Current Practices in Oil and Gas Stimulation

Enhanced Geothermal Systems
Current Techniques Used for Stimulation Oil and Gas Wells

• Hydraulic Fracturing
  • Acid Fracturing
  • Propped Fracturing

• Matrix Stimulation
  • Acidizing (HCl, Acetic, Formic)
  • Non-reactive Formation Damage Systems

• Cavity Completions

• Mechanical
  • Under-reaming
  • Fishbones

• Thermal Shock (Water Injectors)
Question

• How do you stimulate a geothermal wells which consists of a very low permeability, very hard, very hot rock completed with large open holes or slotted liners.

  ✓ Very Low Permeability – We are currently successfully stimulating naturally fractured shales which have perm’s in the 50 to 300 nanodarcy range.

  ✓ Very Hard – We currently stimulate rock which have modulus as high at 10e6 psi. I have personally stimulated naturally fractured granite in Vietnam.

  ✓ Large Open Holes or Slotted Liners – We currently complete wells with 9 inch casing (Bohai Bay) and 10,000 ft slotted liners (Alpine)

The main issue seems to be temperature.
Current Techniques Used for Stimulation Oil and Gas Wells

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  • Acid Fracturing
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  • Under-reaming
  • Fishbones
Hydraulic Fracturing
Basic Physics – Lumped Pseudo 3D Model

\[ L = \frac{Q \times T_P}{4 \, C \, H_P \, \sqrt{T_P} + 2 \, S_P \, H_P + \bar{w} \, H} \]

\[ \bar{w} = \frac{\pi \, P_{Net} \, H}{2 \, E} \]

\[ P_{Net} \propto \left\{ \frac{E''^4}{H_O^4} \left( \frac{\mu \, Q \, L}{E'} \right) + \frac{K_{lc}^4}{H_O^2} \right\}^{1/4} \]

\[ H \propto fn \left( \frac{P_{net}}{\Delta \sigma} \right) \rightarrow H \propto fn \left( H \right) \]

Viscous

Tip
Basic Frac Fluid Composition

- Water Based
- Polymer
- Crosslinker
- pH Buffer
- Clay Control
- Breaker
- Surfactants
- Biocide
- Fluid Loss Control

- Gelled Oil
- Base Oil
- Phosphate Ester
- Polymer
- Crosslinker
- Activator
- Breaker
Materials -- Fluids

Fluid “Recipe”

• Base Fluid (Water or Oil) (1 cp)
  • Clay Control (2% KCl)

• Gelling Agent (10’s of cp)
  a) Guar Gum
  b) HPG
  c) CMHPG
  d) HEC
  • Bactericide
    (protect fluid, NOT formation)

• pH Buffer (aid in mixing)
• Breaker
Oil Based Frac Fluids
Dimethyldioctadecylammonium chloride

An example of a permanently charged cationic quaternary amine surfactant

\[ \text{Dimethyldioctadecylammonium chloride} \]

Increase Concentration above CMC

Aqueous solution

Increase Concentration

Micelle

Rod Like Micelle

Increase Concentration above C*

Three-dimensional gel microstructure from transmission electron micrographs.

Friction Reducers (Synthetic Polymers)

Polyacrylic acid (PAAc)

Polyacrylamide (PAAm)

Hydrolyzed Polyacrylamide (PHPA)

AcrylamidoMethylPropane Sulfonate (AMPS)

Comparison of Friction Pressure for FR, 10# Guar and 2% KCl

Subject to hydrolysis at high temperatures
Consequence of using straight water

• High Friction

\[ P_{Net} \propto \left\{ \frac{E'}{H_O}^4 \left( \frac{\mu Q L}{E'} \right) + \frac{K_{lc}}{H_O^2} \right\}^{1/4} \]

\[ \overline{W} = \frac{\pi P_{Net} H}{2 E} \]

• Small Net Pressure resulting in a Narrow Frac Width

Friction in psi/100 feet of 9" casing
Dimensionless Fracture Conductivity

$$F_{CD} = \frac{k_f w}{k x_f}$$
Proppant Types

Each of these is available in several sizes and types

Quality and performance are variable
New “Microsphere” Materials

Softening Point = 1200°C
Uniaxial Compressive Strength = 60,000 psi
Natural Fractures Outcrops

