Adaptation of SPEE Monograph 4 to Wyoming Horizontal Plays

SPEE Northern Rockies Chapter
Casper, Wyoming

John Seidle
MHA Petroleum Consultants

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Thanks to…

- **Leo Giangiacomo**
- **Bonnie Percy**
- **Mike Borah**
- **Rick Vine**

Outline

1. SPEE Monograph 4 – what's in it?
2. Two applications of Mono 4 to Wyoming wells
3. A new model that isn't discussed in Mono 4

1. SPEE Monograph 4 – What’s in it?

SPEE Monograph 4 – Estimating Developed Reserves in Unconventional Reservoirs

Assess current methods to forecast performance of wells in unconventional reservoirs given different reservoir types, different completions, and different well maturities.

SPEE Monograph 4 -- Committee Members

Jim Erdle (CMG)

Brent Hale (SPEE, Cobb & Associates)

Olivier Houze` (KAPPA Engineering)

Dilhan Ilk (DeGolyer & MacNaughton)

Creties Jenkins (SPEE, Rose & Associates)

John Lee (SPEE, Univ of Houston)

John Ritter (SPEE, Occidental Petroleum)

John Seidle (SPEE, MHA Petroleum Consultants)

Darla-Jean Weatherford (TextRight, technical editor)

Scott Wilson (SPEE, Ryder Scott)

SPEE Monograph 4 -- Chapters

1. **Introduction**
2. **Definition of unconventional reservoirs (UCR)**
3. **Reservoir Characterization Aspects of Estimating Developed Reserves in UCR’s**
4. **Drilling , Completions, and Operational Aspects of Estimating Developed Reserves in UCR’s**
5. **Classical Arp’s Decline Curve Analysis (DCA)**
6. **Fluid Flow Theory & Alternative Decline Curve Methods**
7. **Model-Based Well Performance Analysis and Forecasting**
8. **Discretized Models**
9. **Probabilistic Methods and Uncertainty in Forecasts and Estimated Ultimate Recovery**
10. **Example Problems**

Workflow for Evaluation of *Developed* Reserves in Unconventional Reservoirs

From Dr. John Lee, SPEE Monograph 4

1. **Assess data viability and correlation**
2. **Construct diagnostic plots**
3. **Identify flow regimes**
4. **Analyze and forecast with selected simple models**
5. **Analyze and forecast with semi-analytical models (RTA)**
6. **History match with simulator and forecast**
7. **Reconcile forecasts and estimated ultimate recoveries (EUR's)**

Monograph 4 diagnostic plots to identify flow regimes

1. **Pressure normalized rate**

2. **Flowing material balance**

3. **Square root of time**

Diagnostic plot 1 – pressure normalized rate – identify flow regimes

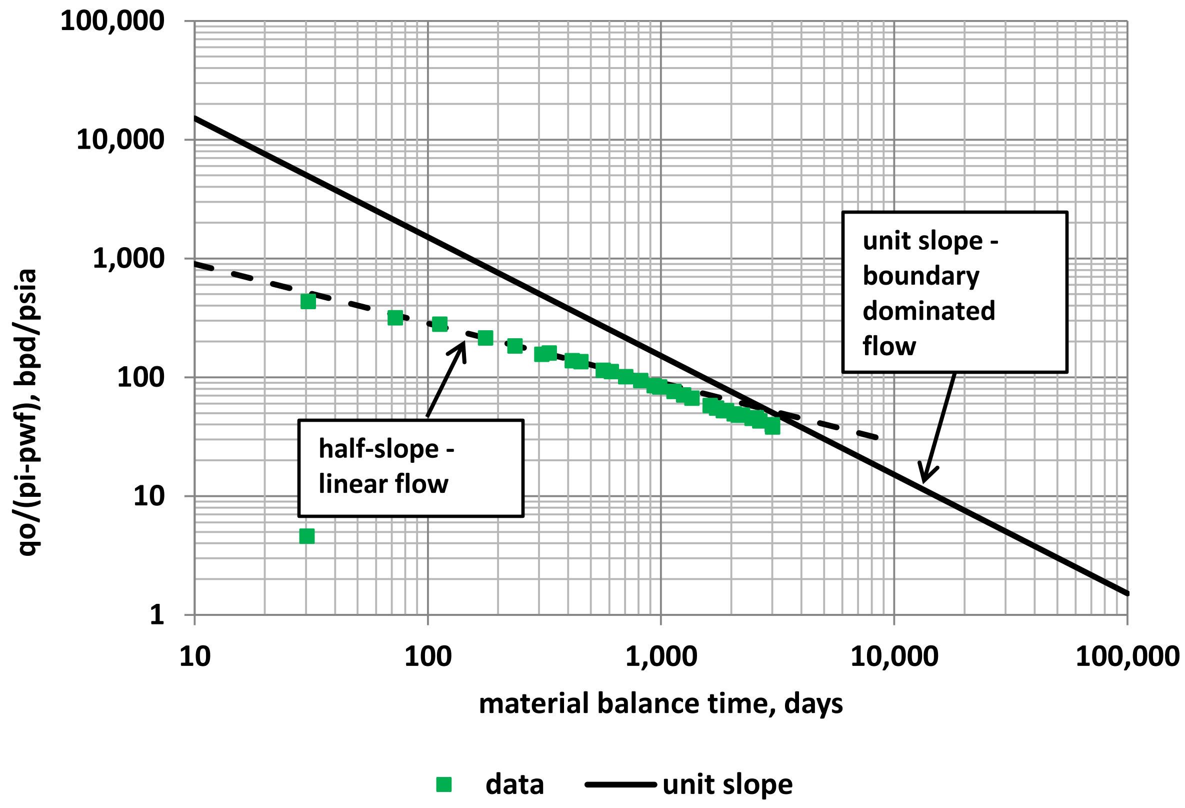
Pressure normalized rate

qo/(pi – pwf)

vs

Material balance time, MBT

Np/qo



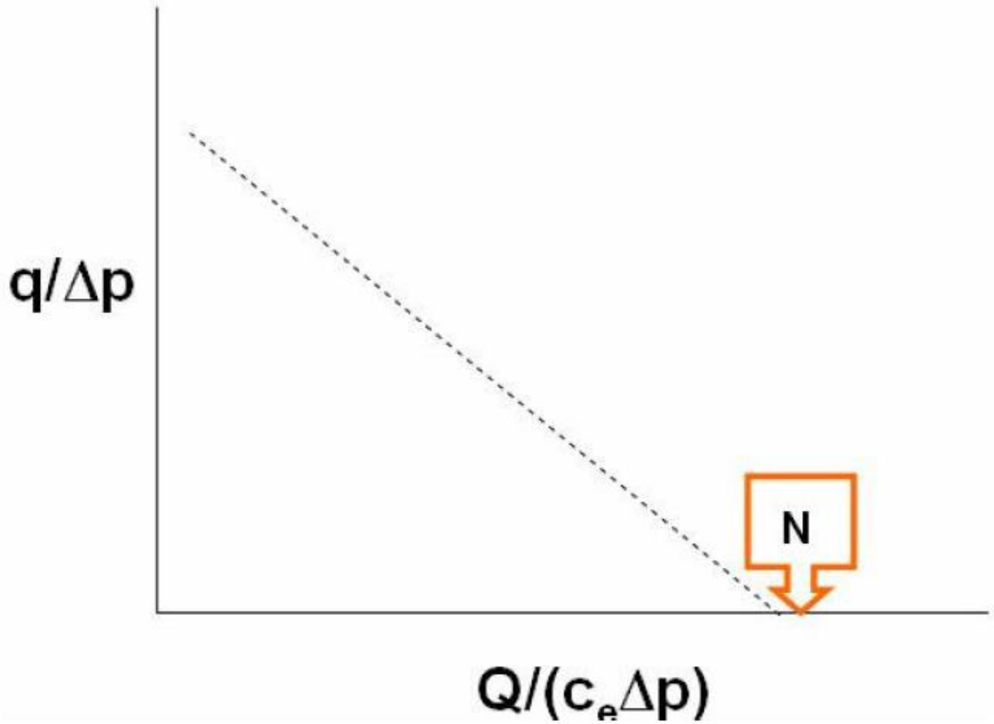
Diagnostic plot 2 – flowing material balance – estimate OOIP

Pressure normalized rate

qo/(pi – pwf)

