

# A New Empirical Analysis Technique for Shale Reservoirs

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# Disclaimer

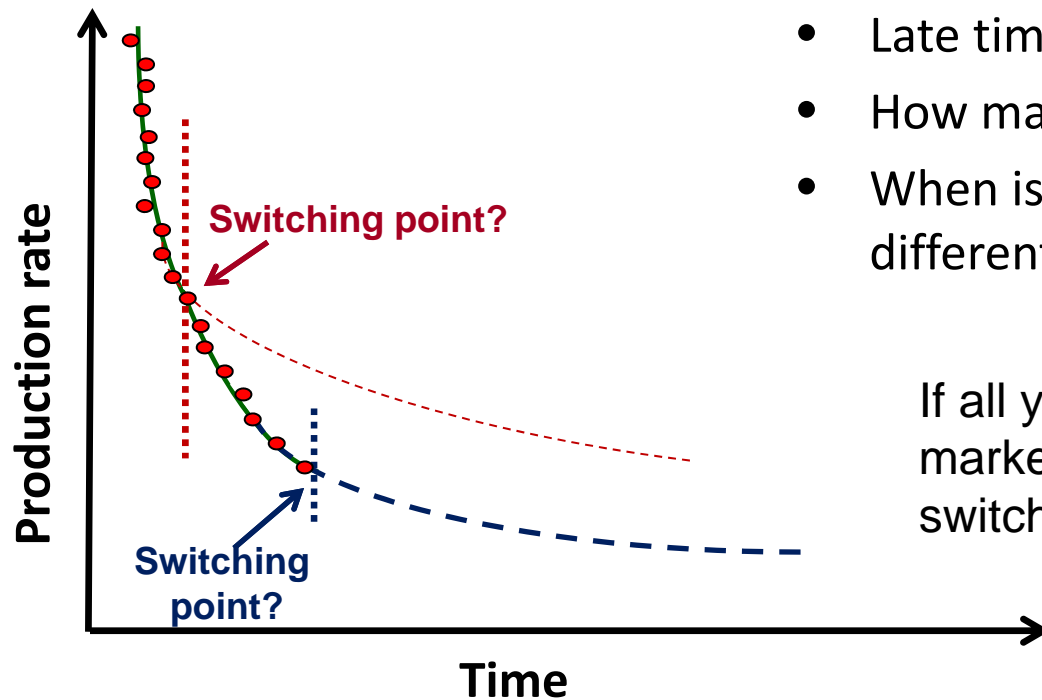
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**The method presented here is not used for any reserve work performed by Ryder Scott at this time.**

# 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**

| Years of History Matched | Best Fit, Arps "b" | Error in Remaining Reserves, % |
|--------------------------|--------------------|--------------------------------|
|                          |                    |                                |
| 2                        | 2.66               | 145                            |
| 5                        | 1.91               | 104                            |
| 10                       | 1.51               | 30.6                           |
| 25                       | 1.20               | 7.9                            |
| 50                       | 1.14               | 0                              |

From Dr. W. John Lee's classnotes —2016 Spring

# Critique of Arps

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

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

in which  $b$  is a positive constant. Integration of Eq. 7 leads to:

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

Arps in 1944

$P$  is the flowrate

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 leads to the misapplication of the Arps time-rate relation 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 a hyperbolic decline:

$$P = P_0 \left( 1 + \frac{bt}{a_0} \right)^{-1/b} \quad [10]$$

## 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

$$a = \beta_l + \beta_e e^{-t^n}$$

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  $D_{\min}$  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.

$$b = -\frac{d \frac{q}{dt}}{dt} \quad \longrightarrow \quad b = -\frac{\beta_e n e^{-t^n} t^{n-1} (nt^n - n - 1)}{[\beta_l + \beta_e e^{-t^n} (1 - t^n)]^2}$$

