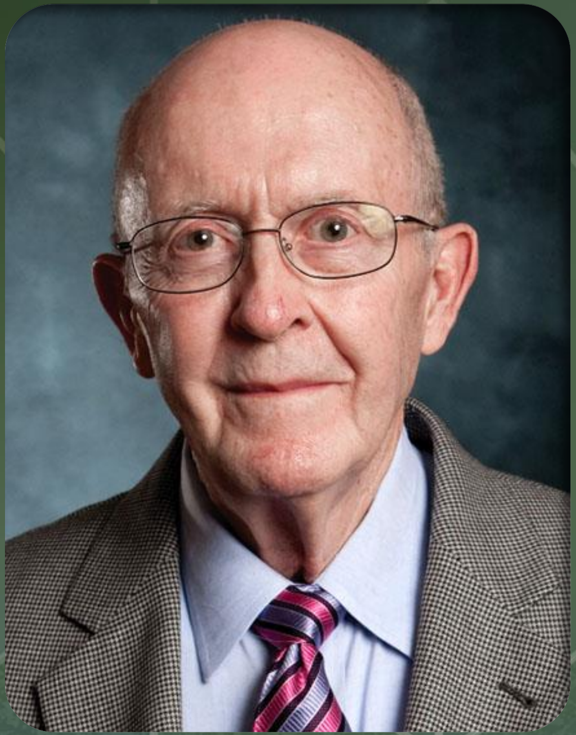
John Lee



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John Lee holds the DVG Endowed Chair in Petroleum Engineering at Texas A&M University. He holds a B.S., an M.S. and a PhD degree in Chemical Engineering from Georgia Tech.

John worked for ExxonMobil early in his career and specialized in integrated reservoir studies. He has taught at Mississippi State University, the University of Houston, and Texas A&M. While at A&M, he also served as a consultant with S.A. Holditch & Associates, where he specialized in reservoir engineering aspects of unconventional gas resources. He served as an Academic Engineering Fellow with the U.S. Securities & Exchange Commission (SEC) in Washington during 2007-2008 to help modernize SEC rules for reporting oil and gas reserves.

John is the author of four textbooks published by SPE and has received numerous awards from SPE, including the Lucas Medal (the society's top technical award), the DeGolyer Distinguished Service Medal and Honorary Membership (the highest recognition awarded society members). He is a member of the U.S. National Academy of Engineering and the Russian Academy of Natural Sciences.

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What Would Arps Think About What We Have Done to His Decline Model?

2021 Ryder Scott Reserves Conference

John Lee
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What Is the Arps Decline Model?

Hyperbolic model is our focus

$$q(t) = \frac{q_i}{(1+bD_i t)^{\frac{1}{b}}}$$

where $0 < b < 1$

How Did Arps Come Up With the Model?

Worked backward from two definitions

- Decline rate, *D* (1/time)

$$D = -\frac{\frac{dq}{dt}}{q} = -\frac{d(lnq)}{dt}$$

- Parameter *b* defined as change in 1/D (loss ratio) with time

$$b = \frac{d\left(\frac{1}{D}\right)}{dt}$$

Key empirical observation: for most wells Arps/Cutler analyzed, *b* was constant (including *b* = 0) throughout all history

Arps' Hyperbolic Decline Model

- Integration for constant *b* leads to Arps' hyperbolic decline model

$$q(t) = \frac{q_i}{(1+bD_i t)^{\frac{1}{b}}}$$

- Implication: Arps hyperbolic decline equation valid only for *constant b*
- Hyperbolic model thoroughly validated (decades of successful application) for constant *b*, which requires BDF

Why Should Anyone Trust the Model?

Arps' (and earlier investigators) finding (1944 and earlier) that the model

- Fit most rate-time data well
- Led to reasonable forecasts of future production
- Rests on well-established empirical observation that *b* is reasonably constant in BDF

What Does the Model Require?

- Production at constant BHP
- Well or reservoir in boundary-dominated flow (BDF) (sometimes inappropriately called "pseudosteady-state flow")
  - No transient flow data (oops!)
- Constant productivity index
  - No change in damage or stimulation
  - Skin factor constant
- Fixed drainage area
- For stabilized flow (BDF) with no change in productivity index, BHP, or drainage area, '*b* ' should be constant for life of well

What Kind of Wells Did Arps Analyze?

