A New Empirical Analysis Technique for Shale Reservoirs

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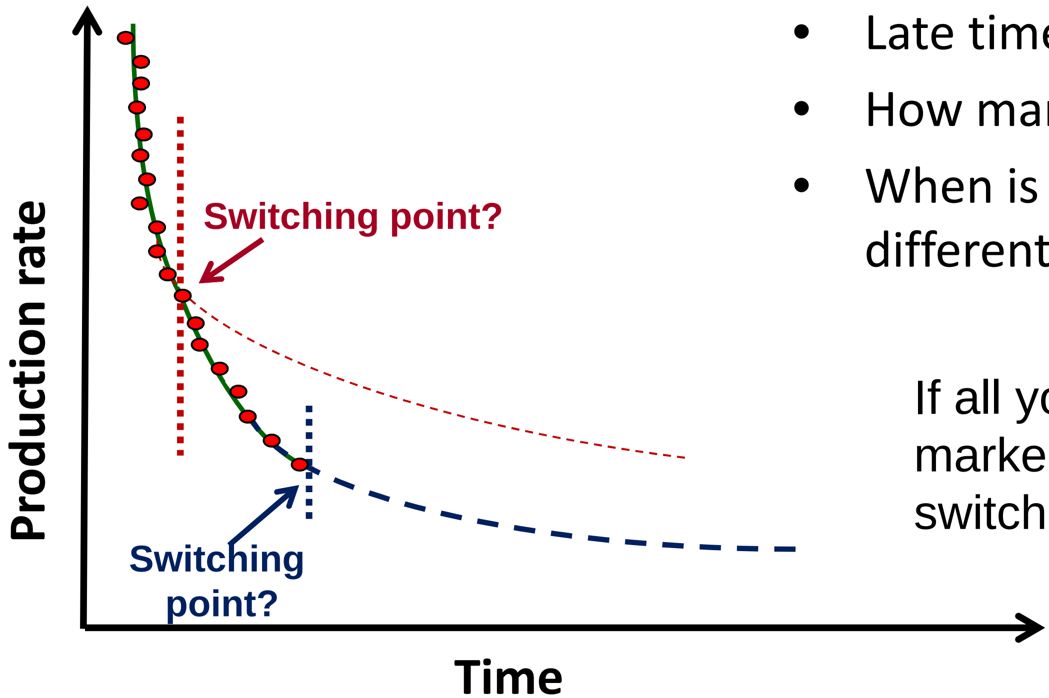
The method presented here is not used for any reserve work performed by Ryder Scott at this time.

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

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:

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

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

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

decline:

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

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.

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 β_e is a constant to account for the early (fully-transient) period, which should be larger than β_l as recommended;
β_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 β_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 β_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.

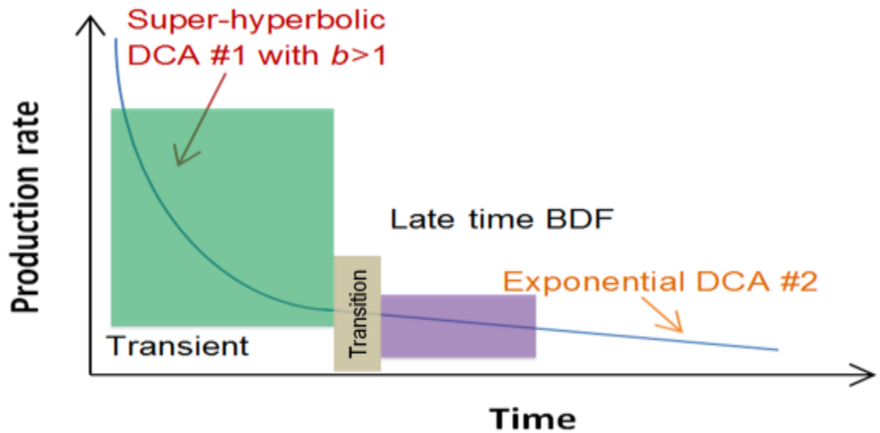
$$b = -\frac{\mathrm{d}\dfrac{q}{\mathrm{d}q/\mathrm{d}t}}{\mathrm{d}t} \quad \Longrightarrow \quad b = -\frac{\beta_e n e^{-t^n} t^{n-1}(nt^n - n - 1)}{\left[\beta_l + \beta_e e^{-t^n}(1-t^n)\right]^2}$$

- *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_{MIN} —CONT'D

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

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

- EEDCA method, β_l dominates the late life projection, as does D_{min} in MH method.

