A New Empirical Analysis Technique for Shale Reservoirs

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The method presented here is not used for any reserve work performed by Ryder Scott at this time.
Outline

- Extended Exponential Decline Curve Analysis
- Problems with Modified Hyperbolic (MH)
- Application in Four Shale Reservoirs
- A Step Fitting Result
- Application in Conventional Reservoirs
- Discussion & Conclusions
A Typical Shale Gas/Oil Decline Curve

- Early time – sharp decline
- Late time – flatter decline
- How many flow regimes?
- When is the switching point of different flow regimes?

If all you have is the data indicated by the markers, how does one determine the switching point?
**$b$-factor Changes with Time**  

Despite Good Match of History, Forecasting Ability Poor, Especially with Limited Early Data

<table>
<thead>
<tr>
<th>Years of History Matched</th>
<th>Best Fit, Arps “$b$”</th>
<th>Error in Remaining Reserves, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.66</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>1.91</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>1.51</td>
<td>30.6</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>1.14</td>
<td>0</td>
</tr>
</tbody>
</table>

From Dr. W. John Lee’s classnotes —2016 Spring
Critique of Arps

Arps in 1944

P is the flowrate

approximately constant, as in Table 2, the following differential equation can be set up:

\[
\frac{d}{dt} \left( \frac{P}{dP/dt} \right) = -b \tag{7}
\]

in which \( b \) is a positive constant. Integration of Eq. 7 leads to:

\[
\frac{P}{dP/dt} = -bt - a_0 \tag{8}
\]

Fulford and Blasingame 2013

The classic Arps [1945] decline curve approach is limited to cases where wells are producing in boundary dominated-flow (implying a \( b \)-parameter between 0 and 1.0) and the \( b \)-parameter can be described by a constant value. In practice, we observe values of the \( b \)-parameter above 1.0 for extended periods of time prior to the onset of boundary-dominated flow. This difference between theory and application where the \( b \)-parameter applied to early-time data is assumed to be greater than 1.0, and held constant until a terminal exponential decline rate is reached (Modified Hyperbolic Model). This approach assumes prior knowledge of both the average \( b \)-parameter for the life of the well, and the terminal exponential decline rate; both of which are unknown for many emerging unconventional plays and may differ within a play as a result of well design. Recent attempts to address this issue have resulted in more rigorous models, such as the Power-Law Exponential (Ilk et al [2008]); however, the Modified Hyperbolic Model remains in popular use within the industry.

In the rate-time relationship for hyperbolic decline:

\[
P = P_0 \left( x + \frac{bt}{a_0} \right)^{-1/b} \tag{10}
\]
Extended Exponential Decline Curve Analysis (EEDCA)

- Keep the same Exponential form of Arps equation for simplicity
  \[ q = q_i e^{-at} \]

- But exponent \( a \) should vary with time
  \[ a = \beta_l + \beta_e e^{-tn} \]
  where \( \beta_e \) is a constant to account for the early (fully-transient) period, which should be larger than \( \beta_l \) as recommended;
  \( \beta_l \) is a constant to account for the late-life period;
  \( n \) is an empirical exponent;
  \( t \) is the time in months.

- Note if the \( \beta_l \) is set equivalent to \( D_{\text{min}} \) as a constant, the EEDCA becomes a 3-parameter equation similar to the Arps hyperbolic equation; if the \( \beta_e \) is set to 0, the EEDCA reduces to the identical form of the exponential equation (with \( a = \beta_l \)).
Critique of Arps #1: Assumption of constant $b$-factor

Arps empirical equation is used to describe production performance. Therefore,

- **Step 1**: we can reproduce similar projections by both Modified Hyperbolic (MH) and EEDCA methods.
- **Step 2**: fix all parameters in the EEDCA method as constants, and bring them into the original $b$-factor definition by Arps, we can investigate if $b$-factor truly changes with time in shale.

\[
b = \frac{\frac{dq}{dt}}{\frac{d^2q}{dt^2}} \quad \quad \quad b = -\frac{\beta e e^{-tn} t^{n-1}(nt^n-n-1)}{[\beta + \beta e e^{-tn} (1-t^n)]^2}
\]

- **Step 3**: plot the $b$-factor over time numerically

If $b$-factor is proved not a constant, we cannot obtain the form of hyperbolic equation!
CRITIQUE OF ARPS #2: ILL-IMPOSED $D_{\text{MIN}}$

- What is the decline rate $D_{\text{min}}$? How to predict?
- $D_{\text{min}}$ independent from early-time data, and can be only determined in the late-life when it is observed (purple box).
- A well generally produces from the same reservoir volumes over its producing life. Therefore, the flowing pattern must be continuous, and the independent projection strategy between early- and late-life is not a robust solution.
- This $D_{\text{min}}$ has no theoretical support but is instead an empirical adjustment; further, the value is also difficult to defend without actual wells that are producing late in their life.
CRITIQUE OF ARPS #2: ILL-IMPOSED $D_{\text{MIN}}$ —CONT’D

- EEDCA $\beta_l$ is always a contributing factor to the production model, starting from the first production data point.

\[ q = q_i e^{-at} \quad a = \beta_l + \beta e^{-t^n} \]

- EEDCA method, $\beta_l$ dominates the late life projection, as does $D_{\text{MIN}}$ in MH method.