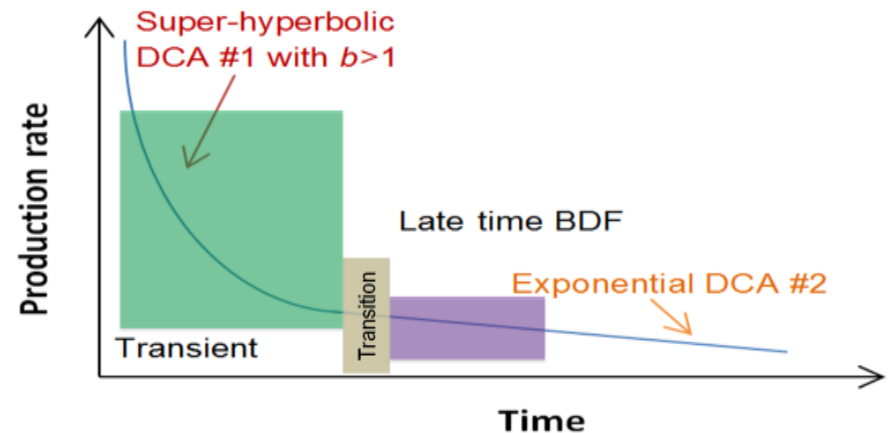
- *Step 3*: plot the  $b$ -factor over time numerically

If  $b$ -factor is proved not a constant, we cannot obtain the form of hyperbolic equation!



## CRITIQUE OF ARPS #2: ILL-IMPOSED $D_{\min}$

- What is the decline rate  $D_{\min}$ ? How to predict?
- $D_{\min}$  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  $D_{\min}$  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  $\beta_1$  is always a contributing factor to the production model, starting from the first production data point.

$$q = q_i e^{-at} \quad a = \beta_l + \beta_e e^{-t^n}$$

- EEDCA method,  $\beta_1$  dominates the late life projection, as does  $D_{\text{min}}$  in MH method.
- $\beta_1$  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  $\beta_1$  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.

$$D = -\frac{\frac{dq}{dt}}{q} = -\frac{1}{q} \frac{dq}{dt} \quad \longrightarrow \quad D = \beta_l + \beta_e e^{-t^n} (1 - nt^n)$$

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

## CRITIQUE OF ARPS #3: SWITCHING POINT IN TIME

### Modeling the transition

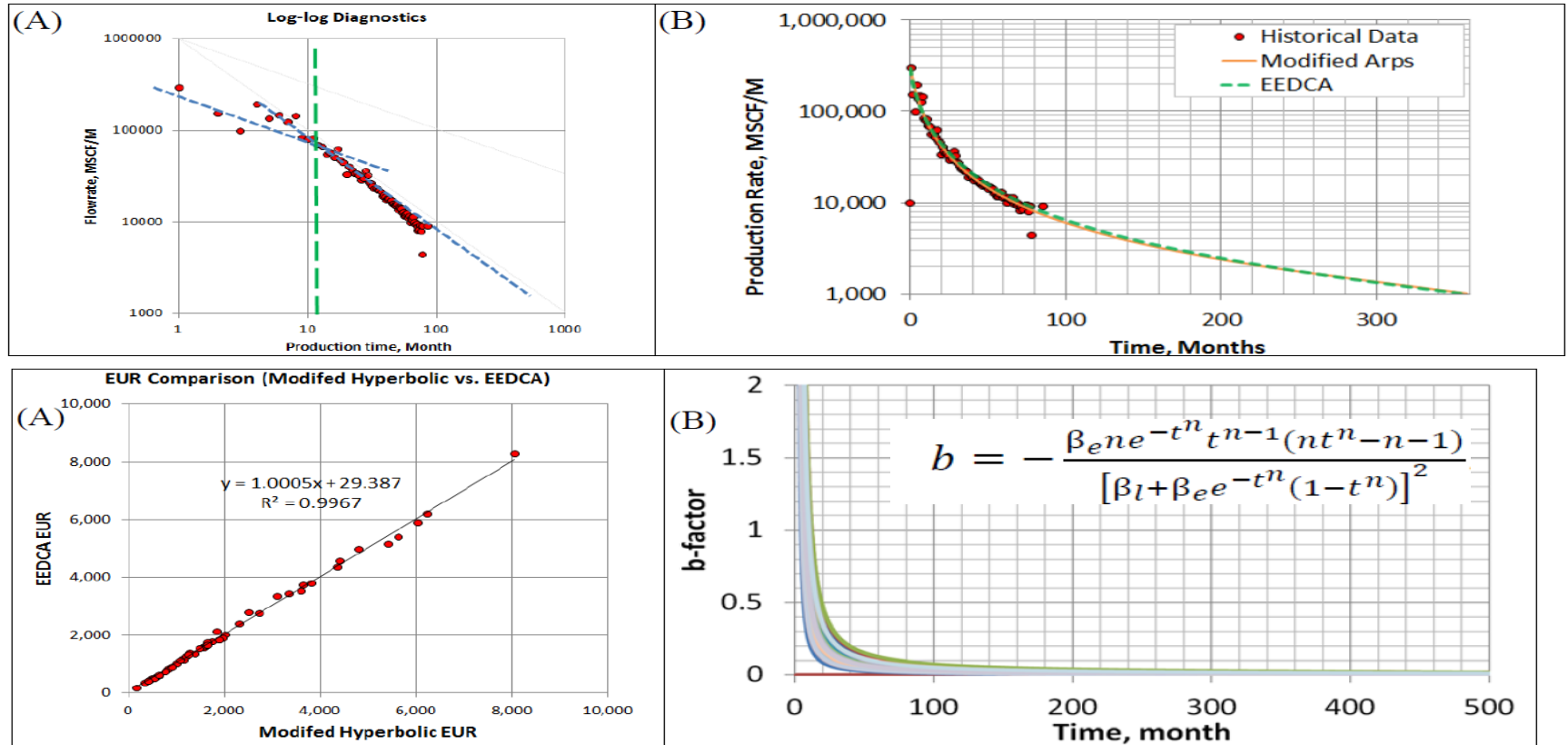
- Arps (modified) combines two distinct equations joined at one point in time;
- EEDCA has a single equation representing continuity from early time through “transition” to late time.