- β_l can be an early-time factor and is expected to react on the projection sooner than D_{min}. We will graphically demonstrate the contribution from β_l with an example well from Haynesville shale.

CRITIQUE OF ARPS #2: ILL-IMPOSED D_{MIN} —CONT'D

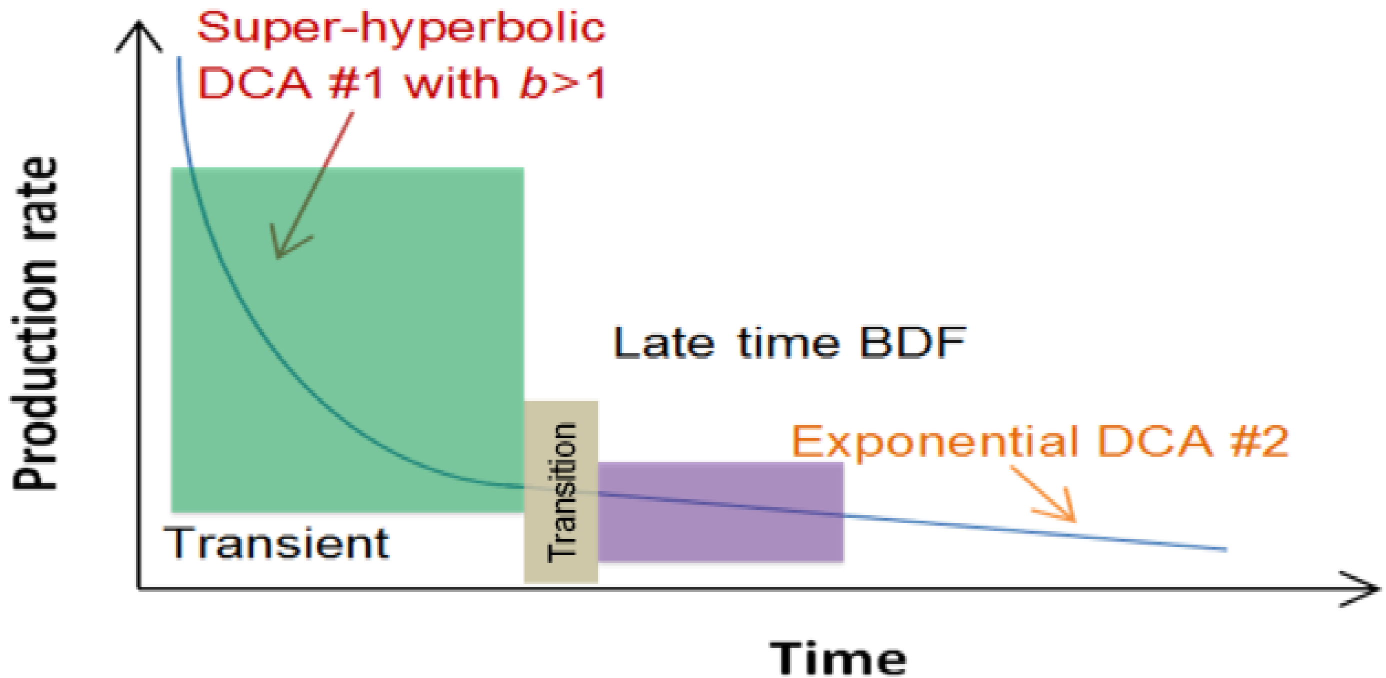
Arps empirical equation is used to describe production performance. Therefore,

- *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



CRITIQUE OF ARPS #3: SWITCHING POINT IN TIME –CONT'D

Modeling the transition

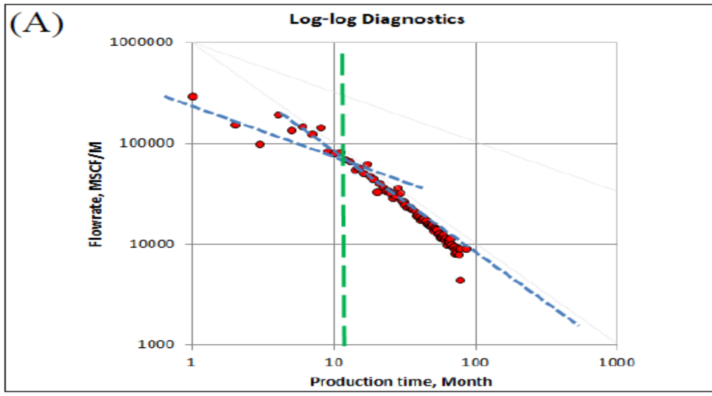
- Arps (modified) combines two distinct equations joined at one point in time;
- EEDCA has a single equation representing continuity from early time through "transition" to late time.