Ithaca Shale Outcrop showing the Geneseo Gas Shale

Eagle Ford Shale Outcrop
West of Del Rio, TX

JPT – May 2015
## Critical Bridging Diameter

<table>
<thead>
<tr>
<th>Material</th>
<th>D50 Calculation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/40 Mesh</td>
<td>$D_{50} = 595\mu \times 3 = 1785\mu = 0.07\text{ inches}$</td>
<td></td>
</tr>
<tr>
<td>40/60 Mesh</td>
<td>$D_{50} = 297\mu \times 3 = 891\mu = 0.035\text{ inches}$</td>
<td></td>
</tr>
<tr>
<td>100 Mesh</td>
<td>$D_{50} = 177\mu \times 3 = 531\mu = 0.02\text{ inches}$</td>
<td></td>
</tr>
<tr>
<td>Silica Flour</td>
<td>$D_{50} = 37\mu \times 3 = 111\mu = 0.004\text{ inches}$</td>
<td></td>
</tr>
<tr>
<td>Deeprop™ 1000</td>
<td>$D_{50} = 25\mu \times 3 = 75\mu = 0.0029\text{ inches}$</td>
<td></td>
</tr>
<tr>
<td>Deeprop™ 600</td>
<td>$D_{50} = 10\mu \times 3 = 30\mu = 0.0012\text{ inches}$</td>
<td></td>
</tr>
<tr>
<td>Deeprop™ 400</td>
<td>$D_{50} = 8\mu \times 3 = 24\mu = 0.0009\text{ inches}$</td>
<td></td>
</tr>
<tr>
<td>Deeprop™ 200</td>
<td>$D_{50} = 5\mu \times 3 = 15\mu = 0.0006\text{ inches}$</td>
<td></td>
</tr>
</tbody>
</table>
Conductivity compared to 100 mesh

- 2 lb/ft² White 100 Mesh
- 2 lb/ft² Deeproptm 1000
- 2 lb/ft² Deeproptm 600
- 2 lb/ft² Deeproptm 400
- 2 lb/ft² Deeproptm 200

2% KCl Water
250 degF
Width vs Stress@ 2 lb/ft²

Pre- and Post-Test Deeprop™ 1000 Particle Size

<table>
<thead>
<tr>
<th></th>
<th>Cumulative Weight Percent Larger Than (micron)</th>
<th>Uniformity Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d10</td>
<td>d25</td>
</tr>
<tr>
<td>Pre-Test</td>
<td>70</td>
<td>43</td>
</tr>
<tr>
<td>Post-Test</td>
<td>79</td>
<td>40</td>
</tr>
</tbody>
</table>
Barnett Shale Example Design

Perforations

Confidential
Conductivity at Stress

**Table:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Pressure, Pres</td>
<td>5200</td>
</tr>
<tr>
<td>Overburden, OB</td>
<td>8610</td>
</tr>
<tr>
<td>Tectonics, T</td>
<td>0</td>
</tr>
<tr>
<td>Closure Pressure, (\sigma_{\text{CL}})</td>
<td>6337</td>
</tr>
<tr>
<td>Bottomhole Flowing Pressure, BHFP</td>
<td>1000</td>
</tr>
<tr>
<td>Propped Width Stress, (\Delta\sigma_{\text{width}})</td>
<td>200</td>
</tr>
<tr>
<td>Proppant Stress, (\sigma_p)</td>
<td>5537</td>
</tr>
</tbody>
</table>

**Graph:**

- **Blue Line:** 2 lb ft\(^2\) Deepprop\(^\text{TM}\) 200
- **Orange Line:** 2 lb ft\(^2\) Deepprop\(^\text{TM}\) 1000

**Conductivity Points:**
- 4.5 md/ft at Fracture Closure Stress (psi) = 2500
- 0.08 md/ft at Fracture Closure Stress (psi) = 2000