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.

$$t_{\text{switching}} = \sqrt[n]{\frac{n+1}{n}}$$

# Haynesville (47 wells)



# Haynesville –cont'd

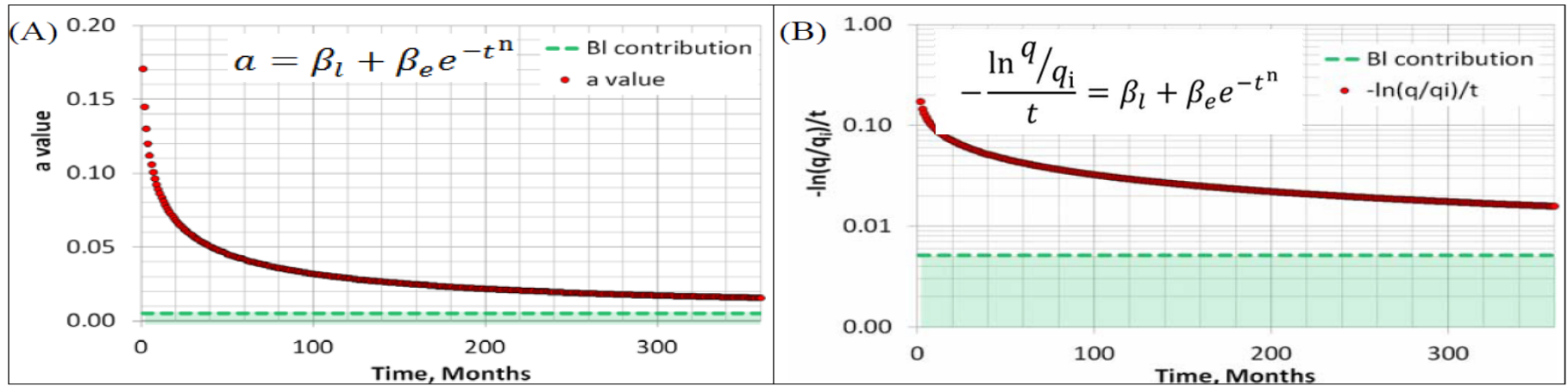
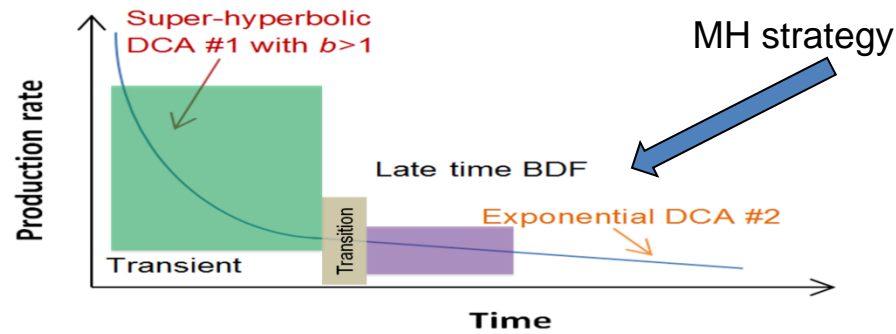
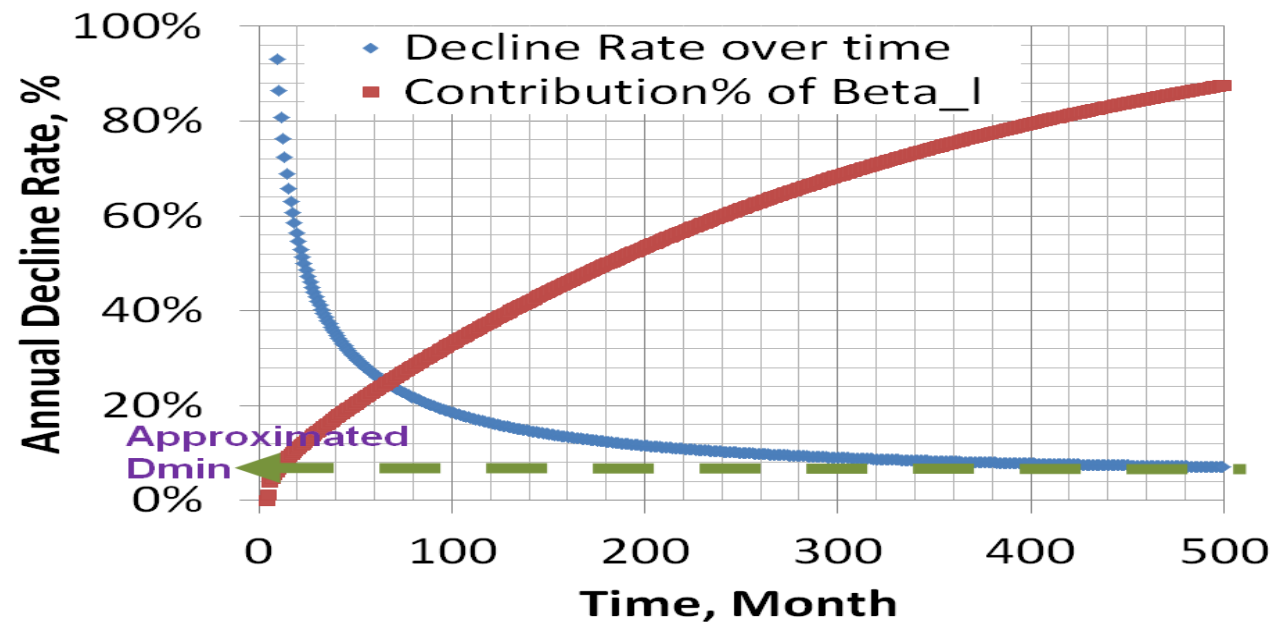


Fig. 5 – (Haynesville) An example well: a-value is the red dot line, which is always contributed from both  $\beta_e$  and  $\beta_l$  parameters. The green area represents the contribution from  $\beta_l$ , which plays more important role in late-time life. The same data is plotted in (A) Cartesian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



# Haynesville –cont'd

- Calculated  $D_{\min}$  by  $D = \beta_l + \beta_e e^{-t^n} (1 - nt^n)$
- Final P50  $D_{\min}$  is 5.26%; Average  $D_{\min}$  is 5.77%



# Summary of Shale Studies

|                                | No. of Studied Wells | Average n-value | Average $\beta_e$ | Average $\beta_i$ | Back Calculated P50 $D_{min}$ | Back Calculated Average $D_{min}$ | Average EUR by EEDCA* | Average EUR by Modified Hyperbolic* | <i>i</i> -th month ( <i>i</i> /12-th year) Switch to Exponential |
|--------------------------------|----------------------|-----------------|-------------------|-------------------|-------------------------------|-----------------------------------|-----------------------|-------------------------------------|--|
| <b>Haynesville</b>             | 47                   | 0.244           | 0.734             | 0.060             | 5.26%                         | 5.77%                             | 2,271                 | 2,241                               | 787 (65.5)   |
| <b>Barnett</b>                 | 25                   | 0.252           | 0.519             | 0.060             | 5.70%                         | 6.00%                             | 1,779                 | 1,764                               | 574 (47.8)   |
| <b>Eagle Ford (Gas Window)</b> | 33                   | 0.259           | 0.687             | 0.060             | 4.43%                         | 5.19%                             | 3,458                 | 3,416                               | 450 (37.5)   |
| <b>Wolfcamp</b>                | 31                   | 0.231           | 0.590             | 0.060             | 6.32%                         | 7.90%                             | 339                   | 338                                 | 1,372 (114.3)  |

