Best Practices in Hydraulic Fracturing

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How do you drill and complete these shales?

Each shale play has its own characteristics, but all roughly follow the formula of horizontal drilling with multistage fracturing.
Stimulating a Horizontal Shale Well

Horizontal Well

Vertical Well

Fracture stimulation

1-4000 m deep

300-3000 m long

1-4000 m deep

300-3000 m long
3 Key Elements of Horizontal Fracturing

1. Water fracs
2. Microseismic Mapping
3. Mechanical Isolation
What Should be Done Prior to Horizontal Drilling?

1. Establish a baseline of potential contaminants in aquifers
   - Natural gas
   - Natural dissolved solids
   - Identification of pre-existing pollution

2. Identify barriers to hydraulic frac growth in the reservoir

3. Construct a reservoir model, including mechanical properties of rocks, identification of natural fractures, amount and type of hydrocarbons

4. Water sources and disposal

5. Logistics
(4) Water well sampling. The Director shall require initial baseline testing prior to the first interior infill well or boundary well ("proposed GWA infill well") drilled within a governmental section. The following shall be used as guidance for the Director in establishing initial baseline testing:

A. Within the governmental quarter section of the proposed GWA infill well, the closest water well ("water quality testing well") completed in the Laramie/Fox Hills Aquifer shall be sampled.
E. Initial baseline testing shall include laboratory analysis of all major cations and anions, total dissolved solids, iron and manganese, nutrients (nitrates, nitrites, selenium), dissolved methane, pH, and specific conductance.

F. If free gas or a methane concentration level greater than 2 mg/l is detected in a water quality testing well, compositional analysis shall be performed to determine gas type (thermogenic, biogenic or an intermediate mix of both). If the testing results reveal biogenic gas, no further isotopic testing shall be required. If the testing results reveal thermogenic gas, carbon isotopic analyses of methane carbon shall be done.
**Thermogenic gas** is formed at deeper depths by:

1. thermal cracking of sedimentary organic matter into hydrocarbon liquids and gas and
2. thermal cracking of oil at high temperatures into gas

Thermogenic gas can be dry, or can contain significant concentrations of "wet gas" components (ethane, propane, butanes) and condensate ($C_{5+}$ hydrocarbons)

**Biogenic gas** is formed at shallow depths and low temperatures by anaerobic bacterial decomposition of sedimentary organic matter.

Biogenic gas is very dry (i.e., it consists almost entirely of methane).
Fracturing Fluids
Waterfracs

- Slickwater (water with friction reducer)
- Low sand concentrations
- 1-5 million gallons per frac
- Low fluid loss
Why Waterfrac? And look at the Refrac!!!
Water Frac Fluids

A FLUID SITUATION:
TYPICAL SOLUTION* USED IN HYDRAULIC FRACTURING

0.49% ADDITIVES*

Potassium chloride 0.06%
Guar gum/Hydroxyethyl cellulose 0.056%
Ethylene glycol 0.043%
Sodium/Potassium carbonate 0.011%
Sodium chloride 0.01%
Borate salts 0.007%
Citric acid 0.004%
N,N-dimethyl formamide 0.002%
Glutaraldehyde 0.001%

Petroleum distillate 0.088%
Acid 0.123%
Water Frac Fluid Additives

Additives are driven to being “green”

The less impact on the environment, the less public resistance to “fracking”.

