day</td>
<td>13%</td>
<td>13%</td>
<td>15%</td>
<td>15%</td>
<td>11%</td>
</tr>
<tr>
<td>VitiniteReflectance</td>
<td>11%</td>
<td>11%</td>
<td>11%</td>
<td>7%</td>
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<tr>
<td>AvgPPG</td>
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<td>8%</td>
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<td>WaterSaturation</td>
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<tr>
<td>LateralLength</td>
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<td>8%</td>
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<td>StageSpacing</td>
<td>1%</td>
<td>1%</td>
<td>5%</td>
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<td>&lt;1%</td>
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<tr>
<td>TOC</td>
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<td>1%</td>
<td>3%</td>
<td>2%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

MLR = Multiple Linear Regression  
PB MLR = Physics-Based Multiple Linear Regression  
ACE = Alternating Conditional Expectations  
GAM = Generalized Additive Model  
MARS = Multivariate Additive Regression Splines
What Drives Production? $/BO Optimization

“There’s a Fine Line Between a Numerator ($) and a Denominator (BO)”, Yogi Berra

Happy Valley
The American Shale Revolution

Better Wells

DJ shows least improvement

+70%
since 2012

+28%
since 2012
What Will Drive You to Happy Valley?

- Tighter staging: 8%
- More fluid: 10%
- More proppant: 4%
- Higher rate: 15%
- Diverters: 15%
- Local proppants: 12%
- Courser staging, more clusters: 21%
- "Lighter" fluids, like HVFRs: 12%
- Something else (e.g. CO2 Injection): 4%
Let’s Frac...
...a Sankey Diagram for Efficiency Loss

Now averaging ~35% of every day for US Frac industry
What Are the Main Sources of Downtime on Your Frac Location (1 Word)?
## Throughput & Downtime

*The Usual Suspects – The W’s*

### Downtime-Summary

<table>
<thead>
<tr>
<th>3rd Wireline Related</th>
<th>3rd Coil Related</th>
<th>3rd Water</th>
<th>3rd Safety</th>
<th>3rd Well Swap Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,154 mins</td>
<td>1,844 mins</td>
<td>1,595 mins</td>
<td>1,586 mins</td>
<td>1,126 mins</td>
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</table>

<table>
<thead>
<tr>
<th>3rd Well or Wellhead</th>
<th>3rd Weather</th>
<th>3rd Fuel</th>
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<tbody>
<tr>
<td>1,614 mins</td>
<td>935 mins</td>
<td>800 mins</td>
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</table>

<table>
<thead>
<tr>
<th>LOS Equipment</th>
<th>3rd Maintenance</th>
<th>3rd Pressure, Pops,</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,819 mins</td>
<td>1,510 mins</td>
<td>3rd Zipper Manifold</td>
</tr>
<tr>
<td></td>
<td></td>
<td>674 mins</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LOS Pump Maintenance</th>
<th>LOS Iron, Burst D, Missile</th>
<th>3rd Other</th>
</tr>
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<tr>
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</table>

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<td>3rd</td>
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</tbody>
</table>
Modern Frac Operations = Bulk Logistics

An Average Frac Day for ~350 US Frac Fleets

- Water – 3 Olympic-size swimming pools
- Diesel – 10,000 gal
- Sand – 10 to 15 train cars
- Additives – 2,500 gal
Modern and Efficient Frac Operations

It’s a Frac’ing Factory

- Redundancy
- Made for purpose
- Extended lifetime
- Efficient delivery
- Better neighbor
Volume Discounting
Thank Your Service Company Representative Today!

+206%
since 2012

-29%
since 2012
World Consumer Savings

$45 \times 30 \text{ billion bbl/year} = \sim $1.3 \text{ Trillion/Year}
A Barrel of WTI Crude Oil Will Trade for .... by the End of 2020

- < $40/bbl: 3%
- $40 - $50/bbl: 15%
- $50 - $60/bbl: 45%
- $60 - $70/bbl: 28%
- $70 - $80/bbl: 7%
- > $80/bbl: F

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# In Summary - The American Shale Revolution