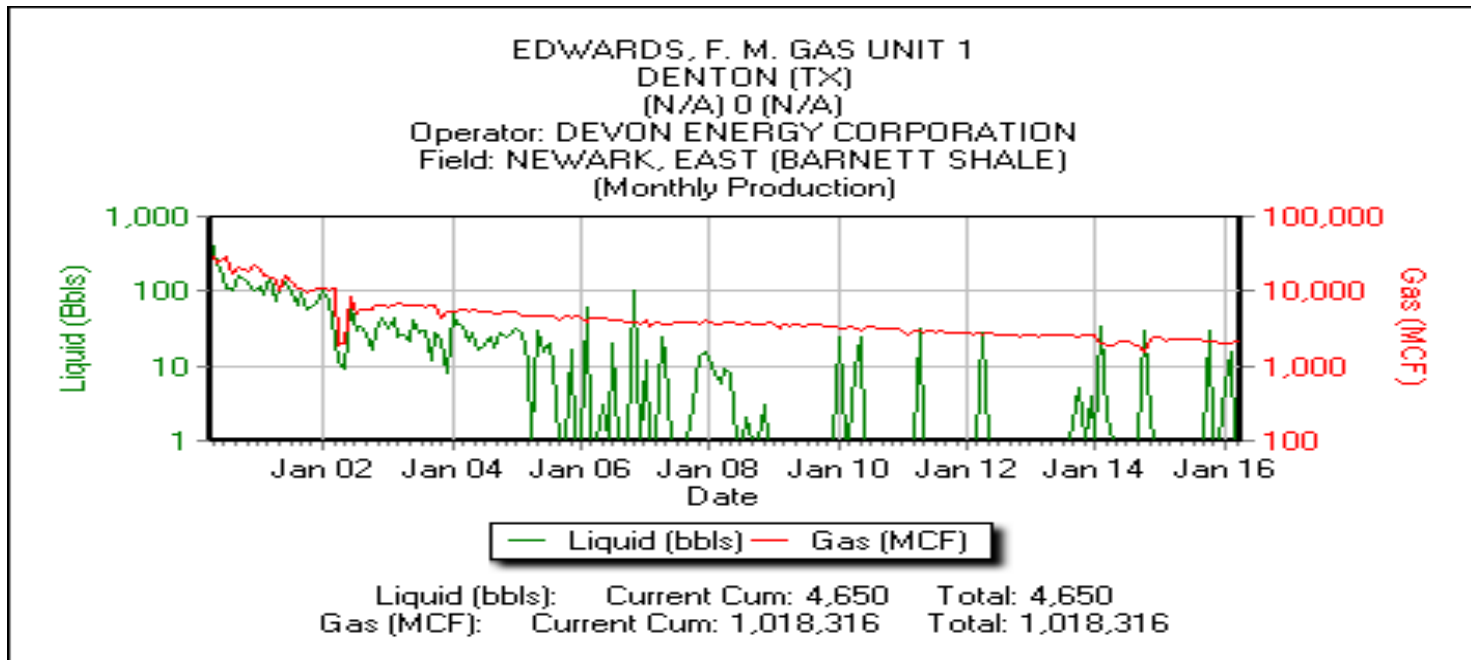
\*EUR Unit: MMscf or MSTB

- The  $D_{min}$  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  $D_{min}$  might be close to the true value, but it still takes a long time to reach the true value.
- Calculated  $t_{switching}$ 's are all longer than 35 years, which indicates  $D$  probably keeps decreasing for the entire life. The forced  $D_{min}$  in MH might not be appropriate.



# 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 *30<sup>th</sup>* month of production, the auto fitting just presented an exponential decline as the *b*-factor is *0* by Arps method.

