Forecasting Production in Shale Gas Reservoirs - A Better Assessment of Reserves

Occidental Petroleum Corporation | GCS Reservoir Study Group | Anadarko Petroleum Convention Center

10th May | Krunal Joshi, Reservoir Engineer
Disclaimer

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Outline

• Problem
• Deterministic forecasting models
• Fixes to the Duong method
• Comparison of deterministic forecasting models for Individual wells
• Comparison of deterministic forecasting models for grouped well sets
• Conclusions
We Have a Problem

• Forecasting methods we use in conventional reservoirs may not work well in
  – Tight oil, gas
  – Oil, gas shales
  – Unconventional resources generally

• There have been various methods proposed
Criteria for Ideal Decline Model in Ultra-Tight Reservoirs

• Forecasts are reasonable and realistic for the well life
• Forecasts reasonable even with <2 years historical production data
• Valid during transient or radial flow
• Valid for boundary-dominated flow
• Easy to use and couple with economics software
A Superior Model Has Higher Accuracy and Precision For a Large Number of Wells

% Error in Reserves

Fig. 6a - High Precision & High Accuracy

% Error in Reserves

Fig. 6b - High Precision but Low Accuracy

% Error in Reserves

Fig. 6c - Low Precision & High Accuracy

% Error in Reserves

Fig. 6d - Low Precision & Low Accuracy
Long-Term Horizontal Shale Gas Well Simulation: Linear Flow Plot

- Fracture Linear Flow
- Fracture Interference Flow
- Outer Matrix Linear Flow
- Structural Boundary Flow

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Forecasting Models

- **Arps (Minimum Decline):** Hyperbolic decline followed by exponential decline after a predetermined decline rate. (Arps, 1945 & Long, 1988)

- **Duong Model:** A decline model based on long-term flow regime approximating linear flow: \( \frac{q}{q_p} = at^{-m} \) (Duong, 2010)
  - Modified Duong: With a Dswitch of 5% followed by a Arps curve of \( b=0.4 \)

- **SEDM/SEPD Model:** A decline model that is a summation of simultaneous exponential declines in different ‘cells’ within a reservoir. (Valko et al., 2009)

  \[ q = q_i \exp \left[ -\left( \frac{t}{\tau} \right)^n \right] \]
Arps (Minimum Decline)

- Best-fit “b” until predetermined minimum decline rate reached; then impose exponential decline (SPE 16237)

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

- Problems
  - Apparent “best” b decreases continually with time
  - Appropriate minimum decline rate based on observed long-term behavior in appropriate analogy – unavailable in new resource plays
SEPD/SEDM Model

\[ q = q_i \exp \left[ -\left( \frac{t}{\tau} \right)^n \right] \]

- ‘Validated’ for wells with both transient and stabilized flow in Barnett Shale
- Forecasts unreliable for <18 months of data
- \( n \) varies from 0.1 to 1 (exponential decline)
- Practical \( \tau \) range is 0.01 to 80
Duong Model

• Based on Long-term linear flow

\[
\frac{q}{G_p} = a t^{-m}
\]

• \( q = q_1 t(a, m) + q_\infty \)

• \( t(a, m) = t^{-m} e^{\frac{a}{1-m}(t^{1-m}-1)} \)
Determination of a & m (Duong)

\[ \frac{q}{G_p} = at^{-m} \]

Historical Data

Duong

slope = m

a=0.731, m=1.067
Determination of $q_1$ & $q_\infty$ (or $q_{inf}$)

$q = q_1 t (a, m) + q_\infty$

$q_{inf}$ or $q_\infty$ is the x-intercept on the above plot.
Duong Forecast

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Field Data Set

- 250 Well Dataset
  - Barnett Shale (200 wells)
    - Denton
    - Tarrant
    - Wise
    - Johnson
  - Fayetteville Shale (50 wells)
    - Van Buuren
  - Drilling Info
  - Horizontal Wells
  - Monthly Rate Data
- 1st production starts 1/1/2004
- Range of total production: 30 to 85 months
Simulated Data Set

• Composite Model
  – Analytical Simulator (Fekete WellTest)
  – SRV permeability different from Outer Matrix permeability

• Barnett (25 simulations)
  – 133874(Chong et al. 2010), 146876(Cipolla et al. 2011), 144357(Strickland et al. 2011), 96917(Frantz et al. 2005), 125530(Cipolla et al. 2010) and 147603(Ehlig-Economides and Economides 2011)

• Marcellus (25 simulations)
  – 133874(Chong et al. 2010), 125530(Cipolla et al. 2010), 144436 (Thompson et al. 2011) and 147603(Ehlig-Economides and Economides 2011).