*Technology & Efficiency Have Improved Our Competitiveness*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2012 Average*</th>
<th>2017 Average*</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Length</td>
<td>ft</td>
<td>5580</td>
<td>7625</td>
<td>37%</td>
</tr>
<tr>
<td>Stage Count</td>
<td></td>
<td>19.3</td>
<td>38.6</td>
<td>100%</td>
</tr>
<tr>
<td>Stage Intensity</td>
<td>ft/stage</td>
<td>296</td>
<td>208</td>
<td>-30%</td>
</tr>
<tr>
<td>Proppant Mass</td>
<td>lbs</td>
<td>3,506,284</td>
<td>11,891,000</td>
<td>239%</td>
</tr>
<tr>
<td>Proppant Mass per Lateral Foot</td>
<td>lbs/ft</td>
<td>677</td>
<td>1,632</td>
<td>141%</td>
</tr>
<tr>
<td>Fluid Volume</td>
<td>bbl</td>
<td>74,411</td>
<td>243,983</td>
<td>228%</td>
</tr>
<tr>
<td>Fluid Volume per Lateral Foot</td>
<td>bbl/ft</td>
<td>14.4</td>
<td>33.2</td>
<td>131%</td>
</tr>
<tr>
<td>Average Proppant Concentration</td>
<td>PPG</td>
<td>1.17</td>
<td>1.21</td>
<td>3%</td>
</tr>
<tr>
<td>Max Rate</td>
<td>bpm</td>
<td>57.6</td>
<td>81.7</td>
<td>42%</td>
</tr>
<tr>
<td>Max Rate per Lateral Foot</td>
<td>bpm/ft/stage</td>
<td>0.20</td>
<td>0.42</td>
<td>105%</td>
</tr>
<tr>
<td>365-Day Cumulative Oil</td>
<td>BO</td>
<td>61,044</td>
<td>108,209</td>
<td>77%</td>
</tr>
<tr>
<td>365-Day Cumulative Oil per Lateral Foot</td>
<td>BO/ft</td>
<td>12.2</td>
<td>17.7</td>
<td>46%</td>
</tr>
<tr>
<td>365-Day Cumulative Oil Equivalent</td>
<td>BOE</td>
<td>91,465</td>
<td>159,942</td>
<td>75%</td>
</tr>
<tr>
<td>365-Day Cumulative Oil Equivalent per Lateral Foot</td>
<td>BOE/ft</td>
<td>18.2</td>
<td>25.7</td>
<td>41%</td>
</tr>
<tr>
<td>Well Cost</td>
<td>Million$</td>
<td>$7.2</td>
<td>$5.1</td>
<td>-29%</td>
</tr>
<tr>
<td>Cost per Barrel Oil Equivalent</td>
<td>$/1-Year BOE</td>
<td>$86</td>
<td>$32</td>
<td>-63%</td>
</tr>
<tr>
<td>Cost per Barrel Oil</td>
<td>$/1-Year BO</td>
<td>$128</td>
<td>$46</td>
<td>-64%</td>
</tr>
</tbody>
</table>

*Average over 10 basin / formations: Williston Middle Bakken and Three Forks, PRB Niobrara and Frontier/Turner, DJ Codell and Niobrara, Delaware Basin Wolfcamp and Bone Spring, Midland Basin Wolfcamp and Eagle Ford; Production metrics from 2016 wells.*
Industry Challenges & Opportunities

- Production Interference
  - Can exemplary kids and save their hippie parents?
  - Can re-fracs / frac protects with some surfactant / CO2 start a “huff ‘n puff” EOR shale revolution?
- Can perforation strategies further reduce stage count to save completion cost?
- Can we replace more “viscosity” with “velocity” in the DJ Basin and save on chemicals?
- Is Regional Sand the next big change in the Rockies for “just-good-enough” proppant economics?
- Efficiency improvements (pumping >50% of all time)
  - Opportunity for downtime and non-pumptime reduction
  - Electric fleet pie in the sky?
Conclusions

• US Shale Revolution has transformed US and World Energy
  • Still remains an almost exclusive American Revolution

• Technological changes continue as operators find better ways to minimize $/BO(E)
  • Similar changes in most US basins, with gradual move to larger volumes, “spread the wealth” delivery in the reservoir and cheaper materials
  • “Big picture” statistical analysis support these changes
  • Possibly seeing diminishing returns in some basins

• Environmental footprint of oil & gas production is shrinking

• Together, operators and service providers are improving pumping efficiencies
  • Room for improvements with the W’s – Wireline, Water, Wellhead and Weather – and Pumps

• Economic and humanitarian benefits are massive
  • Biggest benefit for lower-income citizens of the world
Apart from doubling human life expectancy, reducing global poverty, saving the whales, enhancing human mobility, enabling modern life, providing cheap energy that saves global consumers trillions of $s every year, bringing manufacturing jobs back to the USA, reducing US dependence on foreign oil and reducing US per-capita CO2 emissions to 1964 levels – what have oil, natural gas and frackers ever done for us?