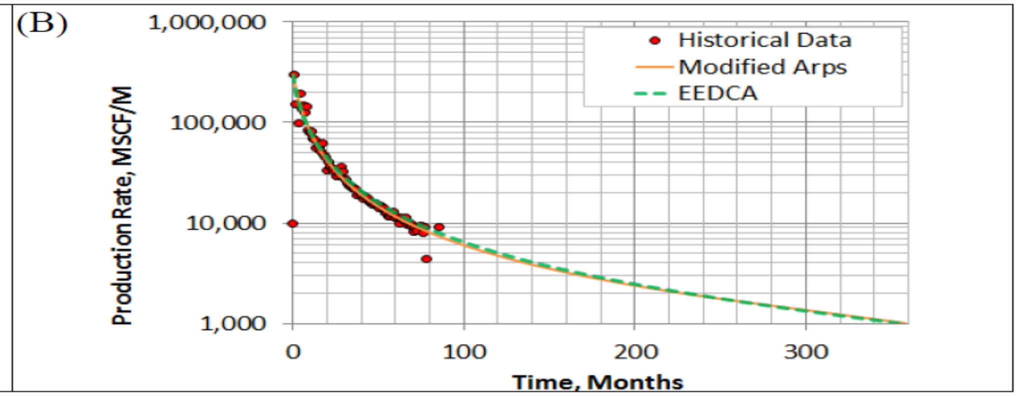
For constant decline rate over time, we have $\frac{dD}{dt} = 0$

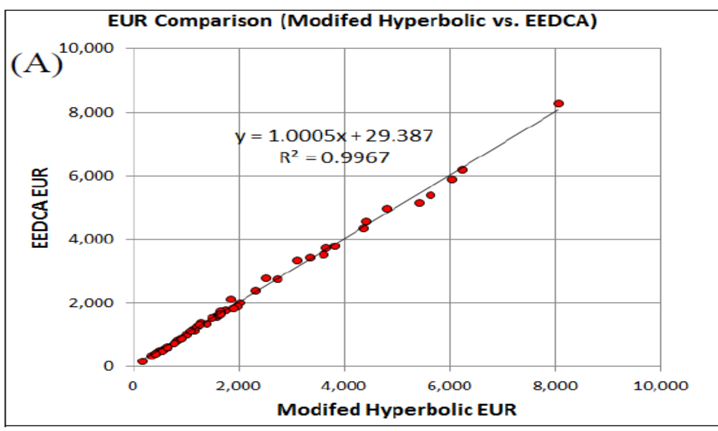
By using EEDCA, we derive equation to calculate switching point for MH method.

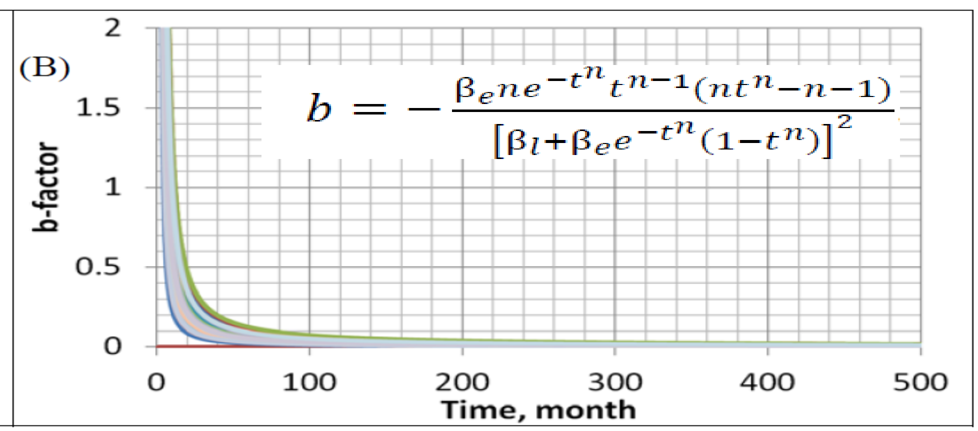
$$t_{\text{switching}} = \sqrt[n]{\frac{n+1}{n}}$$