# Step Fitting – Results

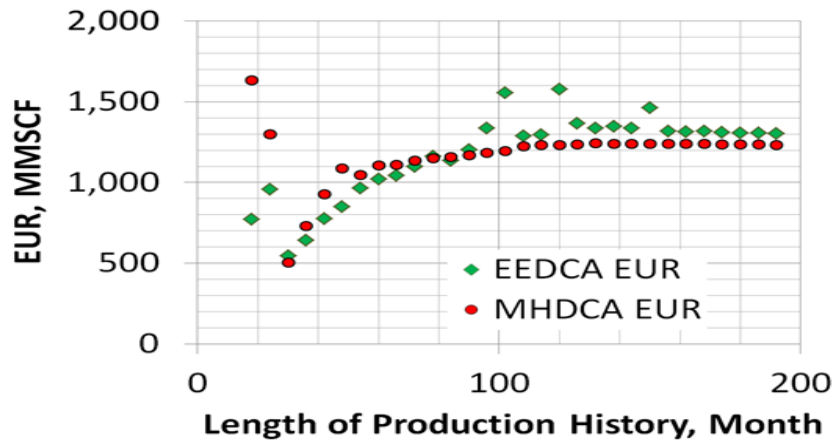


Fig. 16 – Projected EURs vs. available historical data by EEDCA and Modified Hyperbolic