**Notes:**
- 2% KCl Water
- 250 degF
- Confidential
## Pump Schedule/Frac Geometry

### Downhole Pump Schedule

<table>
<thead>
<tr>
<th>Stage</th>
<th>Slurry Volume (M-Gal)</th>
<th>Fluid Volume (M-Gal)</th>
<th>Start Rate (BPM)</th>
<th>End Rate (BPM)</th>
<th>Fines Conc. (Vol Fraction)</th>
<th>Proppant (M-Lbs)</th>
<th>Pump Time (min)</th>
<th>Cum Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.503</td>
<td>8.503</td>
<td>25.000</td>
<td>25.000</td>
<td>0.000</td>
<td>0.000</td>
<td>70.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>8.503</td>
<td>8.503</td>
<td>25.000</td>
<td>24.446</td>
<td>0.500</td>
<td>0.500</td>
<td>70.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>8.503</td>
<td>8.503</td>
<td>25.000</td>
<td>23.917</td>
<td>1.000</td>
<td>1.000</td>
<td>70.000</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>8.503</td>
<td>8.503</td>
<td>25.000</td>
<td>22.923</td>
<td>1.500</td>
<td>1.500</td>
<td>70.000</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>8.503</td>
<td>8.503</td>
<td>25.000</td>
<td>22.923</td>
<td>2.000</td>
<td>2.000</td>
<td>70.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Surface Pump Schedule

- **Wellbore Volume (M-Gal):** 8.36
- **Wellbore Volume to Include As Pad (M-Gal):** 0.00
- **Wellbore Fluid:**
  - **Stage 1:** Slick Water
  - **Stage 2:** 100 Mesh Sand 250F 80-100
  - **Stage 3:** 100 Mesh Sand 250F 80-100
  - **Stage 4:** Ottawa Sand, 250 F, Long Term 40-70
  - **Stage 5:** Ottawa Sand, 250 F, Long Term 40-70
  - **Stage 6:** Ottawa Sand, 250 F, Long Term 40-70

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**Note:**
- **Flow Back Rate (BPM):** 0.000
- **Start Pump Time (YYYY/MM/DD HH:MM:SS):** Confidential
- **TVD ft:**
  - 7600
  - 7800
  - 8000
  - 8200
  - 8400
- **GR API:**
  - 0
  - 150
  - 75.00
- **NPOR V/V:**
  - 0.30
  - -0.10
  - 0.1000
- **DPOR V/V:**
  - 0.30
  - -0.10
  - 0.1000

**Confidential Data:**
- **0.1000 NPOR V/V**
- **0.1000 DPOR V/V**
- **951 ft**
NATURAL FRACTURE WIDTH Time: 35.50 Depth: 8206.84
NATURAL FRACTURE WIDTH

Time: 59.52
Depth: 8206.84

End of Job

Confidential
Deeprop™ 1000
- $D_{95} = 120\mu \times 3 = 360\mu = 0.014$ inches
- $D_{90} = 85\mu \times 3 = 255\mu = 0.01$ inches
- $D_{50} = 25\mu \times 3 = 75\mu = 0.0029$ inches

Deeprop™ 200
- $D_{95} = 14\mu \times 3 = 42\mu = 0.0016$ inches
- $D_{90} = 12\mu \times 3 = 36\mu = 0.0014$ inches
- $D_{50} = 5\mu \times 3 = 15\mu = 0.0006$ inches

100 Mesh
- $D_{95} = 295\mu \times 3 = 885\mu = 0.035$ inches
- $D_{90} = 275\mu \times 3 = 825\mu = 0.032$ inches
- $D_{50} = 177\mu \times 3 = 531\mu = 0.021$ inches
Benefits at a width of 0.06 inches (1.52 mm) and a formation perm of 250 nano-darcies

**Deeprop™ 1000**

<table>
<thead>
<tr>
<th>Permeability (md)</th>
<th>0.00025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (md-ft)</td>
<td>1.14</td>
</tr>
<tr>
<td>Re (ft)</td>
<td>100.000</td>
</tr>
<tr>
<td>Rw (ft)</td>
<td>0.35</td>
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</table>