vs

Normalized cumulative



Diagnostic plot 3 – square root of time plot – estimate A-root-k

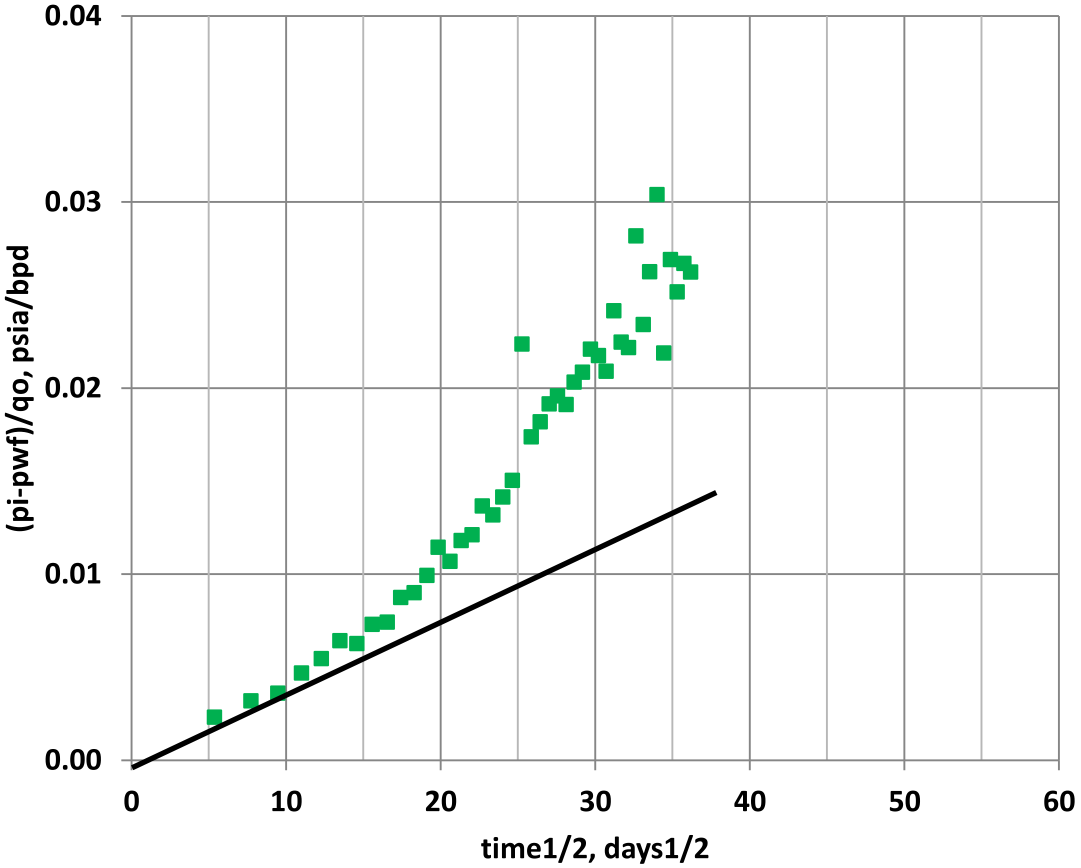
Rate normalized pressure

(pi – pwf)/qo

vs

Square root of time

$$A_f k^{1/2} = 16.26 \frac{B_o}{m} \left(\frac{\mu_o}{\phi c_t} \right)^{1/2}$$



Monograph 4 models

1. Modified Arps
2. Duong
3. Stretched exponential decline
4. Fetkovich
5. Blasingame
6. Agarwal-Gardner

Monograph 4 models – 2

- Many models require bottomhole flowing pressures
- Many models require rock and fluid properties
- None have multi-fractured horizontal well option

Monograph 4 models – 3

- What if I only have public domain rate data?
- We'll look at three models
  1. Modified Arps
  2. Duong
  3. Stretched exponential decline

Model 1 – Modified Arps – start with classic Arps equations

$$q_o = \frac{q_i}{\left(1 + bD_i t\right)^{1/b}}$$

$$N_p\left(t\right) = \frac{q_i^b}{D_i\,(b-1)}\left[q(t)^{1-b} - q_i^{1-b}\right]$$

Rate equation can have long tail and erroneously high recovery

Model 1 – Modified Arps – impose terminal exponential decline, Dmin, on classic Arps equations

$$t_{sw} = \frac{\frac{D_i}{D_{\min}} - 1}{bD_i}$$

$$q_o = q_{sw} \exp\left[-D_{\min}\left(t - t_{sw}\right)\right]$$

$$N_{p\exp} = \frac{q_{sw} - q_{el}}{D_{sw}}$$

Four empirical constants – qi, Di, b, and Dmin

Model 2 – Duong

$$t(a,m) = t^{-m} \exp\left[\frac{a}{1-m}\left(t^{1-m}-1\right)\right]$$

$$q_o = q_1 t(a,m)$$

$$\frac{q_o}{N_p} = a t^{-m}$$

Three empirical constants – a, m, and q1

Ref: Duong, SPE 137748

Model 3 – Stretched exponential decline – SEDM

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

$$N_p = \frac{q_i \tau}{n} \left\{ \Gamma\left[\frac{1}{n} \right] - \Gamma\left[\frac{1}{n}, \left(\frac{t}{\tau} \right)^n \right] \right\}$$

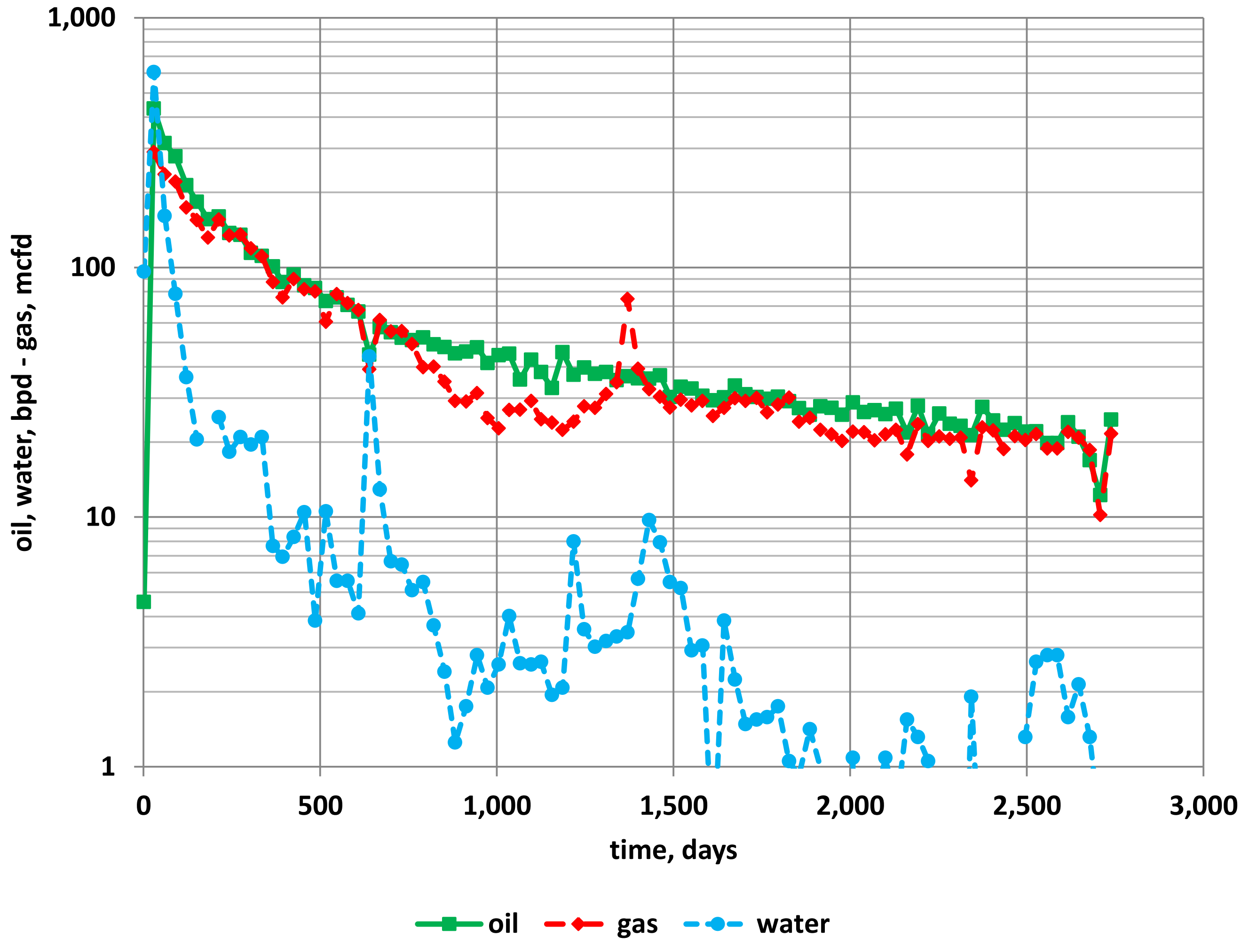
Three empirical constants – qi, n, and τ

Ref: Yu, SPE 166198

2. Two applications of Mono 4 to Wyoming wells

Application # 1 –
Mono 4 model predictions
vs
actual performance

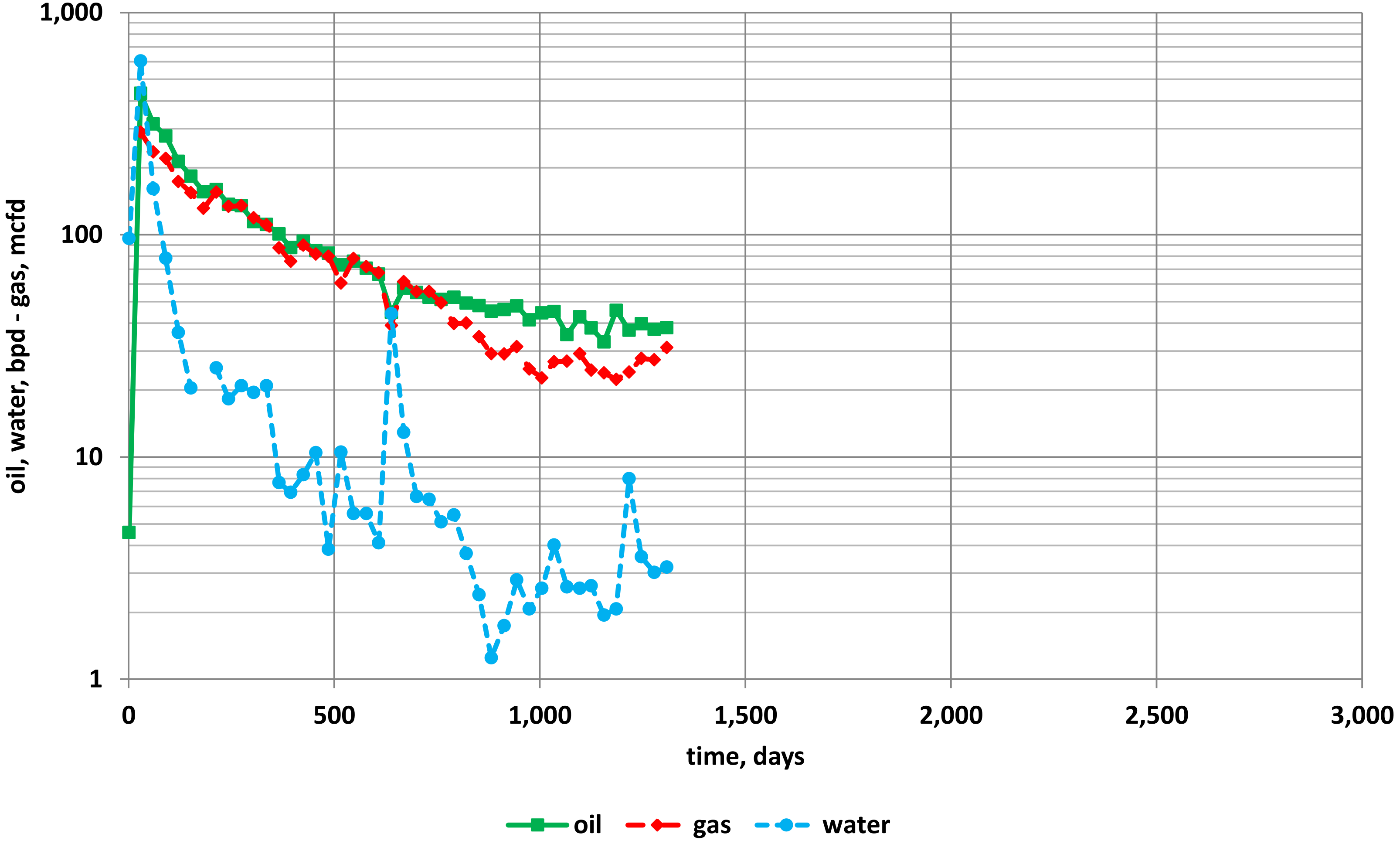
Spillman Draw 16-1H API 4900928224
T35n R73W sec 16



