Abstract

Early in the development of a shale gas resource, optimal well spacing remains unknown as wells are sparsely drilled to hold leases by production. Developing the acreage requires operators to select locations, specify drilling plans, and design completions for multi-stage horizontal wells to maximize the operating metrics as defined by the company.

This presentation builds on our earlier work which presented sensitivity analysis for optimal well spacing with respect to permeability, fracture spacing and half-length under the assumption of uniform and symmetric completion configurations. The well spacing sensitivity to heterogeneity in completion configurations (i.e., non-uniform fracture half-length and asymmetric fracture spacing) are presented in this paper using deterministic modeling and stochastic modeling approaches.

Deterministic modeling results show a strong bias towards the longest repeated fracture half-length in determining the optimal well spacing. Higher reservoir permeability abates the impact of fracture heterogeneity. Fracture modeling, constrained by production logs, temperature logs, and/or microseismic, can be used to aid in the identification of the longest repeated half-length.

This work demonstrates the challenges associated with stochastic modeling of well performance. Examples from synthetic and field results from the Woodford Shale are presented to illustrate uncertainty in reservoir and completion parameter determination. The spacing optimization workflow used captures this uncertain range to effectively determine the impact on recovery factor and Net Present Value (NPV). The importance of the quantity of production history needed to determine optimal well spacing is also presented. Results reveal that with increasing heterogeneity longer production history is required for reliable determination of optimal well spacing. Finally, a completion optimization study is shown how changing the completion design impacts well performance and influences future well spacing decisions.

These conclusions, via the application of deterministic and stochastic modeling on production from field cases and synthetic wells, will aid operators in answering the multi-billion dollar question: how many wells should be placed in a given area? The workflow described in this
presentation not only can answer this question but also help us to understand how to maximize economic return and the ultimate gas recovery.

References Cited


Determining Optimum Well Spacing Using Fracture Characterization in Unconventional Reservoirs
Vivek Sahai, Greg Jackson, Rakesh Rai | May 29, 2014
Agenda

- Stochastic Modeling 6
- Woodford Results 8
- Deterministic Modeling 16
- Synthetic Cases 17
- Effect of Production History 25
- Woodford Completion Design Study 26
- Conclusions 29
Methodologies

- **Deterministic modeling**
  - One set of input parameters
  - One cumulative recovery
    - Kennon et al. (2009), Jayakumar et al. (2011)

- **Stochastic modeling**
  - Range of input parameters
  - Range of cumulative recovery
    - Miller et al. (2010), Boulis et al. (2013)
Stochastic Modeling

\[ J_{it}, R_{comp}, \text{ and } t_c: \]
See Miller et al. (2010)
Flow Regimes

Inverse Productivity Index (psi/d / Msf)

Time

Internal Linear Transient Flow (Half Slope)
Internal Depletion Flow (Unit Slope)

-1/2

-1
Woodford Wells Productivity Index Behavior ($J_{lt}$)

Wells are arranged in increasing order of $J_{lt}$.
Woodford Wells – Completion Resistance

- Low fracture conductivity
- Poor frac to wellbore connection
- Multi-phase effects (i.e. “clean-up”), or Krel effects
- Frac skin
- Casing constrictions

Jackson and Rai (2012)
JIt vs. Liquid Pumped

© 2014 Weatherford. All rights reserved.
Observations Based on Woodford Wells

- Stochastic Modeling:
  - Gives a framework to identify productivity and completion resistance trends
  - Provides for a consistent comparison within a play
- All wells appear to be in linear transient flow
- Linear transient productivity index:
  - Better productivity comparator than IP or 3/6/9 month cum
  - Can be used to identify areas where to optimize completion design
Presenter’s notes: Our previous work demonstrated no drainage extend from the extent of the SRV which depends on the fracture half length. The non-stimulated region does not provide much contribution when considering optimal well spacing. This work assumed that the fracture area in the SRV had uniform fracture half length and uniform fracture spacing. So for large fracture half lengths you will need less wells to get optimal recovery vs. the two cases on the right which show lower fracture half length.
Presenter’s notes: This previous work was for an idealistic case. Information from PLT show that only a few stages and clusters can be contributing to the flow, which results in non-uniform fracture spacing. Microseismic homogeneity does not exist, so we must account for heterogeneity so our study focused on how heterogeneity affected our answer on optimum well spacing.
Optimum Well Spacing

• How do we define “optimal”

• What is the impact of heterogeneity in
  – Fracture area/half-length
  – Fracture spacing
  – Drainage profile