<table>
<thead>
<tr>
<th>Compound*</th>
<th>Purpose</th>
<th>Common application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acids</td>
<td>Helps dissolve minerals and initiate fissure in rock (pre-fracture)</td>
<td>Swimming pool cleaner</td>
</tr>
<tr>
<td>Glutaraldehyde</td>
<td>Eliminates bacteria in the water</td>
<td>Disinfectant; Sterilizer for medical and dental equipment</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>Allows a delayed break down of the gel polymer chains</td>
<td>Table Salt</td>
</tr>
<tr>
<td>N, n-Dimethyl formamide</td>
<td>Prevents the corrosion of the pipe</td>
<td>Used in pharmaceuticals, acrylic fibers and plastics</td>
</tr>
<tr>
<td>Borate salts</td>
<td>Maintains fluid viscosity as temperature increases</td>
<td>Used in laundry detergents, hand soaps and cosmetics</td>
</tr>
<tr>
<td>Polyacrylamide</td>
<td>Minimizes friction between fluid and pipe</td>
<td>Water treatment, soil conditioner</td>
</tr>
<tr>
<td>Petroleum distillates</td>
<td>“Slicks” the water to minimize friction</td>
<td>Make-up remover, laxatives, and candy</td>
</tr>
<tr>
<td>Guar gum</td>
<td>Thickens the water to suspend the sand</td>
<td>Thickener used in cosmetics, baked goods, ice cream, toothpaste, sauces, and salad dressing</td>
</tr>
<tr>
<td>Citric Acid</td>
<td>Prevents precipitation of metal oxides</td>
<td>Food additive; food and beverages; lemon juice</td>
</tr>
<tr>
<td>Potassium chloride</td>
<td>Creates a brine carrier fluid</td>
<td>Low sodium table salt substitute</td>
</tr>
<tr>
<td>Ammonium bisulfite</td>
<td>Removes oxygen from the water to protect the pipe from corrosion</td>
<td>Cosmetics, food and beverage processing, water treatment</td>
</tr>
<tr>
<td>Sodium or potassium carbonate</td>
<td>Maintains the effectiveness of other components, such as crosslinkers</td>
<td>Washing soda, detergents, soap, water softener, glass and ceramics</td>
</tr>
<tr>
<td>Proppant</td>
<td>Allows the fissures to remain open so the gas can escape</td>
<td>Drinking water filtration, play sand</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>Prevents scale deposits in the pipe</td>
<td>Automotive antifreeze, household cleansers, delcing, and caulking</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>Used to increase the viscosity of the fracture fluid</td>
<td>Glass cleaner, antiperspirant, and hair color</td>
</tr>
</tbody>
</table>
How Water Usage Stacks Up in Pennsylvania

At a drilling rate of double the expected peak of 6,000 wells per year, industry water usage still represents less than 1% of Pennsylvania daily water usage.

Source: USGS, Pennsylvania Water Consumption
Geologic Considerations
What is a Shale?

Now we are trying to produce this shale that is $\sim 1000$ times less permeable than tight sands.

And a million times less permeable than conventional Sands.

“milliDarcy”
$\sim 0.1 \text{ to } 10,000 \text{ mD}$

“microDarcy”
$\sim 0.001 \text{ to } 0.1 \text{ mD}$

“nanoDarcy”
$\sim 0.000,010 \text{ to } 0.001 \text{ mD}$

Courtesy, Mike Vincent, consultant
What is a **Desirable** Gas Shale?

**Brittle Shale (Complex Fracturing):**
- low Poisson’s Ratio & high Young’s Modulus
- moderate Clay content : < 40%
- bounded by frac barriers

**Gas-in-place (Bcf per square mile):**
- 30 is good, 150 is better

**Permeability greater than 100 nanodarcies**

**Porosity:** > 4%

**TOC:** >2% (1-3% is typical, 5-15% is great)

**Moderate Water Saturation** < 45%

**Thick zone:** >100 ft

Courtesy, Halliburton
Natural Fracture Networks Are a Key
We Predict a Stimulated Reservoir Volume

Fig. 6—Contrasting fracture-failure geometries shown by means of microseismic monitoring, confirming stress-anisotropy measurements acquired with a 3D sonic tracer tool, where $\sigma_2$—High stress and $\sigma_3$—Low stress. (Image courtesy of Schlumberger.)
What about Vertical Heterogeneity?

Shales
Silty Shales
Mudstones
Silt Stones
Sandy laminations

What a mess!!
But they all may produce!!!
Prediction of Barriers to Fracture Growth

The Di-Pole Sonic log predicts the mechanical properties of the rock by measuring the compressional and shear waves in formations that the wellbore has been drilled through.

This can then be used to predict at what pressure surrounding rocks will fracture, and fracture growth will, or will not be contained.
Determination of Fracture Barriers

Most induced fractures are vertical and are driven toward lower horizontal stress.

For instance a fracture growing in A4 will have a difficult time breaking across the shale above, which is higher stress (in red), and instead will move to the lower stress and stay in zone.

To predict where the fracture goes, you must predict what the stresses are, and for this, you need to know what the rock properties are.