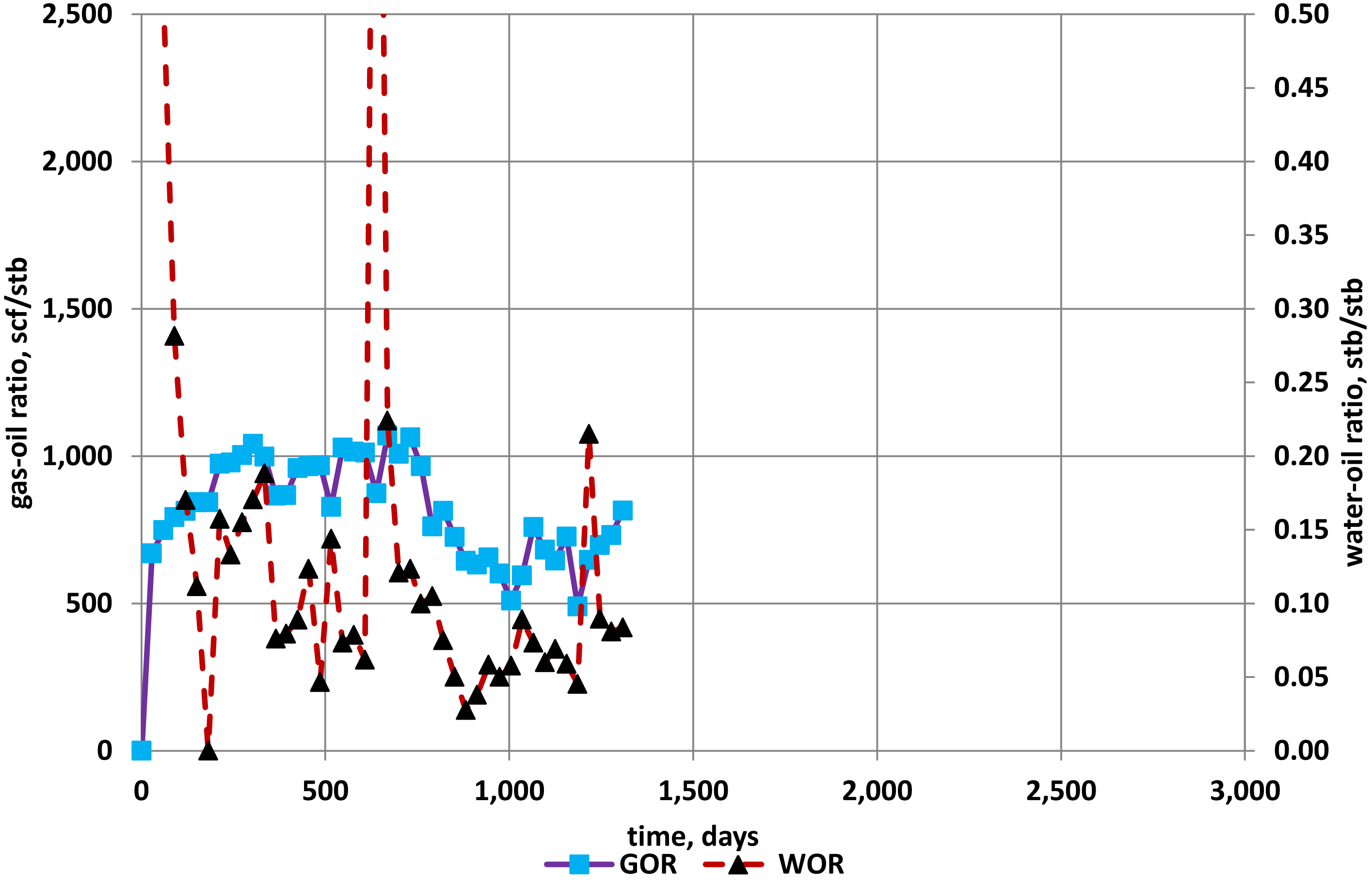
Spillman Draw 16-1H – test of 3 models

- Take first half of production data
- Analyze with three models
  1. Modified Arps
  2. Duong
  3. Stretched exponential decline
- Compare model predictions with second half of production data

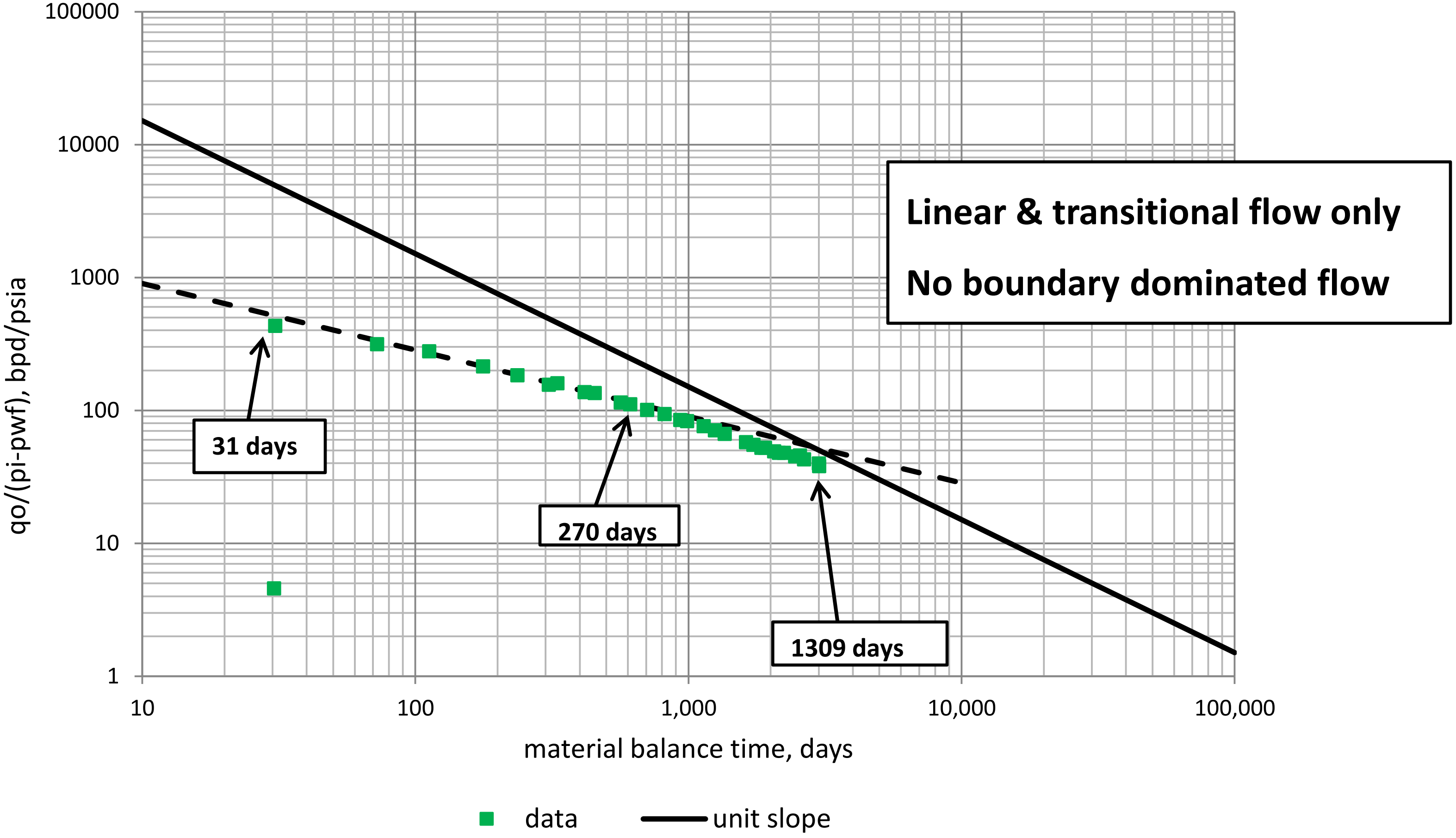
Spillman Draw 16-1H – production data



Spillman Draw 16-1H – gas-oil ratio & water-oil ratio



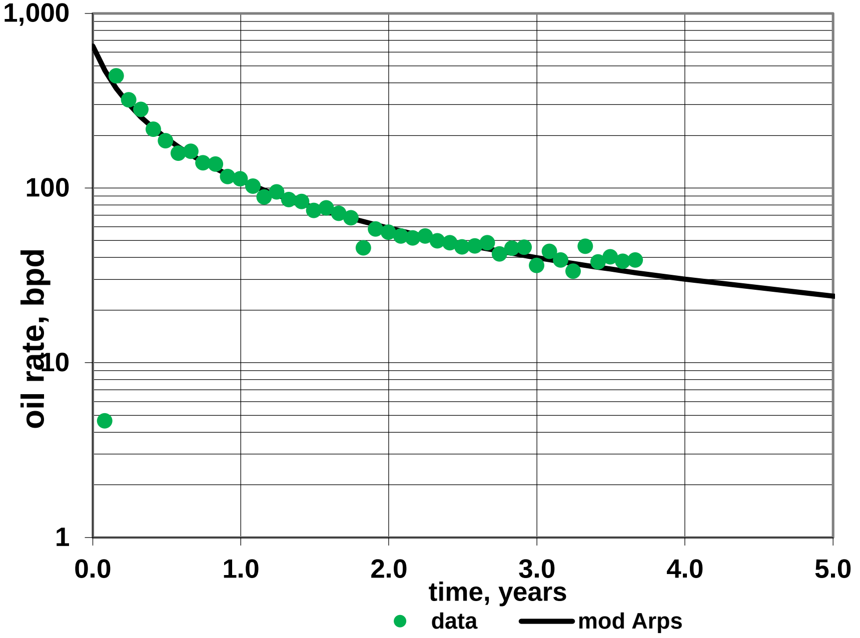
Spillman Draw 16-1H – diagnostic plot #1