Haynesville (47 wells)









Haynesville –cont'd

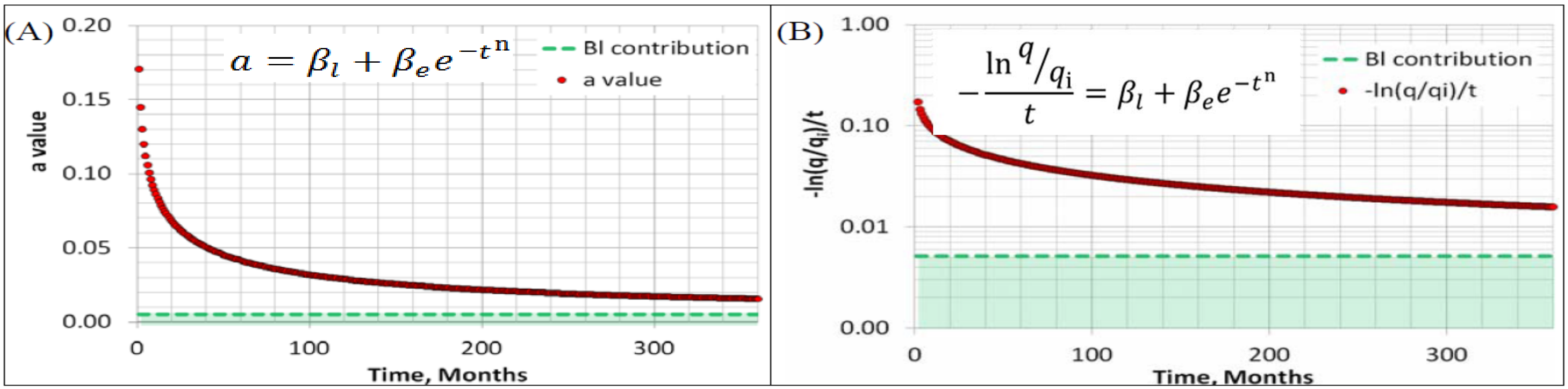
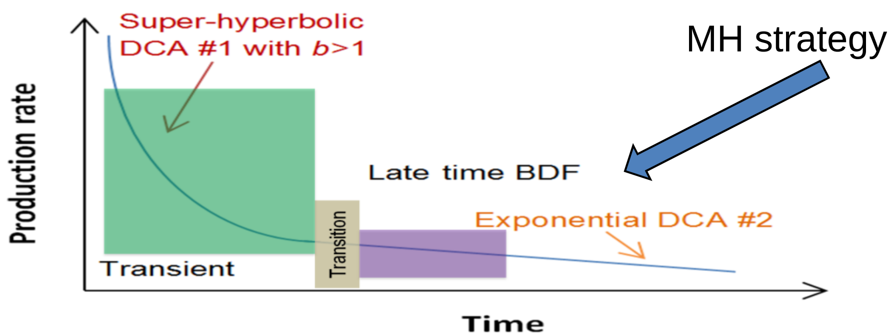
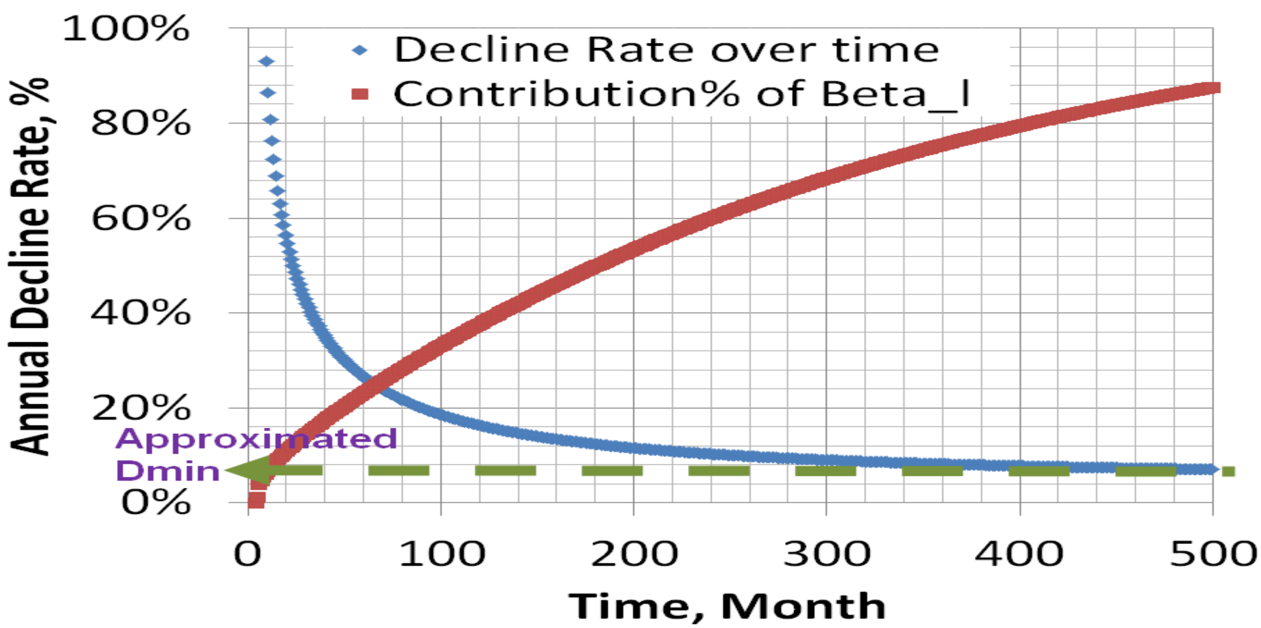