The rock properties, such as Poisson’s ratio and Young’s Modulus, must be determined from cores or logs.
Shales May Have Gas, Wet Gas, or Oil

Eagleford Trend, South Texas (Source – EOG)
Why is wet gas so important?

$5.00 NYMEX equates to $7.28 per mcf price

$5.00 NYMEX Henry Hub
$75.00 NYMEX WTI
Based on 9/09 Gas Quality (1)
Assumes Cryogenic Only

<table>
<thead>
<tr>
<th>Natural Gas &amp; Ethanes</th>
<th>NGLs</th>
<th>Condensate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production by product</td>
<td>.900 mcf</td>
<td>2.450 gallons/mcf</td>
</tr>
<tr>
<td>Gross realized by product</td>
<td>$4.96 net</td>
<td>$1.62 net (2)</td>
</tr>
<tr>
<td>Gathering, transportation and operating expenses</td>
<td>$0.75 to $1.75</td>
<td>Will decline over time as volumes increase</td>
</tr>
</tbody>
</table>

(1) 9/09 Gas Quality
(2) Assumes Cryogenic Only
Horizontal Completion Technology
Why not just a horizontal well?

100 ft
Vertical well

160 ft$^2$ of contact

2,000 ft
Horizontal well

3,207 ft$^2$ of contact

20 x vertical

2,000 ft
Horizontal well with 10 x 150 ft fractures

153,207 ft$^2$ of contact

957 x vertical

48 x horizontal
Fracture Design Stress Effects

There is always a higher horizontal stress in one direction in the rocks being fractured. The fracture aims toward the maximum stress, so the fracture can push apart the lower stress rocks, propagating the fracture.

Production may change the stress in the rock. A new fracture formed from refracturing the rock, will head to high stress, and new reserves.
Waterfracs – Transverse Orientation

- Transverse fracs better than longitudinal
- Potential to activate existing fracture systems
- Paleofracture orientation?
Fracturing Traditional Model (and Wrong in Shales)

**Why does fracturing work?**

- **a** Before Fracture Stimulation; Radial Flow
- **b** Post-Fracture Stimulation, Early Time
- **c** Post-Fracture Stimulation, Late Time
Horizontal Completions (Complex Fracturing)
Demand for more fracs in Barnett (and other shales too!!!)
Why not an openhole, fracture stimulated well?

You would like each fracture equally treated

But you actually get this

(one fracture takes all the fluid)
Horizontal Completions with Mechanical Packers

Establish Mechanical Diversion Using Packers

Allow multiple stimulations along horizontal interval
Horizontal Completions
Frac Baffles or Frac Sleeves

Diversion with Expandable Packers
Sleeves are actuated with balls
Coiled Tubing Frac System

Courtesy, Halliburton
Horizontal Completions
Cemented Perf and Plug

1. Annular Isolation (and diversion accomplished with cement)
2. Frac stages initiated through perforations with stages isolated with composite plugs
3. Bridge plugs are removed with coiled tubing drilling.

composite bridge plug
Green completions take place during the clean-up stage of the completion, after a well has been “fracked.”

The clean-up involves removing the water necessary to frack the well. During this flow back, natural gas is produced with the water.

What makes the well completion “green,” or environmentally friendly, is that the gas is separated from the water and placed in a pipeline instead of being released to the atmosphere.

Green completions have been Devon’s standard practice in the Barnett Shale since 2004.

Devon has reduced methane emissions by more than 25 billion cubic feet in the Barnett Shale area of north Texas during 2,000 green completions.
First, a sand separator (shown at right in this photo) filters out any sand, sending it through a 2-inch pipe into the disposal tank. That filtering leaves a mixture of natural gas and water.

The second piece of equipment (in the left side of this photo) separates the water, which then reunites with the sand in the disposal tank.

The gas, meanwhile, is diverted into a separate pipe and eventually is sent by pipeline to a processing plant.