• Properties Varied:
  – Fracture stages, fracture length and fracture conductivity.
  – Stimulated Reservoir Volume (SRV) permeability
  – In accordance with the ranges in the above papers
Barnett Shale Simulation (Base Case)

Hz Multifrac-Comp Model
Schematic

\[ X_w = 200 \text{ ft} \]
\[ \Delta X_w = -1600.0 \text{ ft} \]
\[ X_w = 2000.0 \text{ ft} \]
\[ \Delta X_w = 0.0 \text{ ft} \]
\[ X_w = 1600.0 \text{ ft} \]
\[ \Delta X_w = 800.0 \text{ ft} \]
\[ 100 \text{ nd} \]
\[ 500 \text{ nd} \]

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Marcellus Shale Simulation (Base Case)

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Fixes to the Duong Model

• Use of qinf
  – Not suggested for short term data.
  – Debatable for long-term data
  – Simulated data can solve the conundrum of whether qinf is necessary or not.

• Modified Duong
  – Accounts for fracture interference
  – Dswitch of 5%, i.e. when decline rate reaches 5%, forecast switches to Arps
Using qinf Does Not Work For Short Term Field Production Data

Forecasting Production in Shale Gas Reservoirs - A Better Assessment of Reserves
Using $q_\infty$ For Simulated Production Data Does Not Work Well
Modified Duong (Dswitch @5%) Works Better Than the Original Duong

Forecasting Production in Shale Gas Reservoirs - A Better Assessment of Reserves
Individual Well Field Production Data
## Comparison of The Modified Duong, SEDM and Arps For a Field Data Set

### Discrepancy (error%) in remaining production for a field dataset

<table>
<thead>
<tr>
<th>History Matched</th>
<th>Duong_Dswitch@5%</th>
<th>SEDM</th>
<th>Arps (Dmin 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-15.98</td>
<td>40.91</td>
<td>10.97</td>
</tr>
<tr>
<td>Std.Dev</td>
<td>29.24</td>
<td>39.06</td>
<td>33.16</td>
</tr>
<tr>
<td>% Wells &lt;15 % error</td>
<td>45.60</td>
<td>22.00</td>
<td>43.20</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-7.77</td>
<td>6.44</td>
<td>5.04</td>
</tr>
<tr>
<td>Std.Dev</td>
<td>17.48</td>
<td>27.75</td>
<td>22.57</td>
</tr>
<tr>
<td>% Wells &lt;15 % error</td>
<td>66.80</td>
<td>48.40</td>
<td>63.20</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-6.90</td>
<td>5.06</td>
<td>3.03</td>
</tr>
<tr>
<td>Std.Dev</td>
<td>14.41</td>
<td>21.90</td>
<td>19.01</td>
</tr>
<tr>
<td>% Wells &lt;15 % error</td>
<td>71.60</td>
<td>59.20</td>
<td>69.20</td>
</tr>
<tr>
<td>24</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-2.49</td>
<td>4.49</td>
<td>2.21</td>
</tr>
<tr>
<td>Std.Dev</td>
<td>16.13</td>
<td>20.51</td>
<td>18.92</td>
</tr>
<tr>
<td>% Wells &lt;15 % error</td>
<td>72.80</td>
<td>64.40</td>
<td>71.60</td>
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<td>36</td>
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<tr>
<td>Mean</td>
<td>-5.04</td>
<td>4.41</td>
<td>2.77</td>
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<tr>
<td>Std.Dev</td>
<td>17.88</td>
<td>21.93</td>
<td>22.54</td>
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<tr>
<td>% Wells &lt;15 % error</td>
<td>71.93</td>
<td>64.91</td>
<td>68.86</td>
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<tr>
<td>Mean</td>
<td>-5.45</td>
<td>1.63</td>
<td>-0.05</td>
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<tr>
<td>Std.Dev</td>
<td>18.08</td>
<td>27.12</td>
<td>26.99</td>
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<tr>
<td>% Wells &lt;15 % error</td>
<td>77.16</td>
<td>69.04</td>
<td>77.66</td>
</tr>
</tbody>
</table>
How Well Do Different Models Forecast With Short Term Data?

Comparison of various empirical models for API# 42-121-32245, matching 12 months of historical data.
How Well Do Different Empirical Models Forecast With Long Term Data?