Fig. 5 – (Haynesville) An example well: *a*-value is the red dot line, which is always contributed from both β_e and β_l parameters. The green area represents the contribution from β_l, which plays more important role in late-time life. The same data is plotted in (A) Cartesian and (B) Semi-Log coordinates.



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

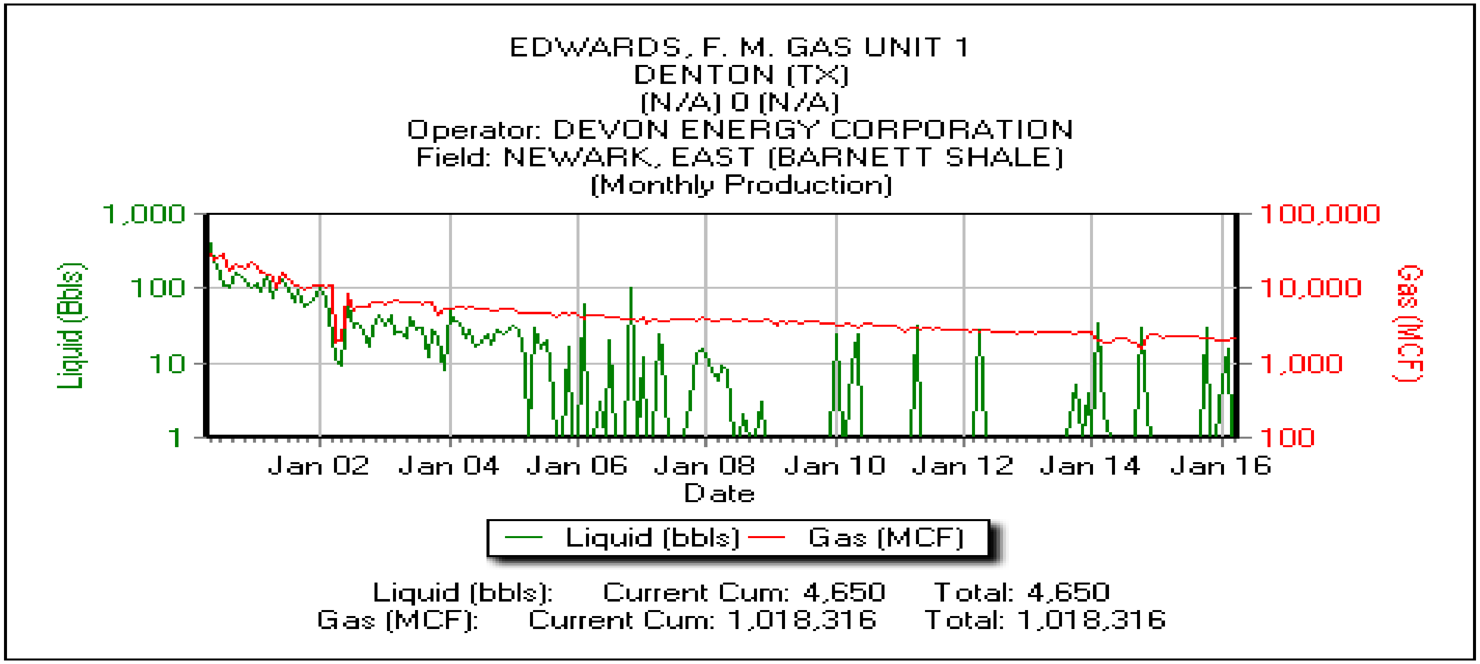
Table 1 -Summary of the Four Studied Shale Reservoirs

