Objective: forecast future production and reserves ...$worth$
Estimation of Production/Reserves

1. Based on skin and flow equation

\[ q = \frac{kh(p - p_{wf})}{141.2\mu B \ln \left( \frac{r_e}{r_w} \right) - 0.75 + S} \]

If multiphase flow then \( k_o = f(S_w) \! \)

2. Comparison/analogy with adjacent wells

Initial state or current state?

Historical production
Of adjacent well

Flow rate
\( q_{oi} \)

predicted

D, b?

time

Reserves?

\( t_a \)

\( q_a \)

Flow rate

Historical production
Of adjacent well

Flow rate

time

Historical production
Of adjacent well

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Historical production
Of adjacent well
2. Comparison/analogy with adjacent wells

Initial state or current state?

Pressure $p_i$, $p$, $t_i$, $t_2$

Flowrate $q_{oi}$?

Accounts for stimulation

$S \leq 0$

$S > 0$

$q_{oi} = ?$

Accounts for depletion

Incremental Reduces!

Incremental

Flow rate $q_a$

Reserves?

predicted $D_t$, $b$?

Time $t_a$?
2. Comparison/analogy with adjacent wells adjusted?

\[ q_{oi} \text{\{Proposed well\}} = \text{adjustment factor} \times q_{oi} \text{\{adjacent well\}} \]

Variations in:
- Thickness
- Area
- Horizontal length
- Stimulation, etc
Abandonment rate?
• Estimate from economic limit equation
• Refine by observing negative cashflow in economic calculations

Abandonment time?
• Same as above
• Can define some time limit; e.g., 15 years, after which production is assumed to have minimal impact on NPV
1. Comparison/analogy with adjacent wells

Initial state or current state?

*Historical production Of adjacent well*

*Predicted production of oil*
General Arps decline equation

\[ q = \frac{q_i}{(1 + bDt)^{1/b}} \]

where

- \( q_i \) = initial rate (neglecting transient decline),
- \( q \) = rate at time \( t \),
- \( D \) = decline constant,
- \( b \) = decline exponent.

where \( b \) can represent:
- exponential decline: \( b = 0 \)
- hyperbolic decline: \( 0 < b < 1 \)
- harmonic decline: \( b = 1 \).
Decline Curve Analysis

Various production decline curves

Arps (1945)
Decline Curve Analysis

Advanced Topics

Composite of analytic and empirical type curves (Fetkovich, 1980)

\[
q_{d0} = \frac{q(t)}{q_i} = \frac{1}{\left[1 + b D_i t\right]^b}; \text{FOR } b > 0
\]

\[
q_{d0} = \frac{q(t)}{q_i} = \frac{1}{e^{D_i t}}; \text{FOR } b = 0
\]
Decline exponent (b) for various drive mechanisms (Fetkovich, et al, 1994)
Decline Curve Analysis

Composite production type curve illustrating layer affects
(Fetkovich, et al, 1994)
Estimation of Production/Reserves

1. Material balance
   - Requires measured reservoir pressure data

2. Volumetrics
   - Account for changes in properties; e.g., Sw.
   - How determine recovery factor?
     - Empirical based on drive mechanism, oil gravity, etc
     - From well logs
     - By EUR\{RTA\}/N\{volumetrics\}
     - Account for pressure depletion?
     - (RF)well = 10% < (RF)field = 25%
       15% remaining for primary?

3. Rate transient analysis

\[ \text{RF}_{wd} = \frac{S_{xo} - S_w(t)}{1 - S_{wi}} \]

Implies as Sw increases, then RF will decrease.
## Estimation of Production/Reserves

### Solution Gas Drive Reservoirs (Arps, 1962)

<table>
<thead>
<tr>
<th>Soln Gor Oil gravity</th>
<th>Sandstones average</th>
<th>Sandstones maximum</th>
<th>Sandstones minimum</th>
<th>Carbonates average</th>
<th>Carbonates maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>maximum</td>
<td>minimum</td>
<td>maximum</td>
<td>minimum</td>
<td>maximum</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>12.8</td>
<td>8.6</td>
<td>2.6</td>
<td>28.0</td>
</tr>
<tr>
<td>30</td>
<td>21.3</td>
<td>15.2</td>
<td>8.7</td>
<td>2.8</td>
<td>32.8</td>
</tr>
<tr>
<td>50</td>
<td>34.2</td>
<td>24.8</td>
<td>16.9</td>
<td>39.0</td>
<td>32.3</td>
</tr>
<tr>
<td>200</td>
<td>15</td>
<td>13.3</td>
<td>8.8</td>
<td>3.3</td>
<td>27.5</td>
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<tr>
<td>30</td>
<td>22.2</td>
<td>15.2</td>
<td>8.4</td>
<td>39.8</td>
<td>32.3</td>
</tr>
<tr>
<td>50</td>
<td>37.4</td>
<td>26.4</td>
<td>17.6</td>
<td>39.8</td>
<td>19.3</td>
</tr>
<tr>
<td>600</td>
<td>15</td>
<td>18.0</td>
<td>11.3</td>
<td>6.0</td>
<td>26.6</td>
</tr>
<tr>
<td>30</td>
<td>24.3</td>
<td>15.1</td>
<td>8.4</td>
<td>30.0</td>
<td>9.6</td>
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<tr>
<td>50</td>
<td>35.6</td>
<td>23.0</td>
<td>13.8</td>
<td>36.1</td>
<td>15.1</td>
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<tr>
<td>1000</td>
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<tr>
<td>30</td>
<td>34.4</td>
<td>21.2</td>
<td>12.6</td>
<td>32.6</td>
<td>13.2</td>
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<tr>
<td>50</td>
<td>33.7</td>
<td>20.2</td>
<td>11.6</td>
<td>31.8</td>
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<td>2000</td>
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<tr>
<td>50</td>
<td>40.7</td>
<td>24.8</td>
<td>15.6</td>
<td>32.8</td>
<td>14.5</td>
</tr>
</tbody>
</table>