<table>
<thead>
<tr>
<th>Xf (ft)</th>
<th>FCD</th>
<th>Rw'/Xf</th>
<th>Rw'</th>
<th>FOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>182.400</td>
<td>0.5</td>
<td>13</td>
<td>2.72</td>
</tr>
<tr>
<td>50</td>
<td>91.200</td>
<td>0.5</td>
<td>25</td>
<td>4.08</td>
</tr>
<tr>
<td>75</td>
<td>60.800</td>
<td>0.5</td>
<td>38</td>
<td>5.77</td>
</tr>
</tbody>
</table>

**Deeprop™ 200**

<table>
<thead>
<tr>
<th>Permeability (md)</th>
<th>0.00025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (md-ft)</td>
<td>0.022</td>
</tr>
<tr>
<td>Re (ft)</td>
<td>100.000</td>
</tr>
<tr>
<td>Rw (ft)</td>
<td>0.350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Xf (ft)</th>
<th>FCD</th>
<th>Rw'/Xf</th>
<th>Rw'</th>
<th>FOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>3.520</td>
<td>0.35</td>
<td>9</td>
<td>2.32</td>
</tr>
<tr>
<td>50</td>
<td>1.760</td>
<td>0.28</td>
<td>14</td>
<td>2.88</td>
</tr>
<tr>
<td>75</td>
<td>1.173</td>
<td>0.2</td>
<td>15</td>
<td>2.98</td>
</tr>
</tbody>
</table>

**100 mesh**

<table>
<thead>
<tr>
<th>Permeability (md)</th>
<th>0.00025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (md-ft)</td>
<td>22.060</td>
</tr>
<tr>
<td>Re (ft)</td>
<td>100.000</td>
</tr>
<tr>
<td>Rw (ft)</td>
<td>0.350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Xf (ft)</th>
<th>FCD</th>
<th>Rw'/Xf</th>
<th>Rw'</th>
<th>FOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>3529.600</td>
<td>0.5</td>
<td>13</td>
<td>2.72</td>
</tr>
<tr>
<td>50</td>
<td>1764.800</td>
<td>0.5</td>
<td>25</td>
<td>4.08</td>
</tr>
<tr>
<td>75</td>
<td>1176.533</td>
<td>0.5</td>
<td>38</td>
<td>5.77</td>
</tr>
</tbody>
</table>
Deepprop 1000 Expected Folds of Increase vs $K_f$ and Natural Fracture $X_f$

Limit of 100 Mesh Penetration
In this case

Limit of DP 1000 Penetration
In this case
## Stokes Law Settling Velocity

\[
V_s (ft / s) = 6.64 \times 10^5 \frac{r_p^2 (ft)}{\mu (cp)} \left( SG_p - SG_F \right)
\]

<table>
<thead>
<tr>
<th>Description</th>
<th>Vs (ft/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/40 Sand</td>
<td>4.28</td>
</tr>
<tr>
<td>40/70 Sand</td>
<td>1.07</td>
</tr>
<tr>
<td>80/140</td>
<td>0.22</td>
</tr>
<tr>
<td>Deeprop™-1000 (D95)</td>
<td>0.26</td>
</tr>
<tr>
<td>Deeprop™-1000 (D50)</td>
<td>0.029</td>
</tr>
<tr>
<td>Deeprop™-200 (D95)</td>
<td>0.0022</td>
</tr>
<tr>
<td>Deeprop™-200 (D50)</td>
<td>0.00029</td>
</tr>
</tbody>
</table>

\[ \mu \text{ (cps)} = 1, \quad SG \text{ of Fluid } = 1, \quad SG \text{ of Proppant } = 2.6 \]
Completion Strategies