Key: Data that provided basis for model were from 1920’s, 1930’s, early 1940’s

- All vertical wells
- No hydraulic fracture stimulation (first in 1947)
- Conventional permeability thus required for commerciality … generally, 10’s to 100’s of md

Why Does Permeability Matter?

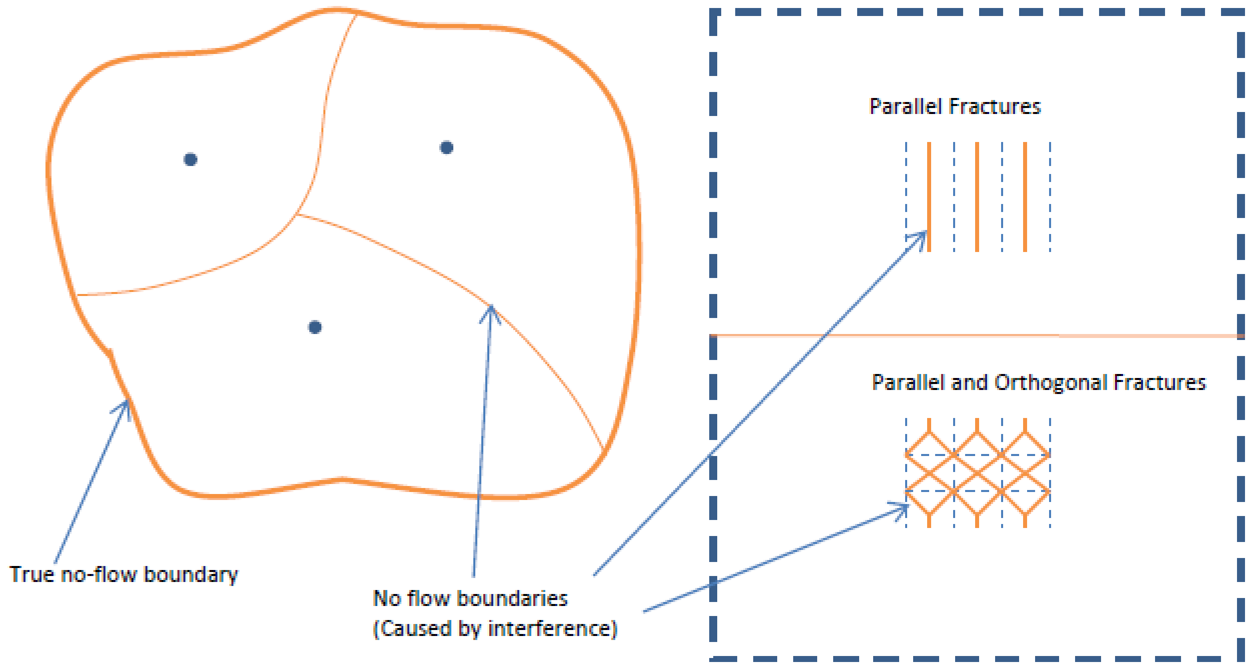
Time to BDF in vertical wells estimated from

$$t_{bdf} = \frac{40\emptyset\mu c_t r_e^2}{k}$$

- For 10 md gas reservoir, $t_{bdf} \approx$ 5 days for 160-acre spacing
- For 100 nd gas reservoir, $t_{bdf} \approx$ 240 years for 160-acre spacing

… Arps' world and our world are different!