### Recovery factor for different drive mechanisms

<table>
<thead>
<tr>
<th>Drive</th>
<th>minimum</th>
<th>Sandstones average</th>
<th>maximum</th>
<th>minimum</th>
<th>Carbonates average</th>
<th>maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water drive</td>
<td>27.8</td>
<td>51.1</td>
<td>86.7</td>
<td>6.3</td>
<td>43.6</td>
<td>80.5</td>
</tr>
<tr>
<td>Solution gas drive without supplemental drives</td>
<td>9.5</td>
<td>21.3</td>
<td>46.0</td>
<td>15.5</td>
<td>17.6</td>
<td>20.7</td>
</tr>
<tr>
<td>Solution gas drive with supplemental drives</td>
<td>13.1</td>
<td>28.4</td>
<td>57.9</td>
<td>9.0</td>
<td>21.8</td>
<td>48.1</td>
</tr>
<tr>
<td>Gas cap drive</td>
<td>15.8</td>
<td>32.5</td>
<td>67.0</td>
<td>Combined with sandstone</td>
<td>Data not available</td>
<td></td>
</tr>
<tr>
<td>Gravity drainage</td>
<td>16.0</td>
<td>57.2</td>
<td>63.8</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Gas depletion</td>
<td>75.0</td>
<td>85.0</td>
<td>95.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas water drive</td>
<td>50.0</td>
<td>70.0</td>
<td>80.0</td>
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</tr>
</tbody>
</table>
Horizontal Well Performance

Horizontal well flow equation
Based on infinite-conductivity horizontal well

\[ J_h = \frac{k_h / \mu_o B_o}{141.2 \left[ \ln \left( \frac{r_e}{r_w} \right) - .75 + S_{CA} + S_f + S_m - 1.386 \right]} \]

where

- \( S_{CA} \) = shape related skin factor
- \( S_f = -\ln(L/4r_w) \), skin factor due to fully-penetrating infinite-conductivity fracture
- \( S_m \) = mechanical skin

Mutalik, et al.
Horizontal Well Performance

- $\text{PI}_{\text{horizontal}} > x\text{PI}_{\text{vertical}}$
- If less than expected, possible cause is $L_{\text{productive}} < L_{\text{drilled}}$.
  - Reservoir heterogeneity
  - Wellbore pressure drop
  - Formation damage
Acceleration Project

- Investigate the economic advantage of accelerating production through stimulation
Acceleration Project

- Assume constant volume tank; therefore recovery same in both cases but time is different

- However, subject to economic limit, thus may capture additional reserves since low production maybe uneconomic.

\[
\text{Reserves}_{(\text{frac})} = \text{Reserves}_{(\text{unfrac})}
\]
Acceleration Project

- Possibility of gaining additional reserves if stimulation communicates with other compartments/layers

Estimation of Production/Reserves

\[
\text{Reserves}_{\text{frac}} > \text{Reserves}_{\text{unfrac}}
\]
Goal for economic analysis – estimate an annual production schedule for oil, gas and water.

Diagram: Flow rate vs. time for years YR1, YR2, ..., with flow rates $q_1, q_2, q_3, \ldots, q_n$. Cumulative production over time for years YR1, YR2, ...
What are the challenges/key technologies of horizontal wells to develop these resources?

1. How to produce from multiple, stacked pays?
### Multilateral wells

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lith</th>
<th>Reservoir Name</th>
<th>Prod</th>
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<tbody>
<tr>
<td>Delaware Mtn.</td>
<td></td>
<td>Brushy Canyon</td>
<td>⬤</td>
</tr>
<tr>
<td></td>
<td>Bone Spring Limestone</td>
<td>⬤</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leonard Shale</td>
<td>⬤</td>
<td></td>
</tr>
<tr>
<td>PERMIAN Bone Spring</td>
<td></td>
<td>Upper Avalon Shale</td>
<td>⬤</td>
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<tr>
<td></td>
<td>Middle Avalon Carbonate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Avalon Shale</td>
<td>⬤</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1&quot; Bone Spring Sand</td>
<td>⬤</td>
<td></td>
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<tr>
<td></td>
<td>2nd Bone Spring Carbonate</td>
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<td></td>
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<tr>
<td></td>
<td>2&quot; Bone Spring Sand</td>
<td>⬤</td>
<td></td>
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<tr>
<td></td>
<td>3rd Bone Spring Carbonate</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>3&quot; Bone Spring Sand</td>
<td>⬤</td>
<td></td>
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<tr>
<td>Wolfcamp</td>
<td></td>
<td>Wolfcamp Shale</td>
<td>⬤</td>
</tr>
<tr>
<td>Crisco Canyon</td>
<td></td>
<td>Penn Shale</td>
<td>⬤</td>
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<tr>
<td></td>
<td>Strawn</td>
<td>⬤</td>
<td></td>
</tr>
</tbody>
</table>