method (auto-fitting results).

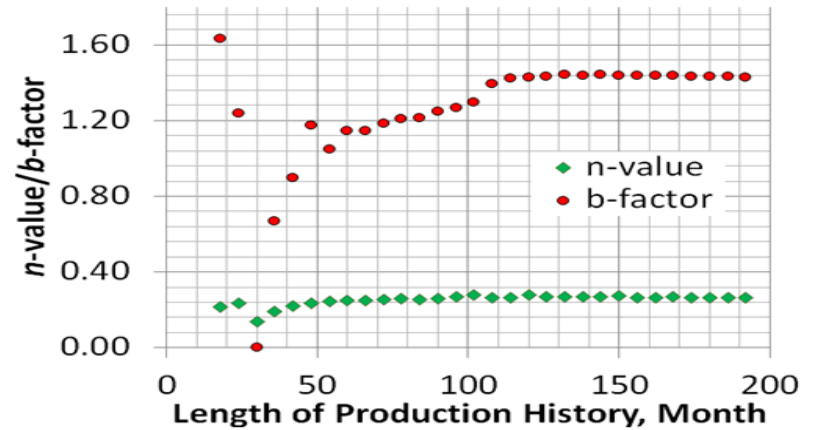
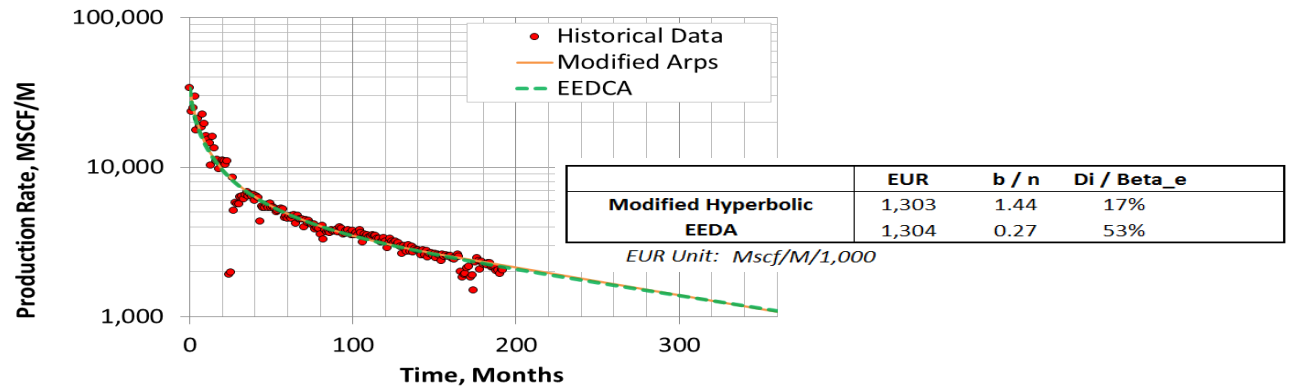
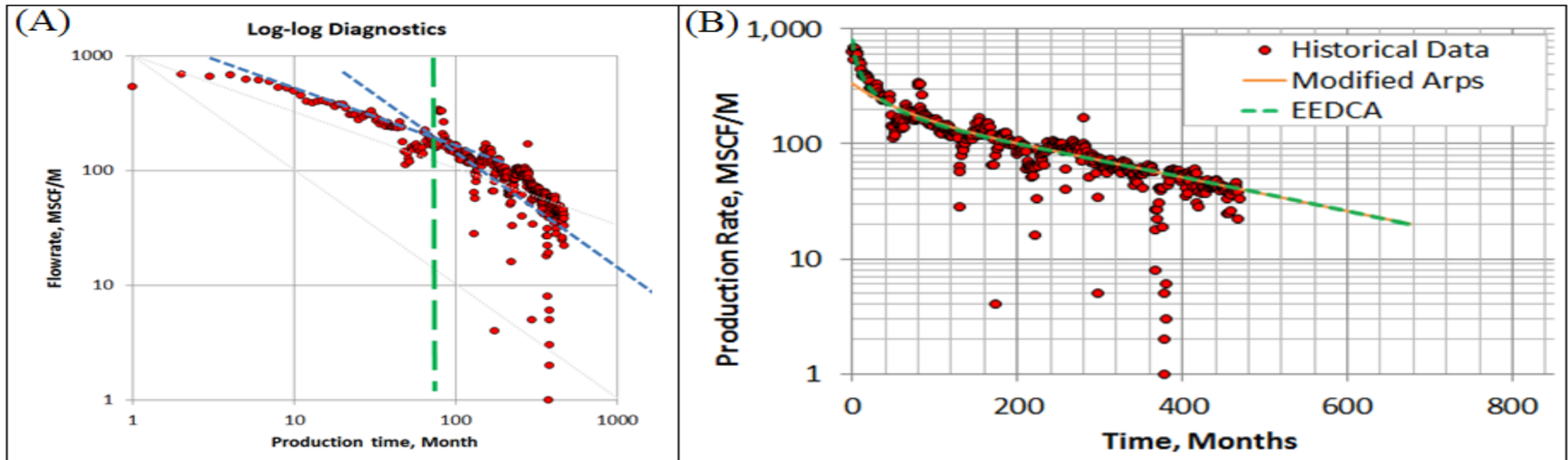