<table>
<thead>
<tr>
<th>Completion Strategies</th>
<th>BD-Balls</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
<th>Stage 6</th>
<th>Stage 7</th>
<th>Stage 8</th>
<th>Stage 9</th>
<th>Stage 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Placed (lbs)</td>
<td>129,740</td>
<td>122,400</td>
<td>125,360</td>
<td>127,040</td>
<td>123,620</td>
<td>125,100</td>
<td>135,680</td>
<td>75,520</td>
<td>182,650</td>
<td>153,660</td>
<td></td>
</tr>
<tr>
<td>Design (lbs)</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td>126,000</td>
<td></td>
</tr>
<tr>
<td>Placed (lbs)</td>
<td>10,900</td>
<td>7,115</td>
<td>7,248</td>
<td>7,175</td>
<td>7,240</td>
<td>7,003</td>
<td>8,391</td>
<td>8,129</td>
<td>8,584</td>
<td>7,777</td>
<td></td>
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<tr>
<td>Design (lbs)</td>
<td>97,012</td>
<td>7,012</td>
<td>7,012</td>
<td>7,012</td>
<td>7,012</td>
<td>7,012</td>
<td>7,012</td>
<td>7,012</td>
<td>7,012</td>
<td>7,012</td>
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</tr>
<tr>
<td>Rate (bpm)</td>
<td>86</td>
<td>87</td>
<td>89</td>
<td>86</td>
<td>89</td>
<td>89</td>
<td>88</td>
<td>83</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>5,443</td>
<td>5,903</td>
<td>5,702</td>
<td>5,715</td>
<td>6,591</td>
<td>6,411</td>
<td>6,686</td>
<td>7,191</td>
<td>7,009</td>
<td>7,669</td>
<td></td>
</tr>
</tbody>
</table>

Woodford Shale: 3-20" Guns CUBEX charged, 0.64" holes, Exp. 80° phasing.
40 Holes per stage.
Total holes: 468 Min. distance between clusters: 128' on existing and 48' on the new stages.
Between stage: 140' on existing and 50' on new ones.

Stage 7: Stage 5: Stage 3: Stage 2: Stage 1
<table>
<thead>
<tr>
<th>Stage 7</th>
<th>Stage 5</th>
<th>Stage 3</th>
<th>Stage 2</th>
<th>Stage 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>6065’-67’</td>
<td>7440’-56’</td>
<td>7050’-52’</td>
<td>6365’-69’</td>
<td>6950’-65’</td>
</tr>
<tr>
<td>6359’-41’</td>
<td>7548’-56’</td>
<td>7972’-74’</td>
<td>6617’-33’</td>
<td>6940’-65’</td>
</tr>
<tr>
<td>6372’-74’</td>
<td>7596’-67’</td>
<td>8032’-34’</td>
<td>8733’-33’</td>
<td>3250’-52’</td>
</tr>
<tr>
<td>7648’-56’</td>
<td>8054’-56’</td>
<td>8054’-56’</td>
<td>9770’-60’</td>
<td>9940’-60’</td>
</tr>
<tr>
<td>7950’-66’</td>
<td>8217’-97’</td>
<td>8954’-56’</td>
<td>9699’-60’</td>
<td>9699’-60’</td>
</tr>
</tbody>
</table>

8', 48 Holes 16', 36 Holes 14', 34 Holes 6', 36 Holes 8', 48 Holes 10', 63 Holes

Estimated TOC behind 5-1/2" @ 4,750'.
Re-Fracs w/Diversion
Treating Long Intervals

Example Data

Distance Along Lateral

Haynesville 1H
- 1st Isotope
- 2nd Isotope
- 3rd

Haynesville 2H

Haynesville 3H

Haynesville 4H

Haynesville 5H
Ekofisk X-04 Field Observation

Bullhead acid jobs may be sub-optimal – 4 zones near heel producing 75%
Breakdown Pressures of 15 Zones
Real Time Fluid Placement Monitoring
Particulate Diverters
Potential Problems

Bio-Degradable Diverting Agent

Before Use

Incomplete Degradation

After I. Abou-Sayed, SPE Web Event
“Shale Formation Re-Fracturing …..”
Diverters – ball sealers
Re-Frac Design Elements
Ball Sealers

Recovery 0.9 gm/cc Lite Ball
(Note torn cover)