Linear & transitional flow only

No boundary dominated flow

Spillman Draw 16-1H – modified Arps



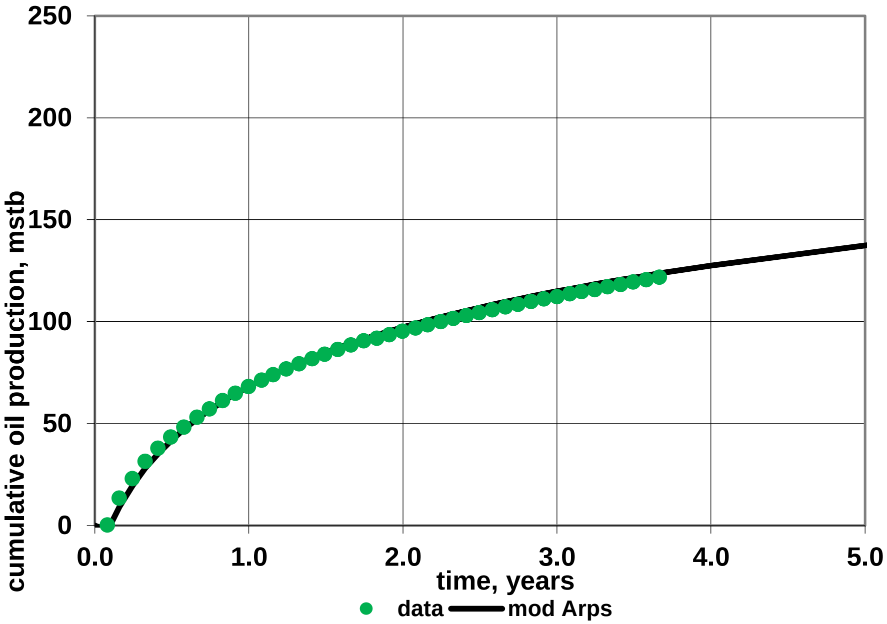
qi = 650 bpd

De = 83 %/yr

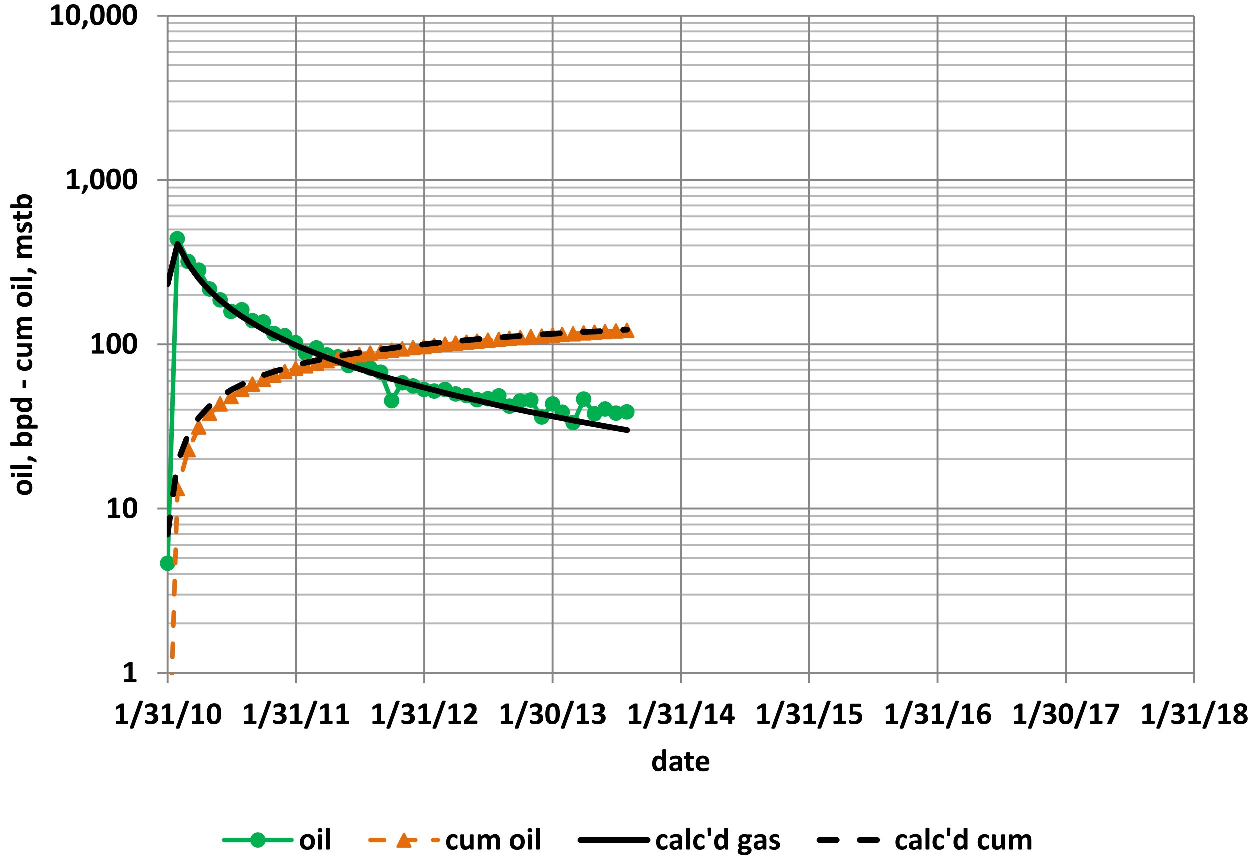
b = 0.95

Dmin = 5 %/yr

tsw = 20.3 yrs



Spillman Draw 16-1H – Duong



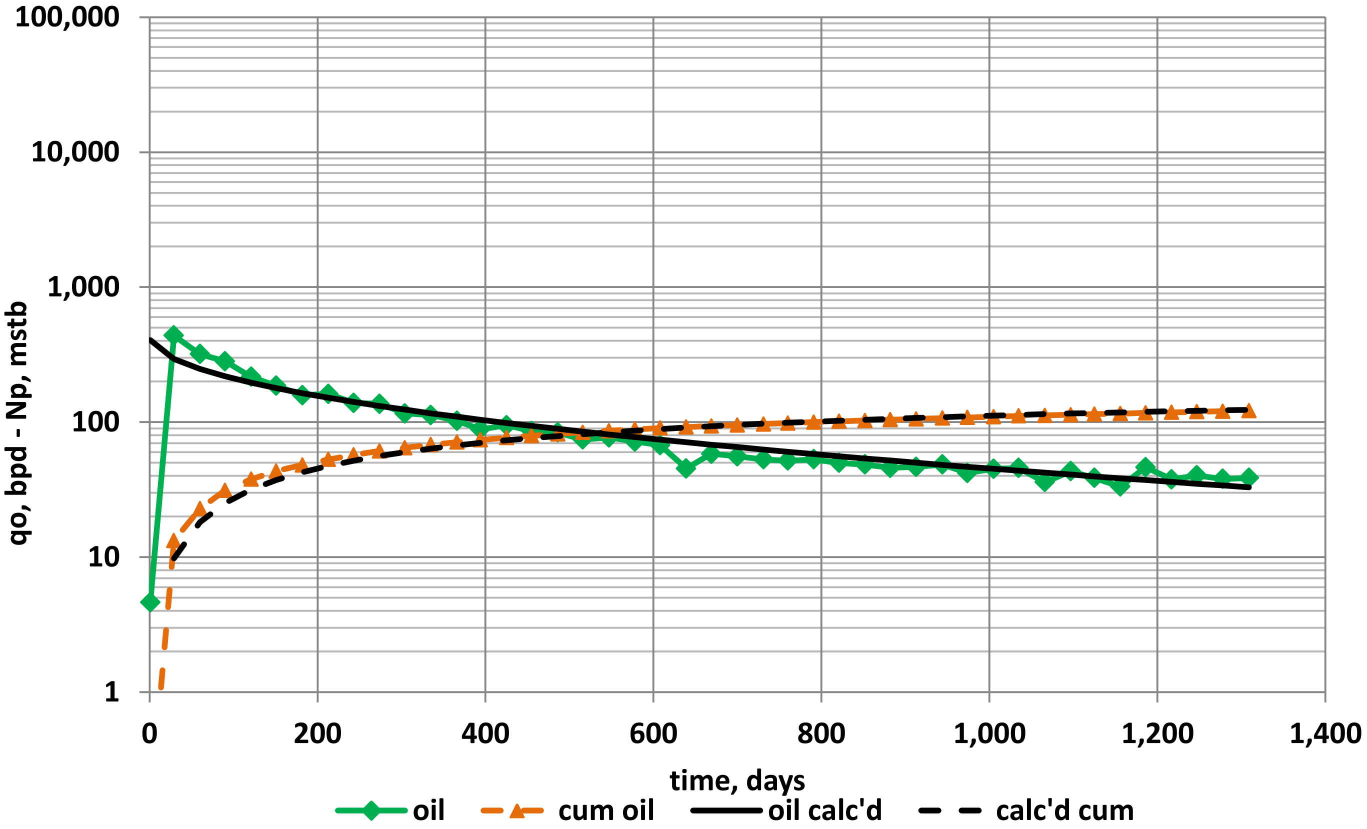
q1 = 242 bpd

a = 2.00

m = 1.23

qinf = -10 bpd

Spillman Draw 16-1H – SEDM

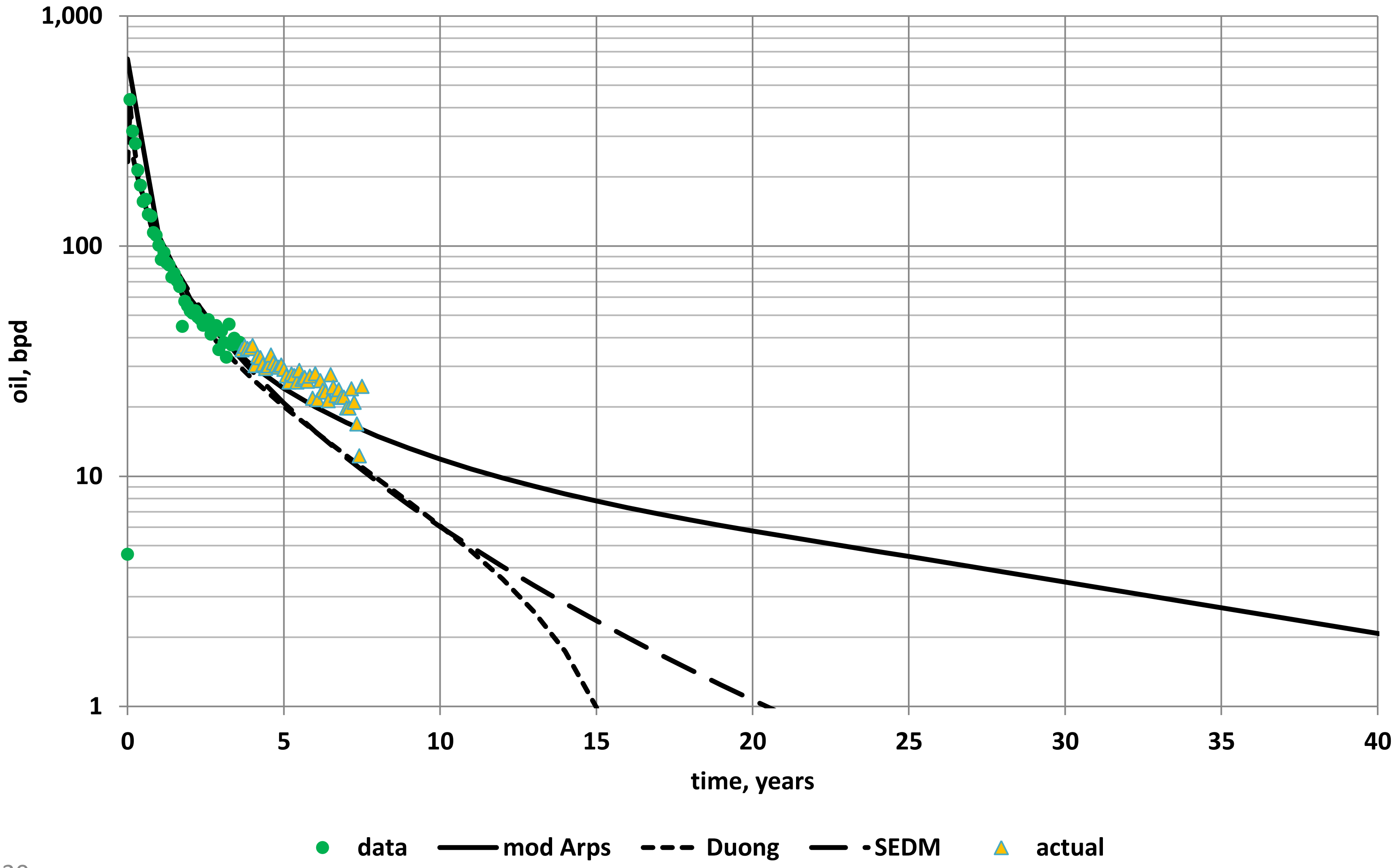


qi = 438 bpd

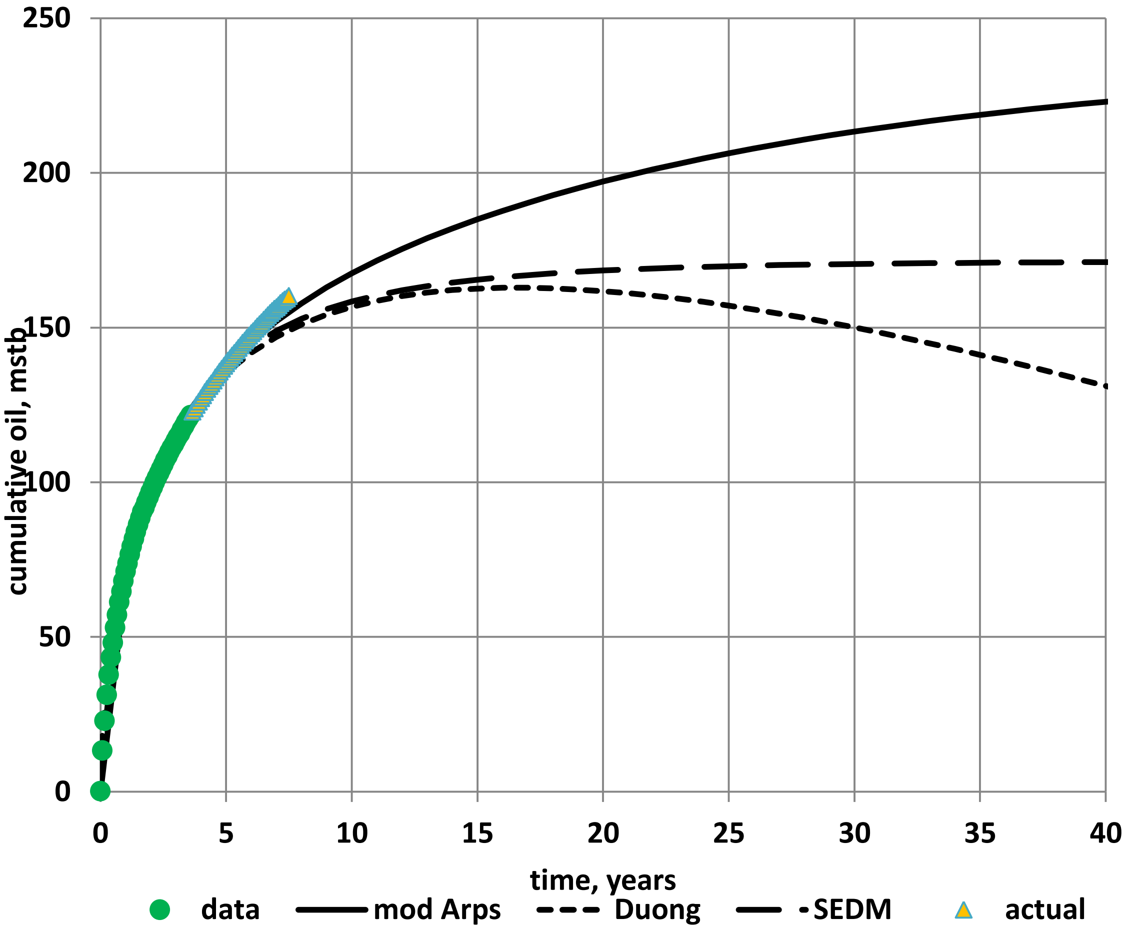
n = 0.491

τ = 189 days

Spillman Draw 16-1H – models vs actual - rates