	No. of Studied Wells	Average n-value	Average β_e	Average β_l	Back Calculated P50 D_{min}	Back Calculated Average D_{min}	Average EUR by EEDCA*	Average EUR by Modified Hyperbolic*	*i*-th month (*i/12-th year*) Switch to Exponential
Haynesville	47	0.244	0.734	0.060	5.26%	5.77%	2,271	2,241	787 (65.5)
Barnett	25	0.252	0.519	0.060	5.70%	6.00%	1,779	1,764	574 (47.8)
Eagle Ford (Gas Window)	33	0.259	0.687	0.060	4.43%	5.19%	3,458	3,416	450 (37.5)
Wolfcamp	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*th month of production, the auto fitting just presented an exponential decline as the *b*-factor is *0* by Arps method.

Step Fitting – Results

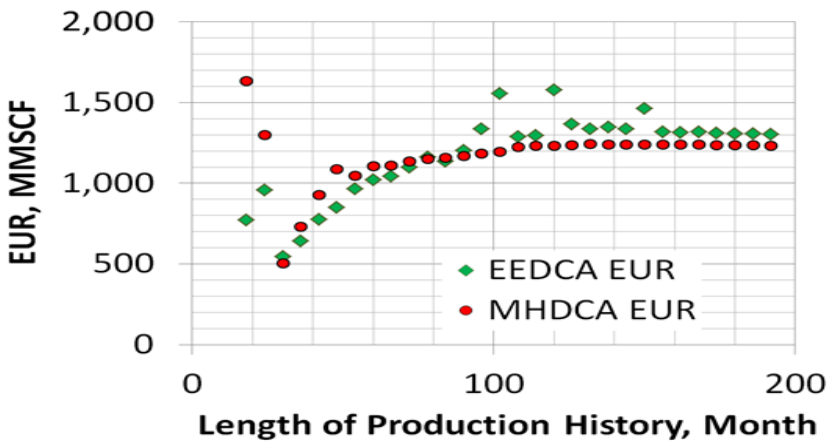


Fig. 16 – Projected EURs *vs.* available historical data by EEDCA and Modified Hyperbolic method (auto-fitting results).

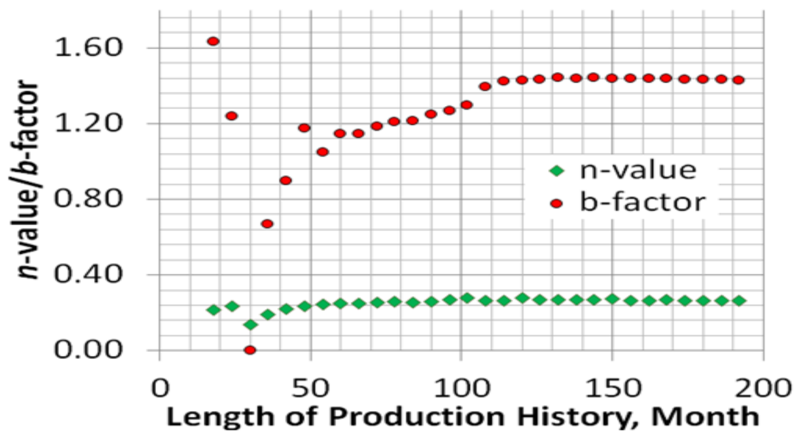
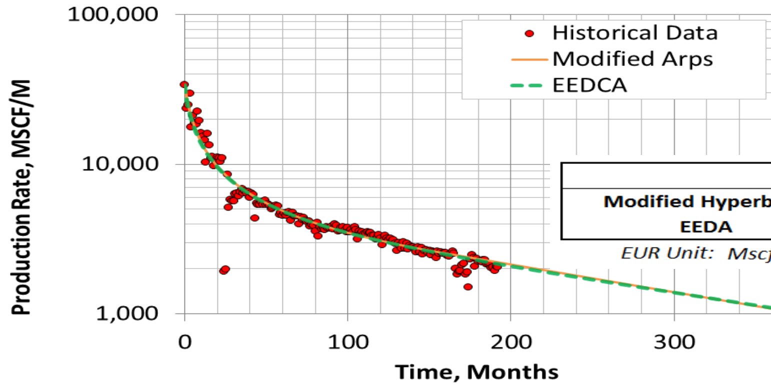


Fig. 17 – *n*-value in EEDCA and Arps *b*-factor *vs.* available historical data (auto-fitting results).