• How does length of production history impact our decision
Presenter’s notes: We use the term “fractures” to refer to hydraulically-induced and propped fractures. Fracture spacing is defined as the distance between two adjacent planar hydraulically-induced fractures along the wellbore. Permeability is simply the matrix or rock permeability connected to the propped hydraulic fractures. The stimulated reservoir volume (SRV) is the total volume that encompasses all fractures (i.e., fracture tip-to-fracture tip). The external reservoir volume (XRV), is the volume outside the SRV that is still assigned to a given well based on its current or future no-flow boundaries. The internal flow (flow within the SRV) and external flow (from XRV, area outside the SRV, toward the SRV) as defined in this paper. The image on the left shows internal linear transient flow that occurs within the SRV at early times, and the image on the right shows a well in predominantly external linear transient flow (Miller et al., 2010) from the XRV to the SRV which happens later in the life of well once the SRV has been depleted.
Synthetic Cases

Base Case

Non-uniform Fracture Spacing

Case R1

Legend

Total fracture area conserved across all cases
Presenter’s notes: The SRV lines up at 5 wells. It is interesting to note that the NPV has only a slight increase past 10 years of production. Again the optimal point defined as the maximum NPV occurs at 5 wells per section. No scales are shown on the NPV curves, since the character of the plot does not change despite what economic assumptions were used.
Optimal Well Spacing Definition

- Number of wells after which next additional well increased the slope less than 50%

\[
\text{Incremental Cumulative for } n^{th} \text{ well} = \frac{Gp - \sum_{i=1}^{n-1} Gp_i}{Gp_1}
\]
Base Case – Incremental Cumulative

- Base Case
- 50% Normalized Incremental Cumulative Value

© 2014 Weatherford. All rights reserved.
Impact of Fracture Half-Length & Fracture Spacing Heterogeneity

- **Base Case (500 ft Uniform Half Length)**
- **Non Uniform Fracture Spacing**
- **Symmetric**
- **Pyramid**

![Graph showing the impact of fracture half-length and fracture spacing heterogeneity.](image-url)
Reservoir Depletion

- Base Case
- Non-uniform Fracture Spacing
- Symmetric Case
- Pyramid Case

© 2014 Weatherford. All rights reserved.
Impact of Fracture Half-Length & Fracture Spacing Heterogeneity

NPV

Incremental Cumulative

Optimum well spacing when additional well provides less than 50% of 1st well

© 2014 Weatherford. All rights reserved.
Impact of Additional Heterogeneity

**Drainage Profile**

Case R1 – Random Half-length
Case R2 – Random Half-length & Fracture spacing

**Incremental Cum Behavior**

- **Base Case**
- **Case R1**
- **Case R2**

- 50% Normalized Incremental Cumulative Value

© 2014 Weatherford. All rights reserved.
Effect of Production History

- Case R2, 6 months
- Case R2, 1 year
- Case R2, 2 Years

- 50% Normalized Incremental Cumulative Value

Normalized Incremental Cumulative

Wells per Section
Effect of Completion Design
Woodford Case Study

Red Section (Completion Design A)
Inner wells have 20% less productivity
- Inner wells drive economics
- Outer wells suggest larger spacing

<table>
<thead>
<tr>
<th>Completion Design</th>
<th>% More Proppant</th>
<th>% Better Productivity</th>
<th>% Higher Rate&lt;sub&gt;90&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>80</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>C</td>
<td>100</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>D</td>
<td>125</td>
<td>90</td>
<td>135</td>
</tr>
</tbody>
</table>

© 2014 Weatherford. All rights reserved.
Asset Monitoring & Reserves Progression
Woodford Case Study

- Eight wells initially planned per section as per completion design A
- Evolution of completion design (B, C & D) impacts well performance and influences future well spacing decisions
- Increased completion cost offset by higher productivity wells
- Planning cycle: Multiple months became 3 weeks
Asset Monitoring & Reserves Progression
Woodford Case Study

- Eight wells initially planned per section as per completion design A
- Evolution of completion design (B, C & D) impacts well performance and influences future well spacing decisions
- Increased completion cost offset by higher productivity wells
- Planning cycle: Multiple months became 3 weeks
Conclusions

- Well spacing decision varies by the choice of optimization metric
- Longest repeated half-length has a strong influence on optimal well spacing
  - High permeability will reduce the impact of heterogeneity
- Non-uniform fracture spacing does not impact the optimal number of wells per section; however, it does reduce cumulative and NPV
Conclusions

- Non-homogeneous fracture half-lengths also reduce the recovery factor and NPV

- Well spacing decisions based on early production tend to overestimate the number of wells required to optimally produce the section
Future Investigation

- Extend into Oil Reservoirs
- Effect of SRV overlap
- Effect of Timing

Zipper Fracture
50% Overlay
Future Investigation

- Extend into Oil Reservoirs
- Effect of SRV overlap
- Effect of Timing
References


Thank You!