- Lower Avalon Shale
- 1st Bone Spring Carbonate
- 1st Bone Spring Sand
What are the challenges/key technologies of horizontal wells to develop these resources?

1. How to produce from multiple, stacked pays?
2. How to improve recovery?
Improving recovery

Spacing and drainage area?
Improving recovery
Waterflood (EOR) opportunities?
Improving recovery

Waterflood (EOR) opportunities?
What are the challenges/key technologies of horizontal wells to develop these resources?

1. How to produce from multiple, stacked pays?
2. How to improve recovery?
3. How to improve the fracture design and increase the SRV?
**Stimulated Reservoir Volume (SRV)** is defined as the volume of a reservoir which is effectively stimulated to increase the well performance.

Estimating SRV from microseismic mapping data *(SPE 118890, 2008)*
SRV, frac spacing and azimuth are key for well placement and spacing strategies.

Optimization dependent on:

1. **Natural geologic and petrophysical features**
   - thickness, stresses, natural fractures, barriers

![Diagram](image)

- $k_{min} = 0.03 \text{ mD}$
- $k_{max} = 3.34 \text{ mD}$
- $k_{Matrix} = 0.01 \text{ mD}$
- 10 m

Horizontal well paths A B
2. Engineering design parameters

An estimated 50% of perforation clusters and 25% of stages are not contributing to production

How to maximize fracture contact area?

a. lateral length and orientation,

b. treatment sizes and number of stages, perforation clusters,

c. diversion techniques and/or openhole packer completion systems.
Engineering design parameters

Source:
*Optimization of Completions in Unconventional Reservoirs*
JPT, July 2011, SPE 143066
What are the challenges/key technologies of horizontal wells to develop these resources?

1. How to produce from multiple, stacked pays?
2. How to improve recovery?
3. How to improve the fracture design and increase the SRV?
4. What are the environmental impacts on horizontal wells and how can they be mitigated?
### Environmental issues with hydraulic fracturing

#### Composition

**Typical shale Fracturing Mixture Makeup**

- **90% WATER**
- **9.5% SAND**
- **0.5% CHEMICAL ADDITIVES**

**Typical Chemical Additives Used in Frac Water**

<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>
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<tr>
<td>Sodium Chloride</td>
<td>Allows a delayed breakdown of the gel polymer chains</td>
<td>Table salt</td>
</tr>
<tr>
<td>Polyacrylamide</td>
<td>Minimizes the friction between fluid and pipe</td>
<td>Water treatment, soil conditioner</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>Prevents scale deposits in the pipe</td>
<td>Automotive anti-freeze, deicing agent, household cleaners</td>
</tr>
<tr>
<td>Borate Salts</td>
<td>Maintains fluid viscosity as temperature increases</td>
<td>Laundry detergent, hand soap, cosmetics</td>
</tr>
<tr>
<td>Sodium/Potassium Carbonate</td>
<td>Maintains effectiveness of other components, such as crosslinkers</td>
<td>Washing soda, detergent, sopa, water softener, glass, ceramics</td>
</tr>
<tr>
<td>Glutaraldehyde</td>
<td>Eliminates bacteria in the water</td>
<td>Disinfectant, sterilization of medical and dental equipment</td>
</tr>
<tr>
<td>Guar Gum</td>
<td>Thickens the water to suspend the sand</td>
<td>Thickener in cosmetics, baked goods, ice cream, toothpaste, sauces</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>Isopropanol</td>
<td>Used to increase the viscosity of the fracture fluid</td>
<td>Glass cleaner, antiperspirant, hair coloring</td>
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Environmental issues with hydraulic fracturing

Contamination

Pathways:
1. by uncemented or poorly cemented wellbores
2. By fracturing into the shallow layers
3. By activating existing fractures above the target formation and subsequently increasing connectivity

Drilled in hydrocarbon bearing zone
Variable groundwater quality
Drilling or other contamination
Hydraulic fracturing of HC zones

Challenges to:
Testing Procedures Interpretation of data
Environmental issues with hydraulic fracturing

Water Usage

• Increase need for fresh water for stimulation of the horizontal wells. An average stimulation treatment consumes 2 million gallons or 6 acre-feet of water per well.

• In comparison, the City of Carlsbad 2010 usage was 8,537 acre-feet. (Source: City of Carlsbad Municipal Water System, 2010 Annual Consumer Report on the Quality of Your Drinking Water)

• Reclaim, recycle and reuse flowback water, or use produced water as base frac fluid.