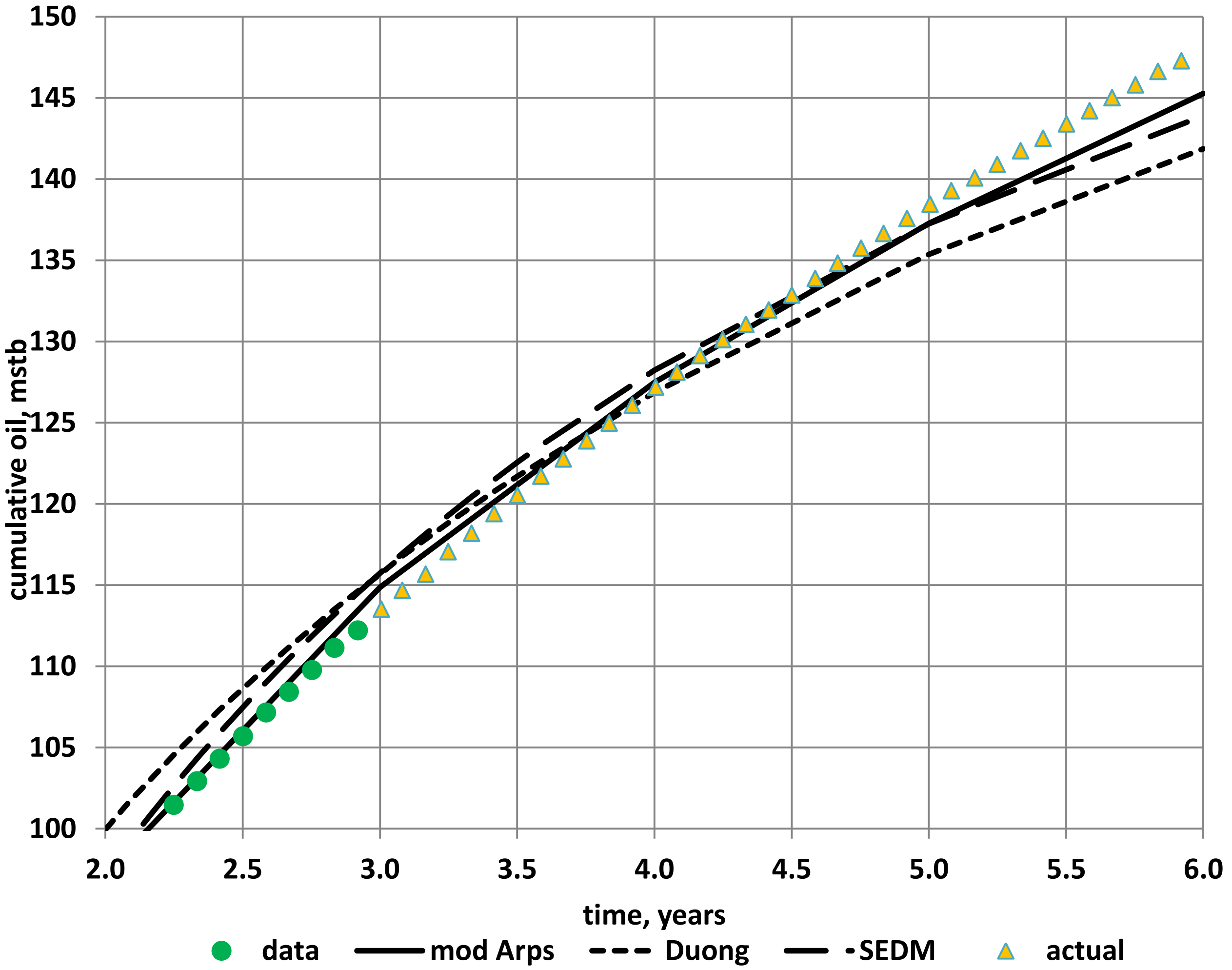


Spillman Draw 16-1H – models vs actual - cums



Duong cum falls at late time due to qinf = -10 bpd

Spillman Draw 16-1H – models vs actual – short term cums



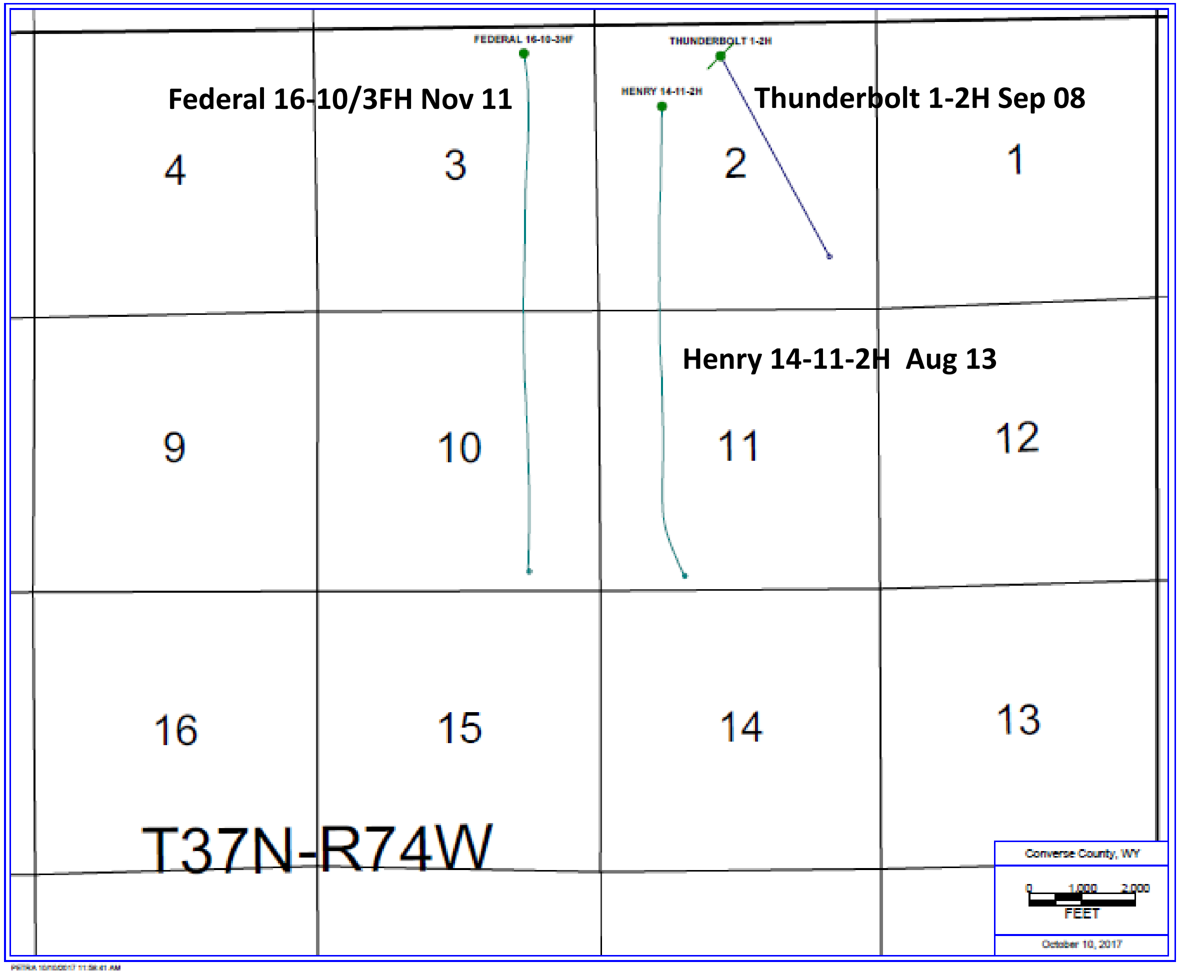
All models sufficiently accurate for 1 year reserves cycle.

Wyoming well # 1 conclusions

- All models acceptable for 1 yr forecast
- No model accurately predicts long term recovery

Application # 2 –
What can Mono 4 diagnostic plots tell us about frac interference?

Do diagnostic plots show frac hits?