7/8" 1.1 RCN
Solid Rubber

Bioballs

Syntactic foam used to lighten ball sealers

<table>
<thead>
<tr>
<th>Type and Size</th>
<th>Specific Gravity</th>
<th>Ball-Core Diameter (in.)</th>
<th>Core Type</th>
<th>Maximum Recommended Perforation Size (in.)</th>
<th>Marking Color</th>
<th>Temperature Range</th>
<th>Maximum ( \Delta P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/8&quot; Rubber (solid)</td>
<td>1.3</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/8&quot; RCN*</td>
<td>1.1</td>
<td>0.5</td>
<td>Nylon</td>
<td>0.38</td>
<td>Green</td>
<td></td>
<td>75°F to 100°F</td>
</tr>
<tr>
<td>5/8&quot; RCN</td>
<td>1.1</td>
<td>0.5</td>
<td>Nylon</td>
<td>0.38</td>
<td>Black</td>
<td></td>
<td>750 psi</td>
</tr>
<tr>
<td>3/4&quot; RCN</td>
<td>1.3</td>
<td>0.625</td>
<td>Nylon</td>
<td>0.52</td>
<td>Black</td>
<td></td>
<td>750 psi</td>
</tr>
<tr>
<td>7/8&quot; RCA*</td>
<td>1.85</td>
<td>0.625</td>
<td>Aluminum</td>
<td>0.52</td>
<td>Silver</td>
<td></td>
<td>750 psi</td>
</tr>
<tr>
<td>7/8&quot; RCN</td>
<td>1.1</td>
<td>0.75</td>
<td>Nylon</td>
<td>0.52</td>
<td>Gray/Green</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8&quot; RCN</td>
<td>1.1</td>
<td>0.75</td>
<td>Nylon</td>
<td>0.52</td>
<td>Gray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8&quot; RCN</td>
<td>1.2</td>
<td>0.75</td>
<td>Nylon</td>
<td>0.52</td>
<td>Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8&quot; RCN</td>
<td>1.3</td>
<td>0.75</td>
<td>Nylon</td>
<td>0.52</td>
<td>Black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8&quot; RCP</td>
<td>1.4</td>
<td>0.75</td>
<td>Nylon</td>
<td>0.52</td>
<td>Blue</td>
<td>&lt;350°F</td>
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<tr>
<td>7/8&quot; RCP</td>
<td>1.0</td>
<td>0.75</td>
<td>Nylon</td>
<td>0.52</td>
<td>Red</td>
<td>&lt;350°F</td>
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<tr>
<td>7/8&quot; RCP</td>
<td>0.9</td>
<td>0.75</td>
<td>Nylon</td>
<td>0.52</td>
<td>Brown</td>
<td>&lt;350°F</td>
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<tr>
<td>7/8&quot; BioBall* HR</td>
<td>1.18</td>
<td>None</td>
<td>None</td>
<td>0.52</td>
<td>Tan</td>
<td>75°F to 100°F</td>
<td>1500 psi</td>
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<tr>
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<td>None</td>
<td>0.52</td>
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<td>200°F to 350°F</td>
<td>5000 psi</td>
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<td>None</td>
<td>0.52</td>
<td>Green</td>
<td>120°F to 200°F</td>
<td>3000 psi</td>
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<tr>
<td>7/8&quot; Lite Ball</td>
<td>1.9</td>
<td>0.75</td>
<td>Syntactic Foam</td>
<td>0.52</td>
<td>Gold</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8&quot; Lite Ball</td>
<td>1.1</td>
<td>0.75</td>
<td>Syntactic Foam</td>
<td>0.52</td>
<td>White</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8&quot; Lite Ball</td>
<td>1.2</td>
<td>None</td>
<td>None</td>
<td>0.52</td>
<td>Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot; RCN</td>
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<td>0.8725</td>
<td>0.875</td>
<td>0.63</td>
<td>Green</td>
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</tr>
<tr>
<td>1&quot; RCN</td>
<td>1.3</td>
<td>0.8725</td>
<td>0.875</td>
<td>0.63</td>
<td>Black</td>
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</tr>
<tr>
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<td>1.2</td>
<td>1.0625</td>
<td>1.0625</td>
<td>0.87</td>
<td>Yellow</td>
<td></td>
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<tr>
<td>1 1/4&quot; RCN</td>
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<td>1.0625</td>
<td>1.0625</td>
<td>0.87</td>
<td>Black</td>
<td></td>
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</tr>
</tbody>
</table>