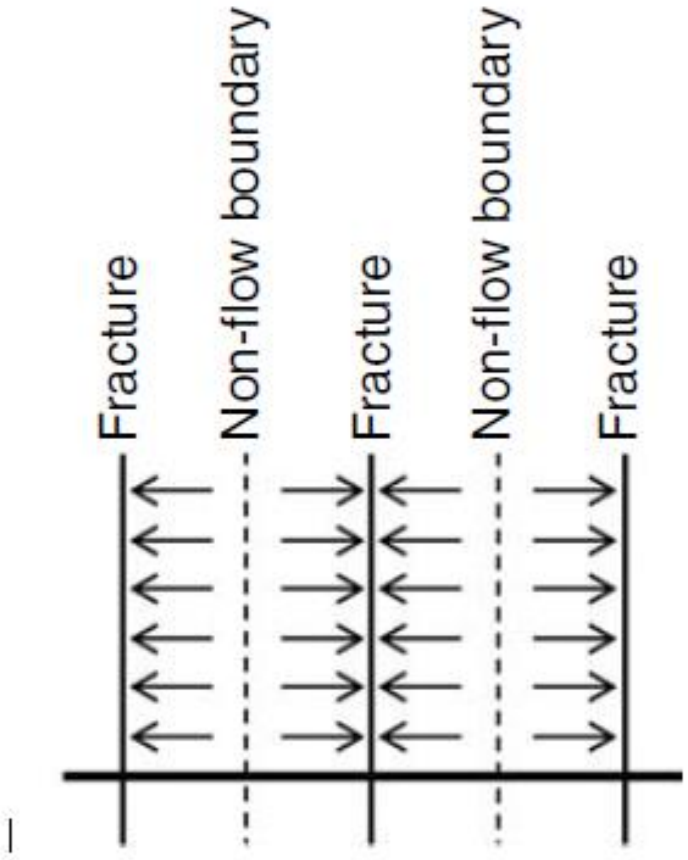
BDF Flow Caused Mostly by Interference



SPE 131787

BDF Caused by Fracture Interference in Horizontal Wells with Multiple Fractures

- Even with close fracture stage spacing, time to BDF can be months or years in resource plays
- So: Can Arps' hyperbolic model work for modern wells in low permeability reservoirs?



SPE 184397

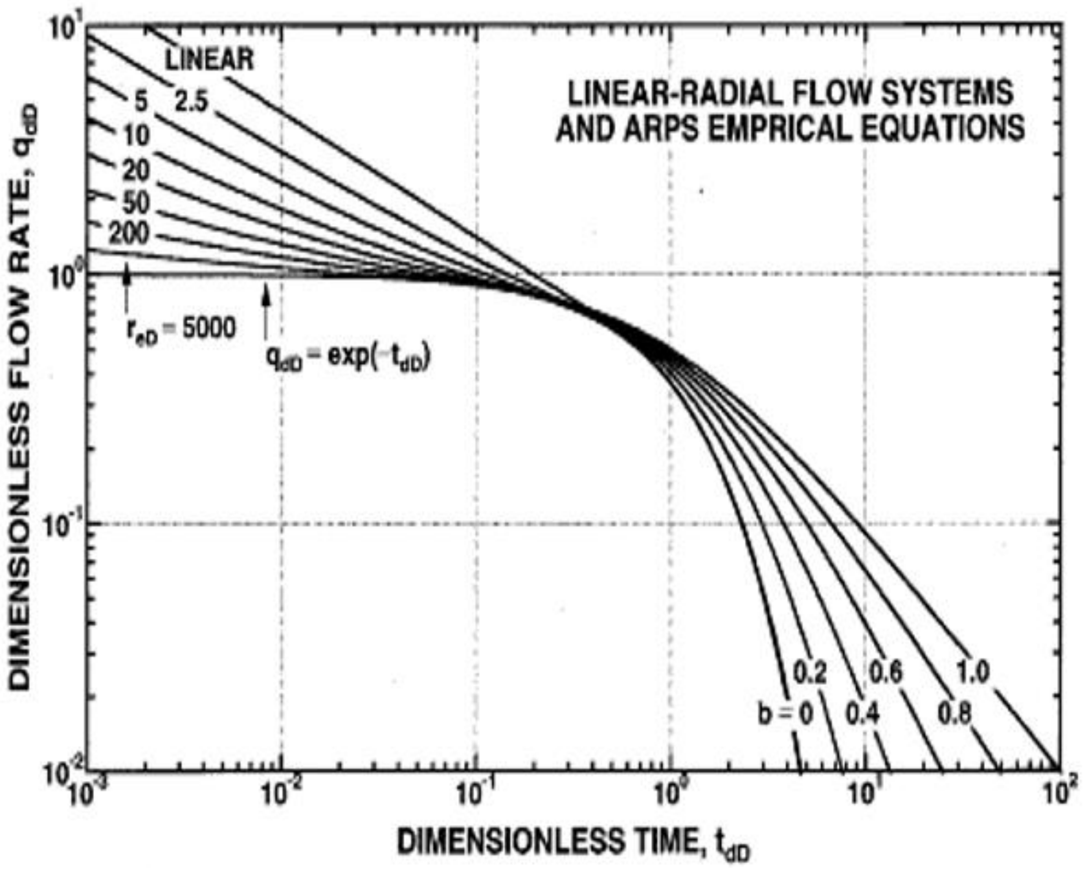
Arps Model in Resource Plays – Can it Work?