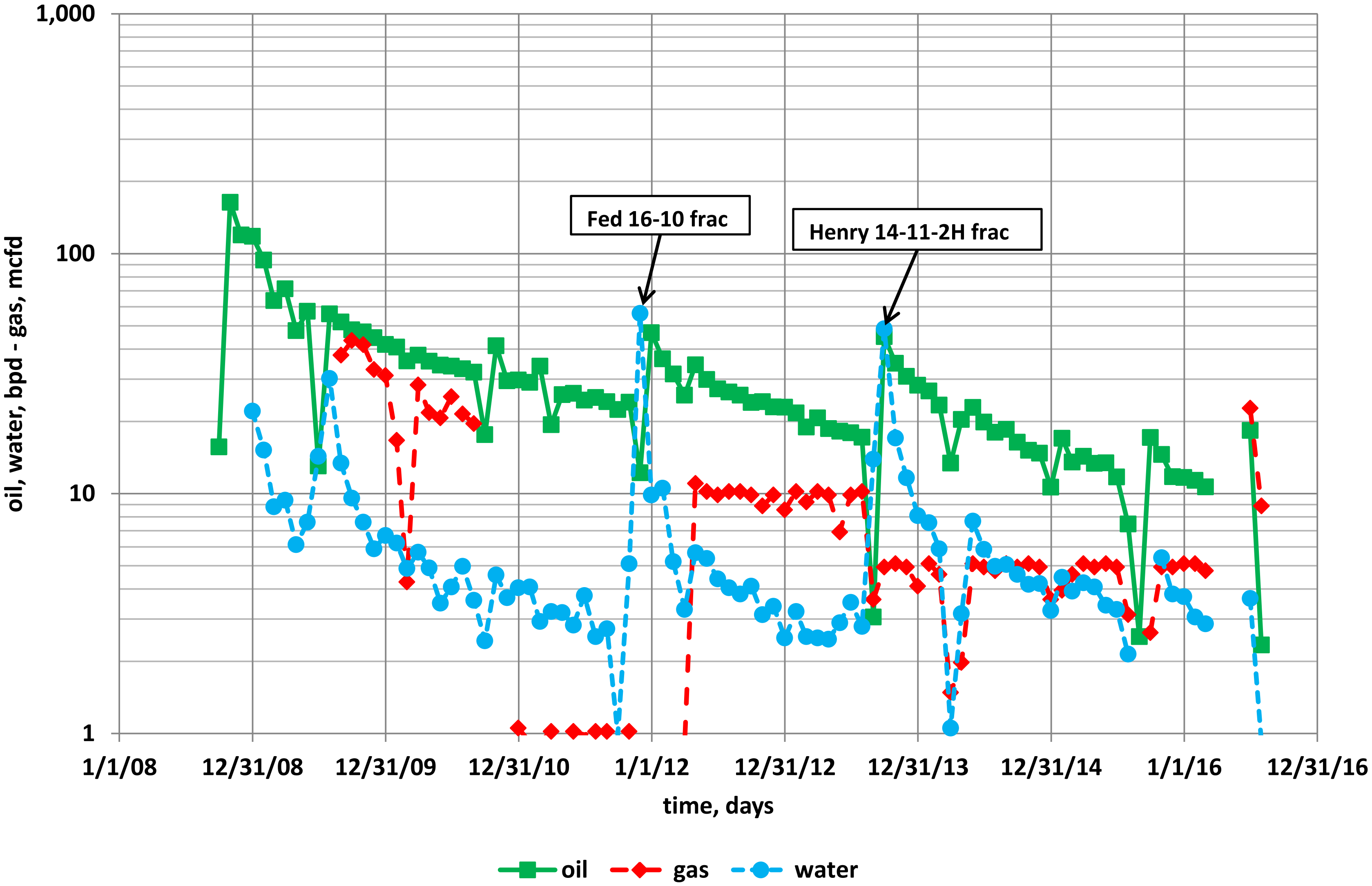


Federal 16-10/3FH Nov 11

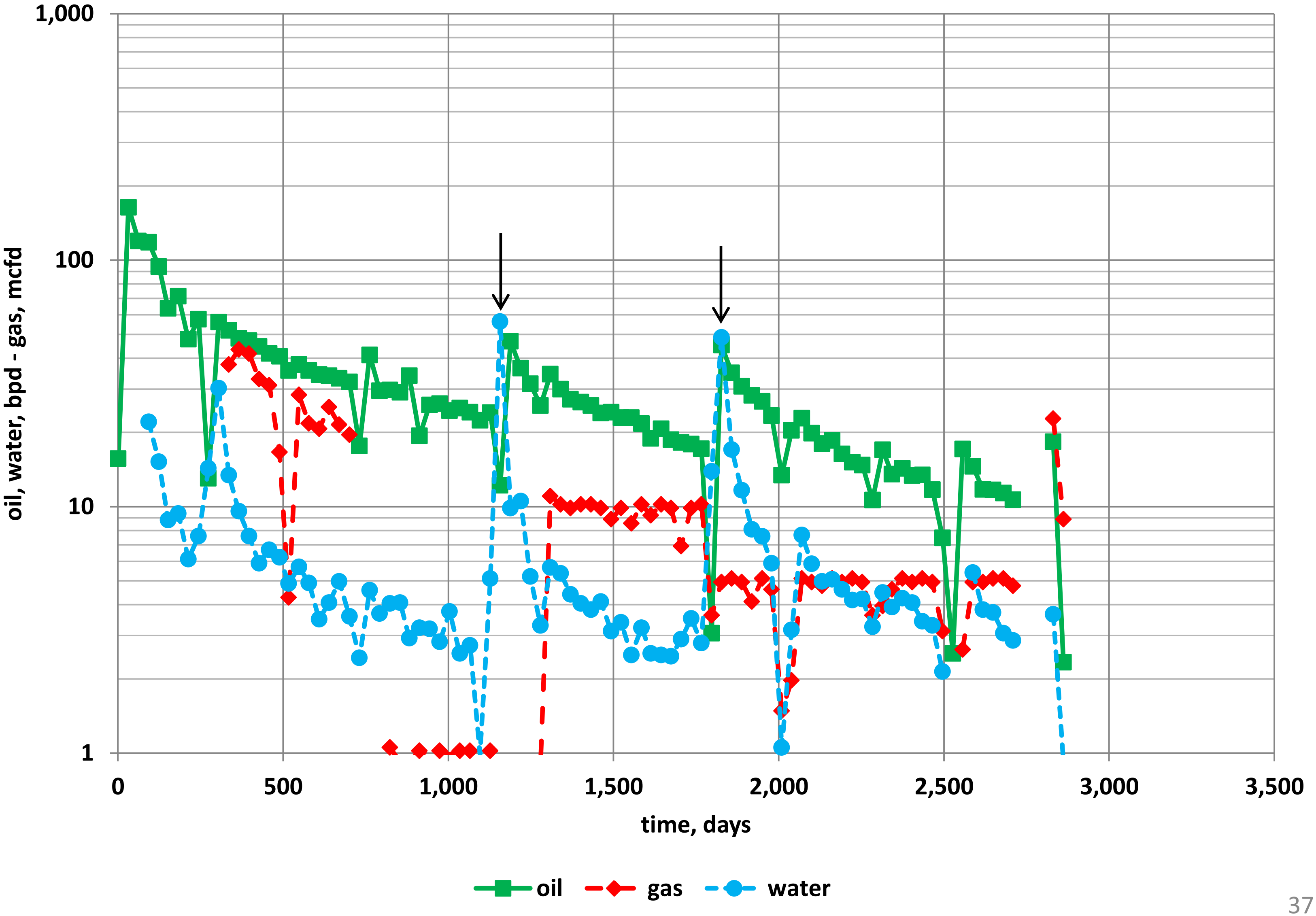
Thunderbolt 1-2H Sep 08

Henry 14-11-2H Aug 13