*RCN = Rubber Coated Nylon
*RCA = Rubber Coated Aluminum
*RCP = Rubber Coated Phenolic
*Bioballs are also available in 5/8, 1, 1 1/4, 1 1/2 and 2 1/4 inch diameters.
Mechanical Diversion

- **OptiStriker™ tension set packer**
  - Unloader high rate
  - 10k 3x stack
  - Shear out release

- **Proprietary Frac Port**
  - Derived from gravel pack tools
  - Tested to 40 bpm for erosion

- **Proprietary Slip Joint**
  - Enables flawless mechanical set
  - High tech materials for increased reliability

- **OptiPacker™ compression set packer**
  - Unloader valve
  - 10k psi element
  - Proven track record: 1,000’s of runs
Frac Sleeves
Positive Diversion Expandable Liner

- Positive Diversion
- Allows Use of Standard Completion Procedures

- Time Consuming → Costs
- Operationally Complex, Risky?
- Destroys Existing Production

**Mechanical Isolation: Expanded Liner**

- Premium connections designed to be expanded
  - Effectively covers existing perforations and frac sleeves
  - Offers minimal loss of ID
  - Provides high burst and collapse ratings
  - Delivers pipe properties similar to L80 pipe after expansion

**Courtesy: Baker Hughes**
Positive Diversion

• Allows Use of Standard Completion Procedures

- Time Consuming → Costs
- Operationally Complex, Risky?
- Destroys Existing Production
Bakken Strata

Post-frac temperature survey

perfs

MGS (1990)
Preliminary Micro Seismic Results

Video
Figure 1 - Stress Concentration for a circular hole in a biaxial stress field
Figure 2 - Cross sectional view of the stress concentration for a circular hole in a biaxial stress field with a packer set at a pressure equal to \( \frac{1}{2} \) the stress concentration created by the open hole.
Figure 4 – Longitudinal view of a wellbore containing multiple packer systems with ball activated sliding sleeves with induced propped fracture treatments.
Colter 44-14H Fracture Mapping Project
Hybrid Liner Design

Colter 44-14H
Bakken Horizontal Well Play
Fracture Mapping Project
7/10/2008

Robert Clark & Clyde Findlay II
Bakken Completions Team

Encore's Branvic 11-1
Rigged with Pinnacle Technologies Seismic Equipment
~900' to the Colter

Seismic View Window
~15,000' to 19,000'

6" Hole

Limestone sections within seismic window
16,350' - 16,800'
17,010' - 17,100'
18,150' - 18,450'
18,550' - 18,820'

4-1/2", 11.6#/ft, P-110 Liner w/4.0" ID

Six Perf & Plug Intervals
From 7" shoe to 17,150'
Separated with swell packers

500' Sleeve interval
1,000' Sleeve interval

Press Operated Vent
19,700' Pinned at 3,950 psi
Over Hydrostatic

TD 20,335'

7" Shoe
11,805'
Swell Pkr
12,436-452'
Swell Pkr
13,438-454'
Swell Pkr
14,144-160'
Swell Pkr
15,149-164'
Swell Pkr
16,143-159'
Swell Pkr
17,150-165'

Hydraulic Pkr
17,653'
Pinned at 1,900 psi
Over Hydrostatic

Hydraulic Pkr
18,669'
Pinned at 1,900 psi
Over Hydrostatic

Hydraulic Pkr
19,642'
Pinned at 2,500 psi
Over Hydrostatic

4-1/2" Shoe
19,974'

Press Operated Vent
19,700' Pinned at 3,950 psi
Over Hydrostatic

Encore's Branvic 11-1
Rigged with Pinnacle Technologies Seismic Equipment
~900' to the Colter