Fig. 17 –  $n$ -value in EEDCA and Arps  $b$ -factor vs. available historical data (auto-fitting results).



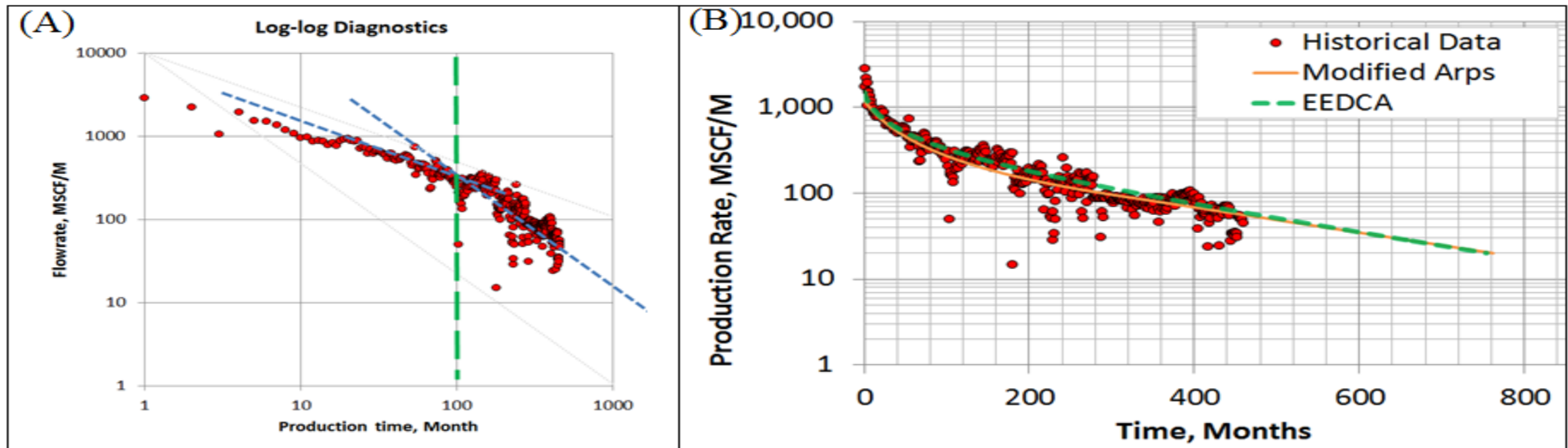
# Tight Gas Case #1

Well MGA-76-1-004



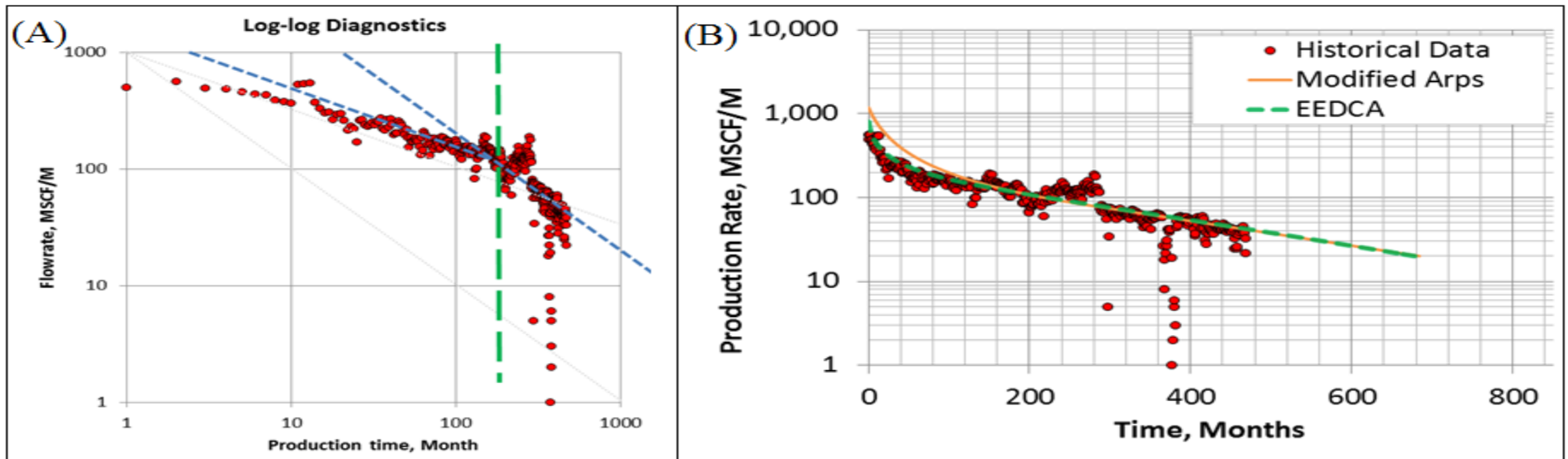
# Tight Gas Case #2

Well EXXON -002



# Tight Gas Case #3

Well MGA-76-1-006



# Tight Gas Case Summary

| Table 2 —Parameters and EUR Comparison<br>Between EEDCA and ARPS for Tight Gas Wells |                      |                     |                |                    |                    |                     |                     |
|--|----------------------|---------------------|----------------|--------------------|--------------------|---------------------|---------------------|
| Lease Name   | <i>b</i> -<br>factor | <i>n</i> -<br>value | MHDCA<br>$D_i$ | EEDCA<br>$\beta_e$ | EEDCA<br>$\beta_l$ | MHDCA EUR,<br>MMSCF | EEDCA EUR,<br>MMSCF |
| MGA-76-1-006   | 1.00                 | 0.26                | 0.05           | 0.43               | 0.05               | 62.97               | 62.35               |
| EXXON -002   | 0.86                 | 0.24                | 0.03           | 0.22               | 0.05               | 122.08              | 122.11              |
| MGA-76-1-004   | 1.00                 | 0.27                | 0.01           | 0.33               | 0.05               | 61.82               | 61.06               |
| <i>Average</i>   | <i>0.95</i>          | <i>0.26</i>         | <i>0.03</i>    | <i>0.33</i>        | <i>0.05</i>        | <i>82.29</i>        | <i>81.84</i>        |

## Discussion

- If the assumption of a constant  $b$ -factor is inappropriate for shale, the hyperbolic equation is invalid.
- $D_{\min}$  and  $\beta_1$  dominate the late-life projection in modified hyperbolic and EEDCA, respectively. Unlike the  $D_{\min}$  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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