Comparison of various empirical models for API# 42-497-35453, matching 36 months of historical data.
Individual Well Simulated Data
### Discrepancy (Error %) in remaining production

<table>
<thead>
<tr>
<th>History Matched</th>
<th>Duong_qinf=0 (Dswitch @5%)</th>
<th>Arps (Dmin @ 5%)</th>
<th>SEPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>22.23</td>
<td>-12.38</td>
<td>38.62</td>
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<td></td>
<td>19.56</td>
<td>19.80</td>
<td>14.39</td>
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<tr>
<td>12</td>
<td>5.55</td>
<td>-15.17</td>
<td>22.37</td>
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<tr>
<td></td>
<td>17.43</td>
<td>20.98</td>
<td>17.96</td>
</tr>
<tr>
<td>18</td>
<td>-4.33</td>
<td>-18.27</td>
<td>21.40</td>
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<td>16.09</td>
<td>21.16</td>
<td>19.36</td>
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<tr>
<td>24</td>
<td>1.00</td>
<td>-18.64</td>
<td>14.96</td>
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<td>13.10</td>
<td>18.47</td>
<td>18.31</td>
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<tr>
<td>36</td>
<td>-13.97</td>
<td>-16.79</td>
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<tr>
<td></td>
<td>9.84</td>
<td>13.31</td>
<td>16.24</td>
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<tr>
<td>48</td>
<td>-13.88</td>
<td>-13.75</td>
<td>10.41</td>
</tr>
<tr>
<td></td>
<td>7.99</td>
<td>10.81</td>
<td>18.72</td>
</tr>
</tbody>
</table>
How Well Do Different Models Forecast With Short Term Data?

A Barnett Shale simulation matching 12 months of history

Barnett Case#1 (12 months matched)

Production Rate, MSCF/Month

Time, Months

EOH

Simulation
Arps (Dmin @5%)
SEPD
Modified Duong (Dswitch @ 5%)

A Barnett Shale simulation matching 12 months of history
How Well Do Different Empirical Models Forecast With Long Term Data?

A Barnett Shale simulation matching 36 months of history

Barnett Case#1 (36 months matched)

A Barnett Shale simulation matching 36 months of history
Field Grouped Data Sets
How Well Do Different Models Forecast For Short Term Grouped Data?

Johnson County (130 wells)- 18 months matched

<table>
<thead>
<tr>
<th>Method</th>
<th>Reserves (After EOP) (BSCF)</th>
<th>Avg Reserves (After EOP) BSCF/Well</th>
<th>%Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arps (Dmin@5%)</td>
<td>197.168</td>
<td>1.517</td>
<td>-17.7</td>
</tr>
<tr>
<td>Modified Duong (Dswitch@5%)</td>
<td>132.856</td>
<td>1.022</td>
<td>-4.8</td>
</tr>
<tr>
<td>SEPD</td>
<td>116.648</td>
<td>0.897</td>
<td>-7.2</td>
</tr>
</tbody>
</table>
How Well Do Different Models Forecast For Long Term Grouped Data?

Denton County (81 wells) – 36 months matched

<table>
<thead>
<tr>
<th>Method</th>
<th>Reserves (After EOP) (BSCF)</th>
<th>Avg Reserves (After EOP) BSCF/Well</th>
<th>%Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arps (Dmin @5%)</td>
<td>75.244</td>
<td>0.929</td>
<td>1.5</td>
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<tr>
<td>Modified Duong (Dswitch@5%)</td>
<td>90.007</td>
<td>1.111</td>
<td>-2.0</td>
</tr>
<tr>
<td>SEPD</td>
<td>71.074</td>
<td>0.877</td>
<td>2.2</td>
</tr>
</tbody>
</table>
What About Oil Wells?

• Same as Gas Wells
  – $D_{\text{switch}}/D_{\text{min}}$ values vary for different plays
  – Interference

• Account for solution gas

• Operational issues need to be accounted for
  – Pump Issues, Paraffin Issues
  – Higher reserves potential if issues fixed
Conclusions

• Previously mentioned modifications to the Duong makes the Duong model even more robust and accountable for fracture interference.

• The Modified Duong ($D_{\text{switch}}$) method provides more accurate results than the SEDM and Modified Arps ($D_{\text{min}}$) Model when more than 12 months of historical production data is available, although some error is still associated with those forecasts.

• None of the models studied produces accurate forecasts with 6 months or less of historical production data.

• For grouped well sets the SEPD and Modified Duong ($D_{\text{switch}}$) work exceptionally well providing reasonable forecasts.
Acknowledgements

Crisman Institute at Texas A&M for their funding
Quiz

• With greater than 12 months of historical production data, which of these decline models provided the lowest error in remaining production for an individual well?

  a. SEPD/SEDM
  b. Modified Duong (Dswitch @ 5%)
  c. Arps (Dmin @ 5%)
  d. Duong
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