Seismic View Window
~15,000' to 19,000'

6" Hole

Limestone sections within seismic window
16,350' - 16,800'
17,010' - 17,100'
18,150' - 18,450'
18,550' - 18,820'

4-1/2", 11.6#/ft, P-110 Liner w/4.0" ID

Six Perf & Plug Intervals
From 7" shoe to 17,150'
Separated with swell packers

500' Sleeve interval
1,000' Sleeve interval

Press Operated Vent
19,700' Pinned at 3,950 psi
Over Hydrostatic

TD 20,335'

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Hydraulic Pkr
17,653'
Pinned at 1,900 psi
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Pinned at 1,900 psi
Over Hydrostatic

Hydraulic Pkr
19,642'
Pinned at 2,500 psi
Over Hydrostatic

4-1/2" Shoe
19,974'

Press Operated Vent
19,700' Pinned at 3,950 psi
Over Hydrostatic

TD 20,335'

7" Shoe
11,805'
Swell Pkr
12,436-452'
Swell Pkr
13,438-454'
Swell Pkr
14,144-160'
Swell Pkr
15,149-164'
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16,143-159'
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17,150-165'

Hydraulic Pkr
17,653'
Pinned at 1,900 psi
Over Hydrostatic

Hydraulic Pkr
18,669'
Pinned at 1,900 psi
Over Hydrostatic

Hydraulic Pkr
19,642'
Pinned at 2,500 psi
Over Hydrostatic

4-1/2" Shoe
19,974'

Press Operated Vent
19,700' Pinned at 3,950 psi
Over Hydrostatic

TD 20,335'

7" Shoe
11,805'
Swell Pkr
12,436-452'
Swell Pkr
13,438-454'
Swell Pkr
14,144-160'
Swell Pkr
15,149-164'
Swell Pkr
16,143-159'
Swell Pkr
17,150-165'

Hydraulic Pkr
17,653'
Pinned at 1,900 psi
Over Hydrostatic

Hydraulic Pkr
18,669'
Pinned at 1,900 psi
Over Hydrostatic

Hydraulic Pkr
19,642'
Pinned at 2,500 psi
Over Hydrostatic

4-1/2" Shoe
19,974'

Press Operated Vent
19,700' Pinned at 3,950 psi
Over Hydrostatic

TD 20,335'
Sleeve Interval 1
Map View

Events sized and colored by energy
Bernoulli's equation: \[ \frac{v^2}{2} + \frac{p}{\rho} = C \]

Stagnation pressure causes fracture

Ambient pressure equals hydrostatic or frac extension pressure
Bottom Hole Assembly

- Connector
- Knuckle Joint & Shear Disconnect
- Centralizer
- Jet Sub
- Ball Sub
Jetting Tools

- Many different types & styles of housings and jets
- Replaceable nozzles
- Typical flowrate of 1 bbl/min per 3/16” nozzle or 0.6 bbl/min per 1/8” nozzle
- Typical sand concentration of 1 ppg (100 mesh) if only hydrajetting - or just use the frac sand that is on location
To Prepare C-447 for Fracturing the Existing Completion was Fitted with 464′ of Blank, 5 1/2″, 17#/#ft, K-55, SFJ Liner below a Rental 9 5/8″ x 7″ (crossed over to 5 1/2″) Hydraulic Set Model SLP-R Liner Hanger with a 2′ Tieback Extension with Crossover an Hanger Setting Tool (shown in red)

7″ by 9 5/8″ Hydraulic Set Liner Hanger at 6566-69′
9 5/8″ Casing set at 6605′
Liner Top at 6610′

582′ of 7″, 26#/#ft, 8rd, 2″ x 100mesh Slotted Liner ID = 6.276″

Gap Clearance
6.276″-5.5″/2 = 0.388″

Kiel’s Rule - To prevent sand moving up into SFJ liner/slotted liner annulus, the gap clearance must be 80% or less. Bridging will occur if this is obeyed. There must be a threshold where this will not work.

Bottom Bullnose and Baffle Plate