- $\beta_l$ can be an early-time factor and is expected to react on the projection sooner than $D_{\text{MIN}}$. We will graphically demonstrate the contribution from $\beta_l$ with an example well from Haynesville shale.
CRITIQUE OF ARPS #2: ILL-IMPOSED $D_{\text{MIN}}$ — CONT’D

Arps empirical equation is used to describe production performance. Therefore,

- **Step 1**: we can reproduce similar projections by both MH and EEDCA methods.
- **Step 2**: fix all parameters in the EEDCA method as constants, and bring them into the original decline rate definition by Arps.

\[
D = \frac{dq}{dt} = -\frac{1}{q} \frac{dq}{dt} \quad \Rightarrow \quad D = \beta_1 + \beta_3 e^{-tn} (1 - nt^n)
\]

- **Step 3**: Plot the decline rate over time numerically

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CRITIQUE OF ARPS #3: SWITCHING POINT IN TIME

Modeling the transition
• Arps (modified) combines two distinct equations joined at one point in time;
• EEDCA has a single equation representing continuity from early time through “transition” to late time.

For constant decline rate over time, we have \( \frac{dD}{dt} = 0 \)

By using EEDCA, we derive equation to calculate switching point for MH method.
\[
t_{\text{switching}} = n \sqrt{n+1} \sqrt[n]{n}
\]
Haynesville (47 wells)

(A) Log-log Diagnostics

(B) Production Rate, MCFG/M

(EUR Comparison (Modified Hyperbolic vs. EEDCA)

(B) $b = -\frac{\beta e_n e^{-t^n} t^{n-1} (n t^n - n - 1)}{[\beta t + \beta e^{-t^n} (1-t^n)]^2}$

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Haynesville –cont’d

Fig. 5 – (Haynesville) An example well: a-value is the red dot line, which is always contributed from both $\beta_0$ and $\beta_1$ parameters. The green area represents the contribution from $\beta_0$, which plays more important role in late-time life. The same data is plotted in (A) Cartesian and (B) Semi-Log coordinates.

$\alpha = \beta_1 + \beta_0 e^{-\tau^n}$

$-\frac{\ln(q/ql)}{t} = \beta_1 + \beta_0 e^{-\tau^n}$

MH strategy
Haynesville – cont’d

• Calculated $D_{\text{min}}$ by $D = \beta_1 + \beta_e e^{-t^n} (1 - nt^n)$
• Final P50 $D_{\text{min}}$ is 5.26%; Average $D_{\text{min}}$ is 5.77%
Summary of Shale Studies

The $D_{\text{min}}$ approach is an approximate practice, if the relative dropping rate of decline rate at any two adjacent months is less than 0.1.

The approximate $D_{\text{min}}$ might be close to the true value, but it still takes a long time to reach the true value.

Calculated $t_{\text{switching}}$’s are all longer than 35 years, which indicates $D$ probably keeps decreasing for the entire life. The forced $D_{\text{min}}$ in MH might not be appropriate.

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Table 1 - Summary of the Four Studied Shale Reservoirs

<table>
<thead>
<tr>
<th></th>
<th>No. of Studied Wells</th>
<th>Average n-value</th>
<th>Average $\beta_c$</th>
<th>Average $\beta_i$</th>
<th>Back Calculated P50 $D_{\text{min}}$</th>
<th>Back Calculated Average $D_{\text{min}}$</th>
<th>Average EUR by EEDCA*</th>
<th>Average EUR by Modified Hyperbolic*</th>
<th>$i$-th month (/12-th year Switch to Exponential)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haynesville</td>
<td>47</td>
<td>0.244</td>
<td>0.734</td>
<td>0.060</td>
<td>5.26%</td>
<td>5.77%</td>
<td>2,271</td>
<td>2,241</td>
<td>787 (65.5)</td>
</tr>
<tr>
<td>Barnett</td>
<td>25</td>
<td>0.252</td>
<td>0.519</td>
<td>0.060</td>
<td>5.70%</td>
<td>6.00%</td>
<td>1,779</td>
<td>1,764</td>
<td>574 (47.8)</td>
</tr>
<tr>
<td>Eagle Ford (Gas Window)</td>
<td>33</td>
<td>0.269</td>
<td>0.687</td>
<td>0.060</td>
<td>4.43%</td>
<td>5.19%</td>
<td>3,458</td>
<td>3,416</td>
<td>450 (37.5)</td>
</tr>
<tr>
<td>Wolfcamp</td>
<td>31</td>
<td>0.231</td>
<td>0.590</td>
<td>0.060</td>
<td>6.32%</td>
<td>7.90%</td>
<td>339</td>
<td>338</td>
<td>1,372 (114.3)</td>
</tr>
</tbody>
</table>