Short answer: yes!

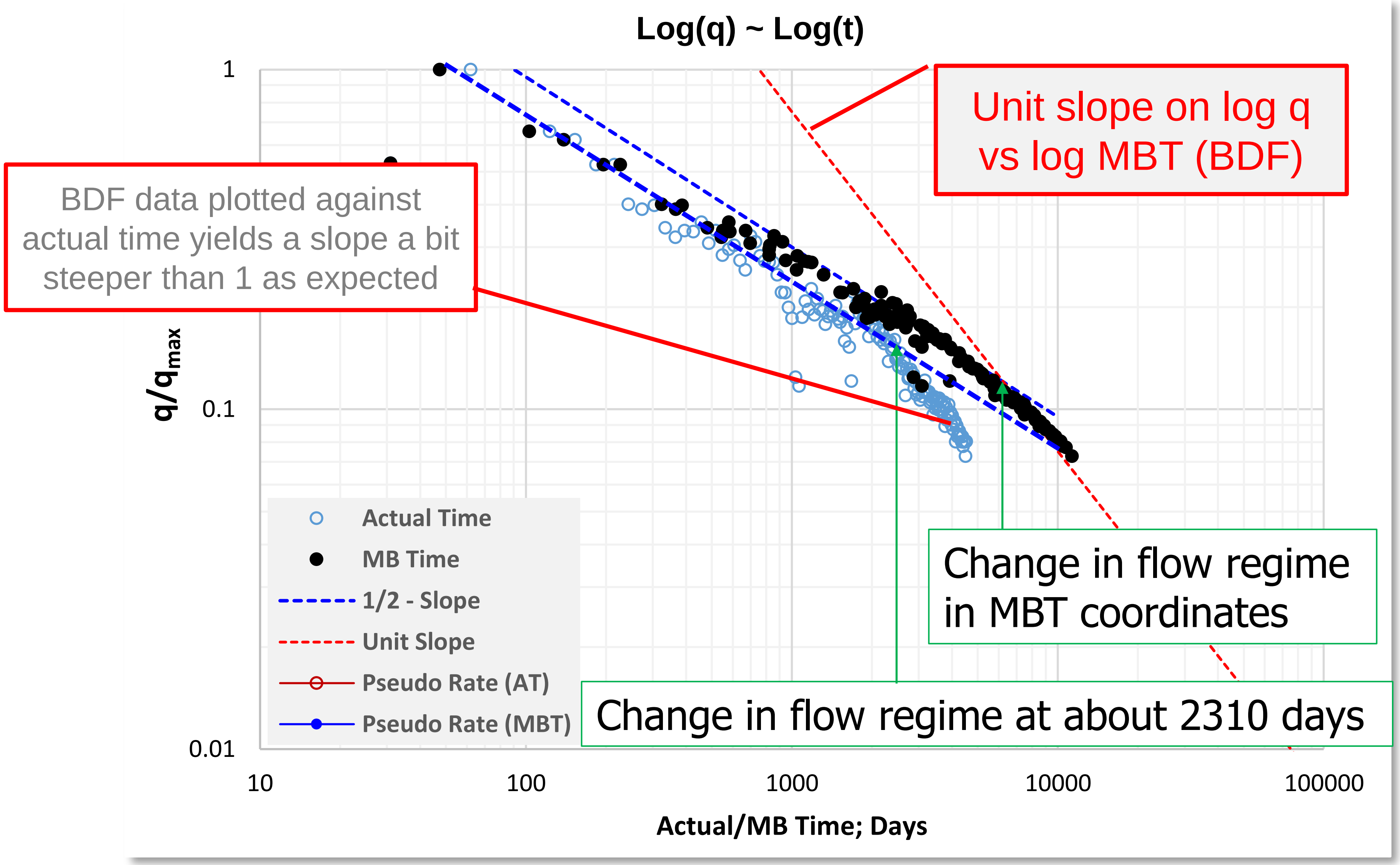
- How?
  - Divide flow history into multiple segments, apply model to each
    - Transient flow –often near linear flow
    - BDF – where Arps validated model
    - Transition region between transient and BDF
    - Early off-trend ramp-up period
  - How can we identify segments?
    - Log-log rate-time plots, assisted by rate-”material balance time” plots
    - Material-balance time: cumulative production/rate