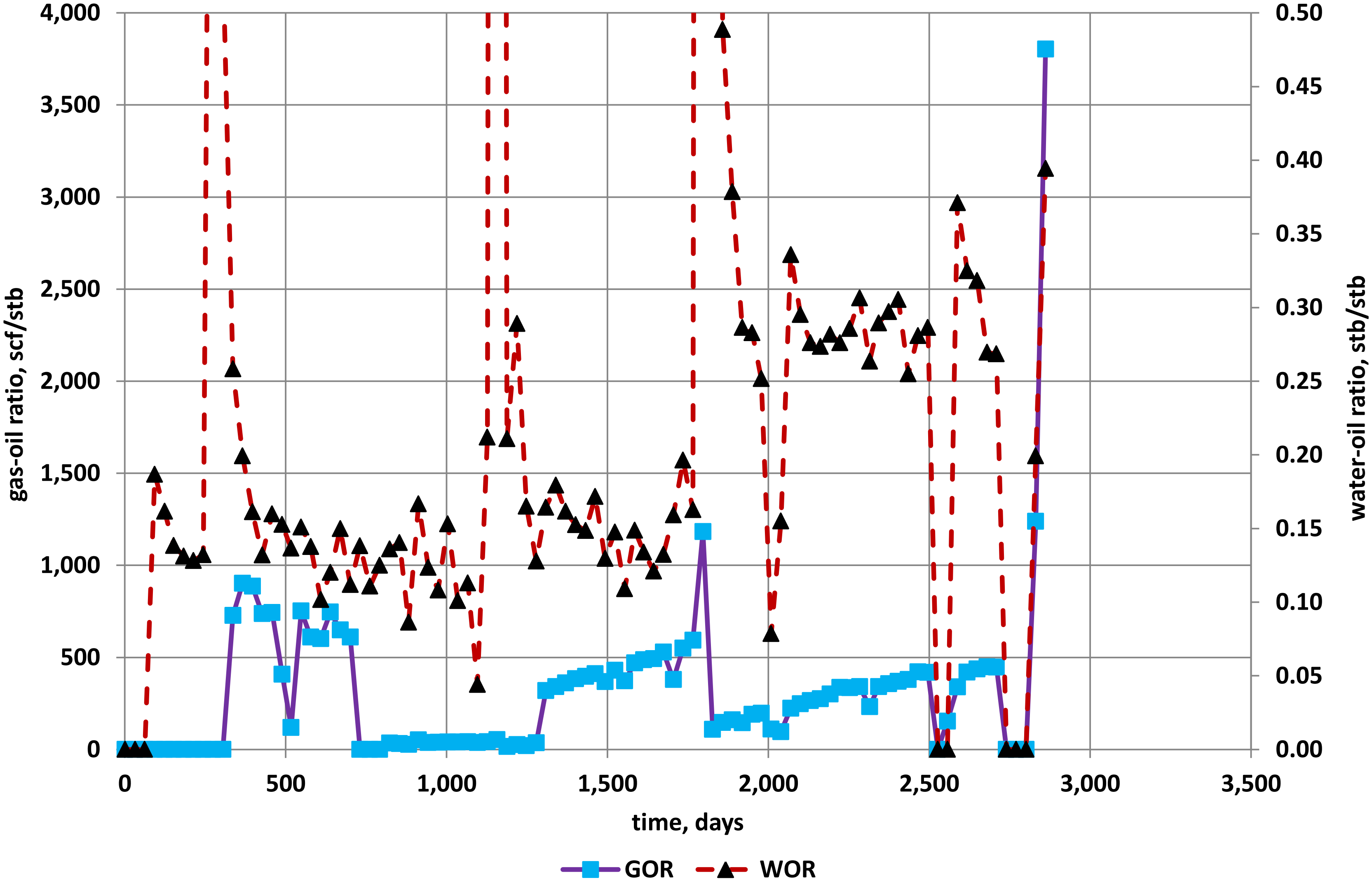
Thunderbolt 1-2H production data



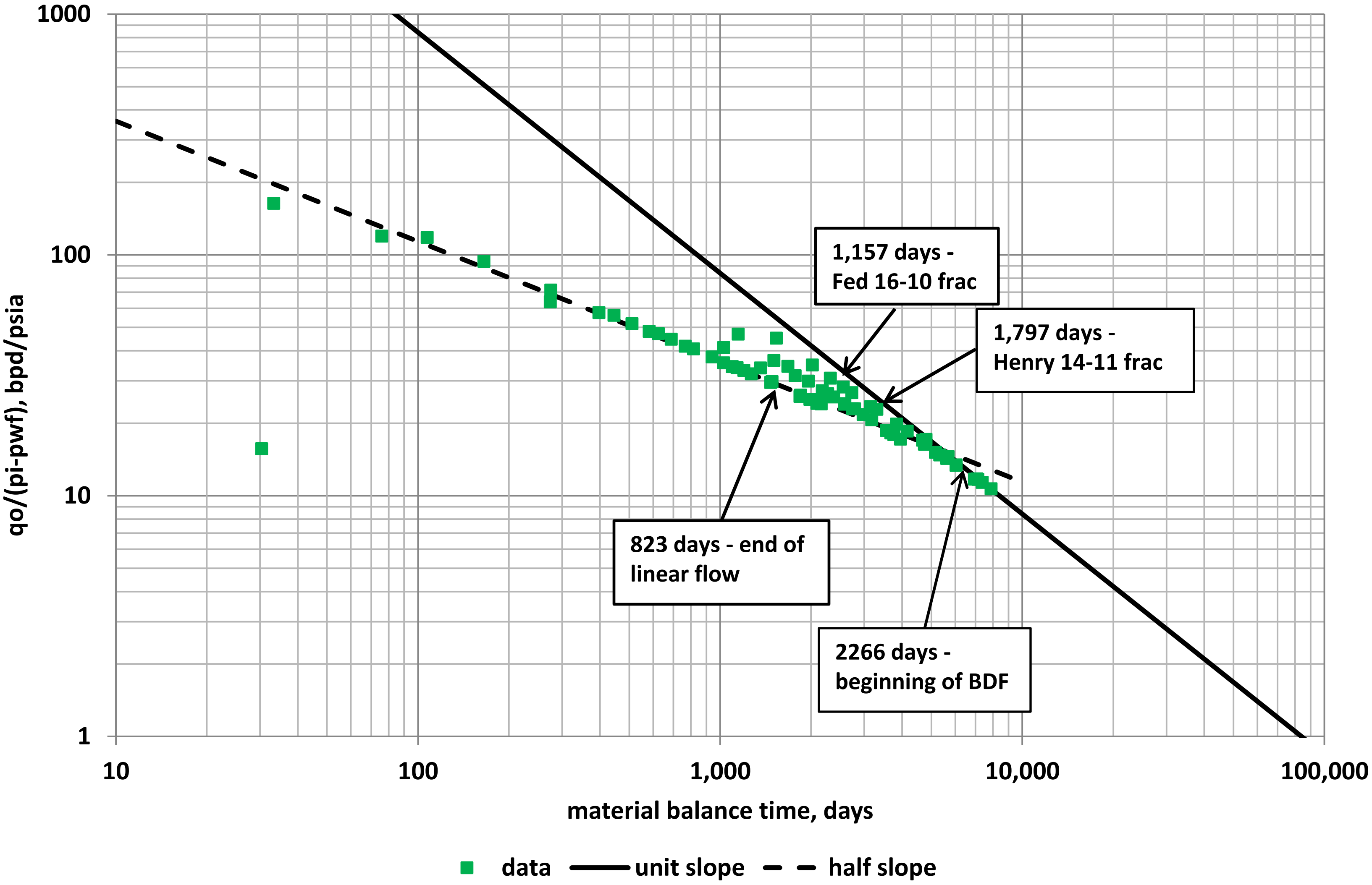
Thunderbolt 1-2H frac hits at 1157 & 1797 days