The key to the green completion is that a pipeline must be available for immediate usage.
Microseismic
Microseismic Improves Diagnostics

Microseismic

- Maps the fracture growth
- Identifies azimuth
- Measures frack distance from aquifer
- Requires observation well
Microseismic Barnett Shale Horizontal

Side View

Plane View
Barnett Microseismic Fracture Heights vs. Deepest Aquifer

Barnett Mapped Frac Treatments/TVD

Depth (ft)

Frac Stages [sorted on Perf Midpoint]
Marcellus Microseismic Fracture Heights vs. Deepest Aquifer
Marcellus Case History
Impact of 100 Rigs on Marcellus Gas Production

Average monthly natural gas production
billion cubic feet per day

Pennsylvania Rotary Rig Count

3 BCFPD – 3 years
(500,000 BOPD Equivalent)
### Range Marcellus Shale Fracs

**Bigger Jobs and Lower Costs – Better Well Results**

<table>
<thead>
<tr>
<th>Year</th>
<th>Proppant, lbs.</th>
<th>Water, gallons</th>
<th>Stages</th>
<th>Lateral Length, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>923,000</td>
<td>2,225,000</td>
<td>3</td>
<td>1,794’</td>
</tr>
<tr>
<td>2007</td>
<td>2,765,000</td>
<td>2,646,000</td>
<td>7</td>
<td>2,198’</td>
</tr>
<tr>
<td>2008</td>
<td>3,418,000</td>
<td>3,127,000</td>
<td>8</td>
<td>2,495’</td>
</tr>
<tr>
<td>2009 (Short)</td>
<td>3,241,000</td>
<td>3,227,000</td>
<td>8</td>
<td>2,514’</td>
</tr>
<tr>
<td>2009 &amp; 2010 (Long)</td>
<td>5,154,000</td>
<td>3,887,000</td>
<td>10</td>
<td>3,038’</td>
</tr>
</tbody>
</table>

**Experimenting With Longer Laterals (2,900’ to 5,000’) and More Stages (9-17)**
Marcellus Well Results – Range Resources

Marcellus Zero Time Plot by Well Type

- 2009/2010 Long Laterals
- 2009 Short Laterals
- 2008 Avg
- 2007 Avg
- 2006 Avg

# of Days
As of June 30, 2010 (Gas only)

- 2006 (1 well)
- 2007 (6 wells)
- 2008 (15 wells)
- 2009 Short Laterals (30 wells)
- 2000/2010 Long Laterals (45 wells)
Based upon ~3,000 foot lateral, 10 stage frac and 6 well pad

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Preparation (^{(1)})</td>
<td>$270,000</td>
</tr>
<tr>
<td>Drilling</td>
<td>1,300,000</td>
</tr>
<tr>
<td>Tubulars</td>
<td>330,000</td>
</tr>
<tr>
<td>Facilities</td>
<td>250,000</td>
</tr>
<tr>
<td>Completion Operations (^{(2)})</td>
<td>1,850,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$4,000,000</td>
</tr>
</tbody>
</table>

Completion (fracking) costs much more than drilling
Conclusions

1. Shale plays are very widespread
2. Each shale play is different, and needs careful evaluation
3. Shales may produce natural gas, natural gas liquids and/or oil
4. Shale completions are still improving
5. Aquifers can and are being protected
Eagleford Oil and Wet Gas

Estimated ROR (%) by Core Area

- Eagle Ford - Black Hawk
- Eagle Ford - Hawkville
- Haynesville

NYMEX Gas Price, $/Mcf
How will the Rocks Break?

We will achieve different Stimulated Reservoir Volume (SRV) and drainage area depending on how wellbore is placed relative to the stress fields.
Natural Gas Cheap Compared to Oil, Driven by Shale Gas Production

The shale plays are widely separated, with different geologic properties, but they have one uniform effect:

They are driving down natural gas prices in the US

Crude oil prices

Natural Gas equivalent prices

Difference in price between natural gas and oil for equivalent energy value
Even though the rig count dropped by over 50%, US natural gas production has continued to climb. This is due to better completions, producing more gas with less rigs!!
It is key to determine how important the natural fractures are.
(Very Complex Fracturing)

Warpinski, Sandia Labs. Nevada Test Site, Hydraulic Fracture Mineback

See SPE 119143 for discussion of implications of frac complexity
Logistics – Stimulation
Complex Fracture Geometries

Figure 1 - Fracture growth and complexity scenarios

(SPE 114173) (SPE 119890) Discrete Fracture Network (DFN) Model (SPE 115769)