But Does Data Fall on Straight Line ?

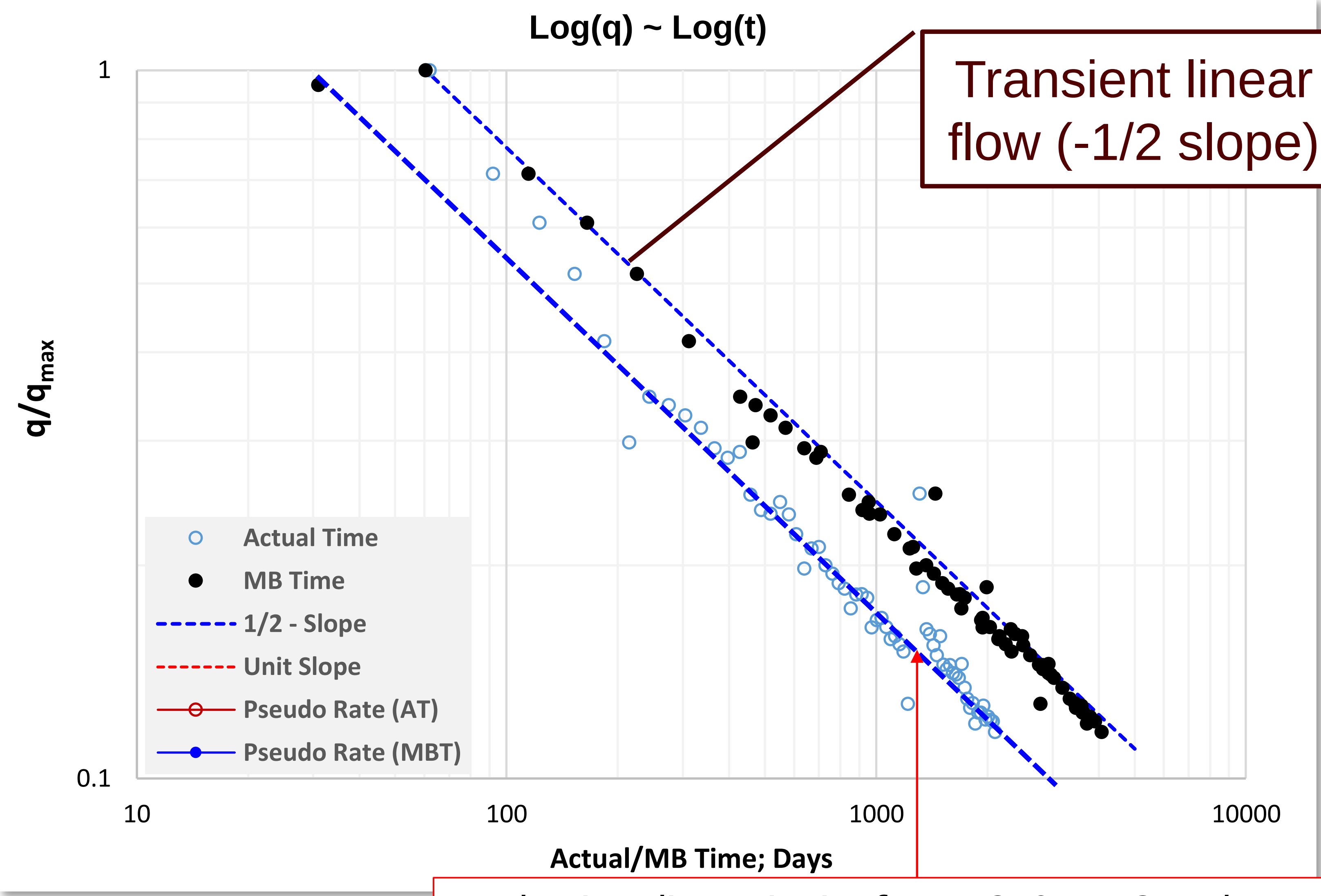
- Sometimes, yes
  - Early time "linear flow" *b* = 2
  - Also "power law" … straight line
  - BDF:
    - When *b* large, eventually
- Sometimes, no
  - BDF:
    - When *b* small, no