*EUR Unit: MMscf or MSTB

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SPE 181536 • Effective Applications of Extended Exponential Decline Curve Analysis to both Conventional and Unconventional Reservoirs
Step Fitting – Candidate Well

- A Barnett gas well has been production since Apr. 2000. API is 42-121-30703-00-00.
Step Fitting – Procedure

• All the curve fittings by MH and EEDCA were done by VBA auto-fitting to remove individual bias.
• Started with 18 months data and compared results from both methods.
• Repeated this procedure with additional 6 months data until the complete 192 month production history was used.
• In the extreme case at the 30th month of production, the auto fitting just presented an exponential decline as the $b$-factor is 0 by Arps method.
Step Fitting – Results

Fig. 16 – Projected EURs vs. available historical data by EEDCA and Modified Hyperbolic method (auto-fitting results).

Fig. 17 – n-value in EEDCA and Arps b-factor vs. available historical data (auto-fitting results).
Tight Gas Case #1

Well MGA-76-1-004

(A) Log-log Diagnostics

(B) Production Rate, MSCF/M

Historical Data
Modified Arps
EEDCA
Tight Gas Case #2

Well EXXON -002

(A) Log-log Diagnostics

(B) Production Rate, Mscf/M

- Historical Data
- Modified Arps
- EEDCA
Tight Gas Case #3

Well MGA-76-1-006

(A) Log-log Diagnostics

(B) 10,000

Production Rate, MSCF/M

Time, Months

Historical Data
Modified Arps
EEDCA

Production time, Month

Flowrate, MSCF/M

1,000

100

10

1

0 200 400 600 800

1,000

100

10

1
## Tight Gas Case Summary

<table>
<thead>
<tr>
<th>Lease Name</th>
<th>$b$-factor</th>
<th>$n$-value</th>
<th>MHDCA $D_i$</th>
<th>EEDCA $\beta_s$</th>
<th>EEDCA $\beta_l$</th>
<th>MHDCA EUR, MMSCF</th>
<th>EEDCA EUR, MMSCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGA-76-1-006</td>
<td>1.00</td>
<td>0.26</td>
<td>0.05</td>
<td>0.43</td>
<td>0.05</td>
<td>62.97</td>
<td>62.35</td>
</tr>
<tr>
<td>EXXON -002</td>
<td>0.86</td>
<td>0.24</td>
<td>0.03</td>
<td>0.22</td>
<td>0.05</td>
<td>122.08</td>
<td>122.11</td>
</tr>
<tr>
<td>MGA-76-1-004</td>
<td>1.00</td>
<td>0.27</td>
<td>0.01</td>
<td>0.33</td>
<td>0.05</td>
<td>61.82</td>
<td>61.06</td>
</tr>
<tr>
<td>Average</td>
<td>0.95</td>
<td>0.26</td>
<td>0.03</td>
<td>0.33</td>
<td>0.05</td>
<td>82.29</td>
<td>81.84</td>
</tr>
</tbody>
</table>
Discussion

• If the assumption of a constant $b$-factor is inappropriate for shale, the hyperbolic equation is invalid.

• $D_{\text{min}}$ and $\beta_1$ dominate the late-life projection in modified hyperbolic and EEDCA, respectively. Unlike the $D_{\text{min}}$ in Arps method, the $\beta_1$ always contributes in curve fitting, potentially from the first production data point.

• Any independent projection strategy between early- and late-life is not a robust solution, whatever a segment projection strategy or MB.
Conclusions

• EEDCA has advantages for shale evaluations:
  – It does not require an estimate of when to switch to exponential decline.
  – The assumption of a constant $b$-factor is likely invalid for shale. However, EEDCA is not limited to that constraint.
  – $\beta_l$ can be calibrated by early-life production data, whereas $D_{\min}$ is independent and isolated from the early-life data.

• EEDCA can be applied for various conventional wells in an exponential or hyperbolic decline behavior

• EEDCA becomes a 3-parameter equation $(q_i, \beta_e, n)$ in shale early-life if $\beta_l$ is set as a fixed value (similar to a small $D_{\min}$). Easy to fit.

For details, please refer to SPE papers 175016 and 181536.
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