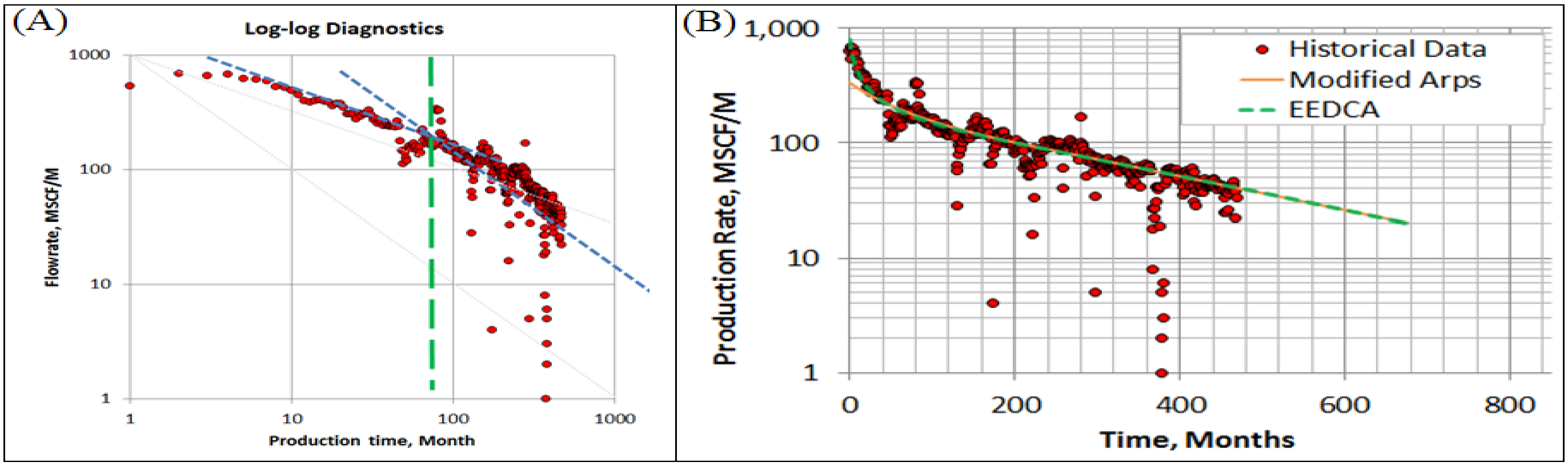


	EUR	b / n	Di / Beta_e
Modified Hyperbolic	1,303	1.44	17%
EEDA	1,304	0.27	53%

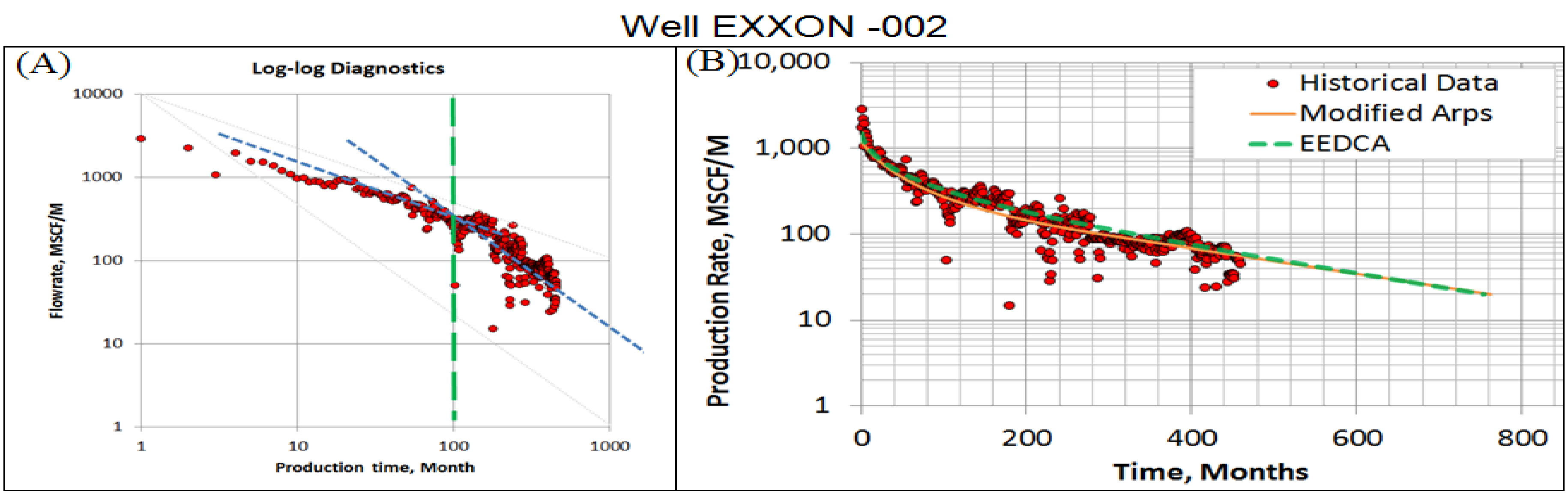
EUR Unit: Mscf/M/1,000

Tight Gas Case #1

Well MGA-76-1-004

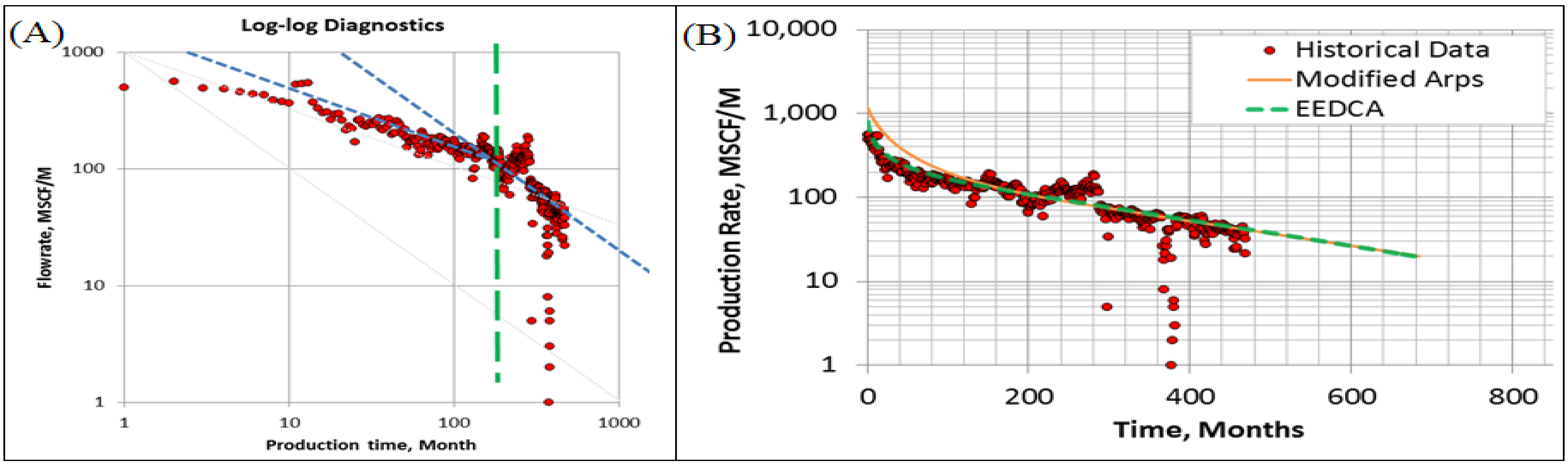


Tight Gas Case #2



Tight Gas Case #3

Well MGA-76-1-006



Tight Gas Case Summary

Table 2 —Parameters and EUR Comparison Between EEDCA and ARPS for Tight Gas Wells

Lease Name	*b*-factor	*n*-value	MHDCA D_i	EEDCA β_e	EEDCA βl	MHDCA EUR, MMSCF	EEDCA EUR, 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
Average	*0.95*	*0.26*	*0.03*	*0.33*	*0.05*	*82.29*	*81.84*

Discussion

- If the assumption of a constant *b*-factor is inappropriate for shale, the hyperbolic equation is invalid.
- D_{min} and β_l dominate the late-life projection in modified hyperbolic and EEDCA, respectively. Unlike the D_{min} in Arps method, the β_l 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.
  - β_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, β_e, n) in shale early-life if β_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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