What Does Actual Field Data Look Like?



Do We Always See BDF?



Transient linear flow (-1/2 slope)

Production discontinuity from 1219 to 1311 days

Simple Method to Determine "*b*"

- Consider Arps hyperbolic decline model

$$q = \frac{q_i}{(1+bD_it)^{\frac{1}{b}}}$$

- Suppose (bD_it)»1. Then, taking logs,

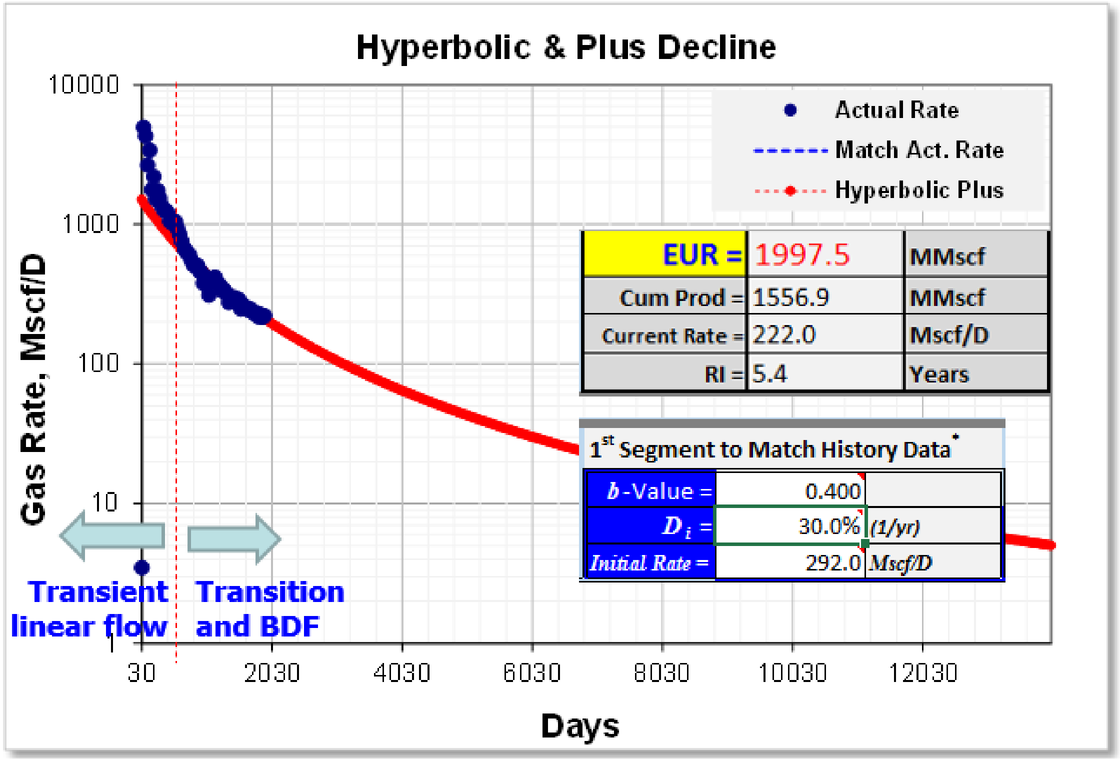
$$log(q)=log(q_i)-\left(\frac{1}{b}\right) log(bD_it) = constant - \left(\frac{1}{b}\right) log(t)$$

- Conclusion: straight line on log-log *q* vs. *t* plot, slope = - $\left(\frac{1}{b}\right)$ … slick way to determine *b* ***if*** data fall on straight line
- Example: slope $= -\frac{1}{2} \rightarrow b = 2$ during transient flow

But How Can We Forecast with a Multi-Segment Arps Model?

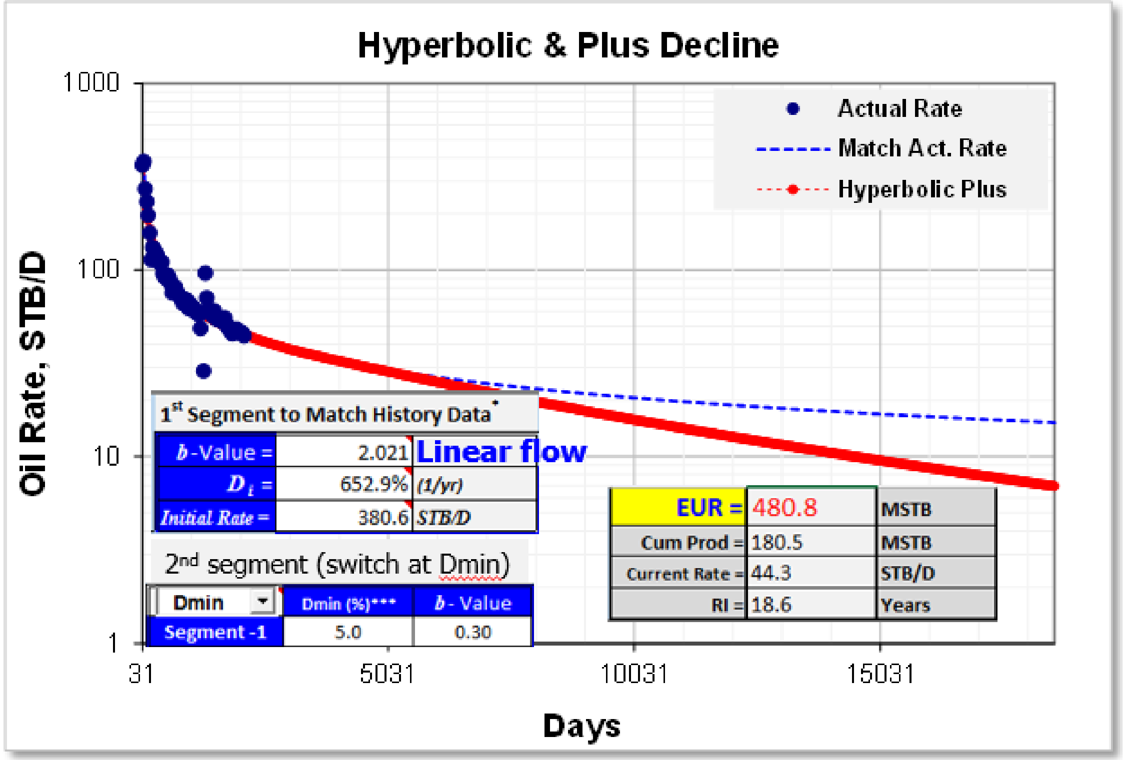
When we have some data in BDF, continue trend (same *b*) to life of well or economic limit rate

- Assumption: interference with offset wells will have negligible impact



But What if We Have Only Transient Flow?

- Switch to transition model at specified D_{switch}, and switch to BDF model at specified D_{min} with specified b_{BDF}
- Decline rates at switch points and b_{BDF} from analogy or modeling



What Would Arps Think About This Procedure?

Good reason to believe he would approve

- Honors early ramp-up period, which he observed
- Honors hyperbolic decline model he advocated during BDF
- Adds transient flow regime present in modern low-*k* wells
  - When data lie on straight line on log-log plot, Arps hyperbolic model still appropriate (*b* constant)
  - b>1, but not for life of well … no laws of physics violated
- Adds transition flow regime with varying *b*, but can use constant *b* (from analog) as first approximation

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