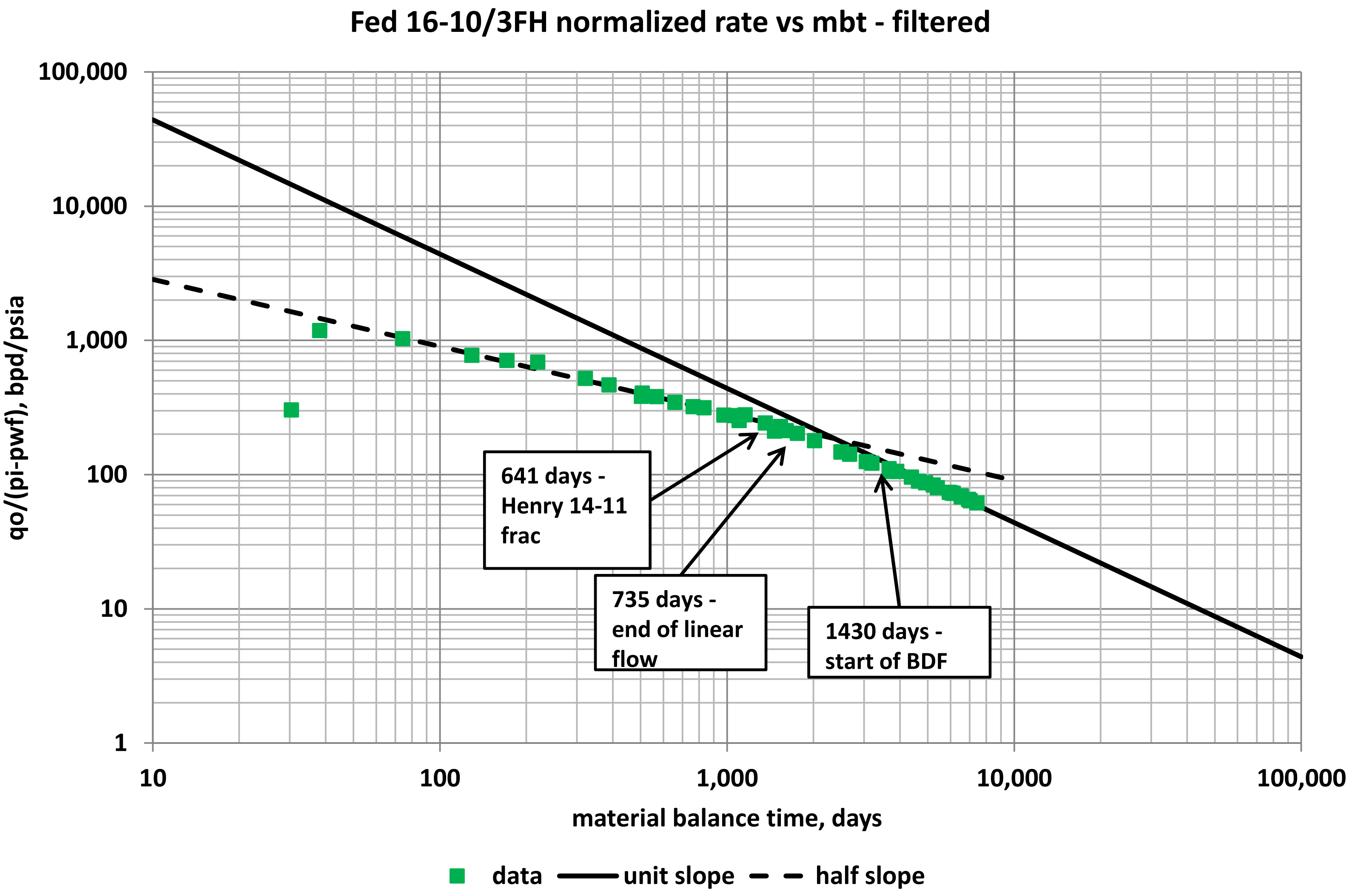
Thunderbolt 1-2H GOR & WOR plots



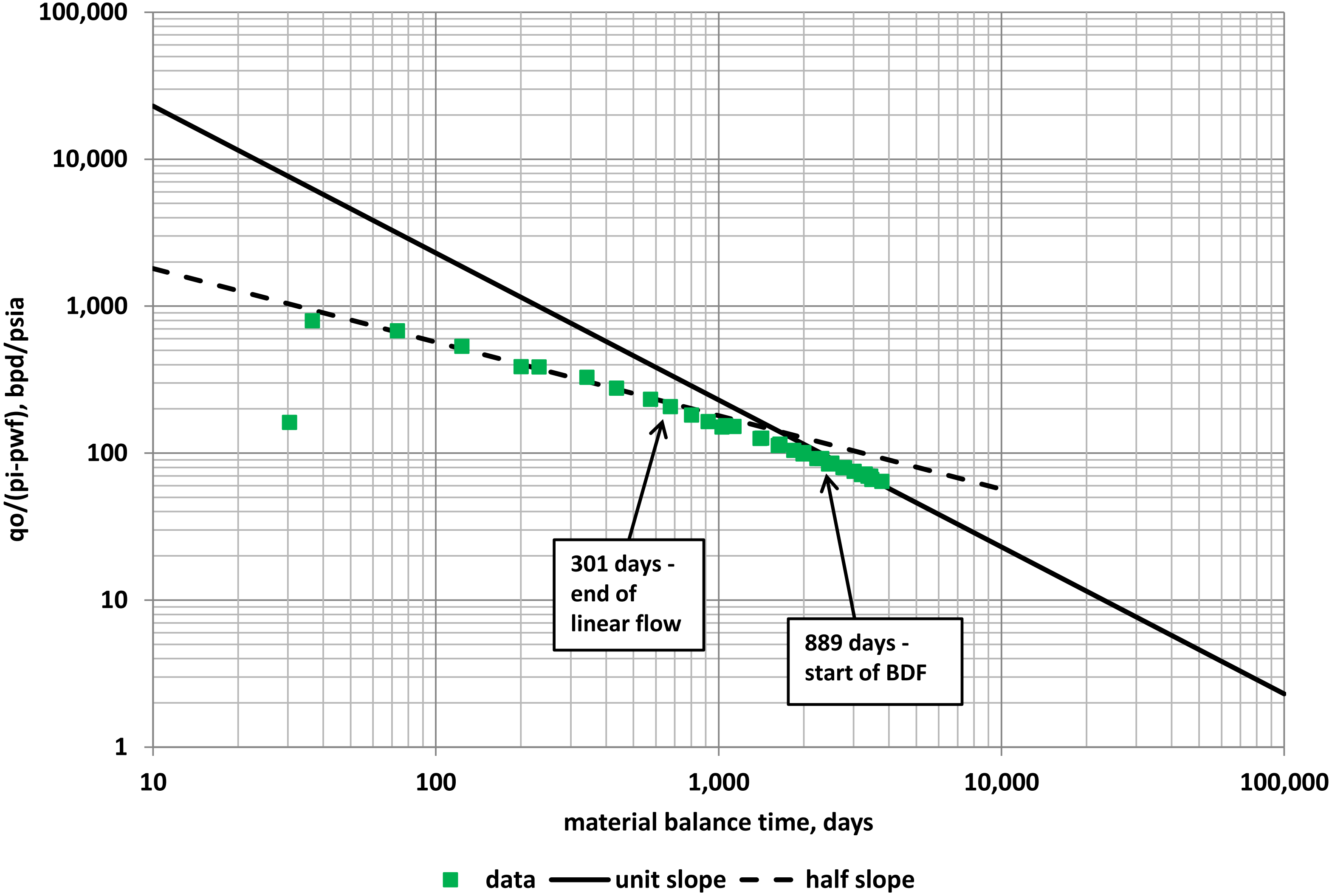
Thunderbolt diagnostic plot



Fed 16-10/3FH diagnostic plot



Henry 16-11-2H diagnostic plot



301 days - end of linear flow

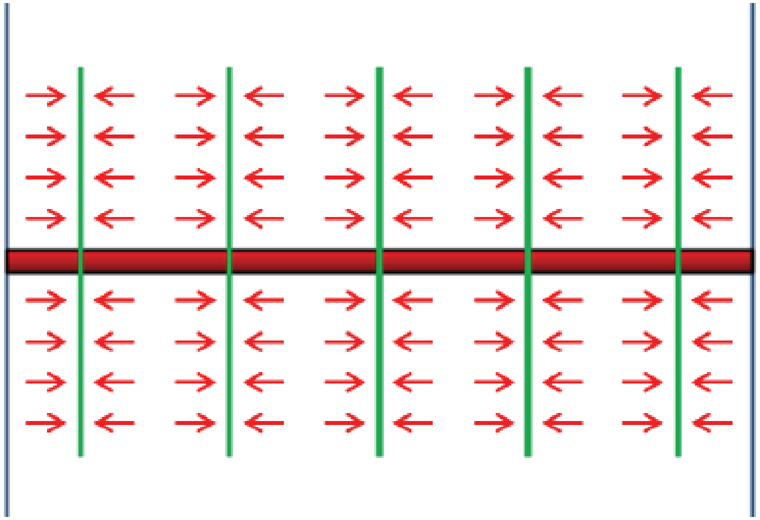
889 days - start of BDF

Observations

- Thunderbolt 1-2H diagnostic plot became noisy when offset wells fracked.
- Fed 16-11H diagnostic plot shows frac hit coincides +/- with end of linear flow
- Henry 14-11-2H diagnostic plot early time behavior not affected after hitting offsets during stimulation

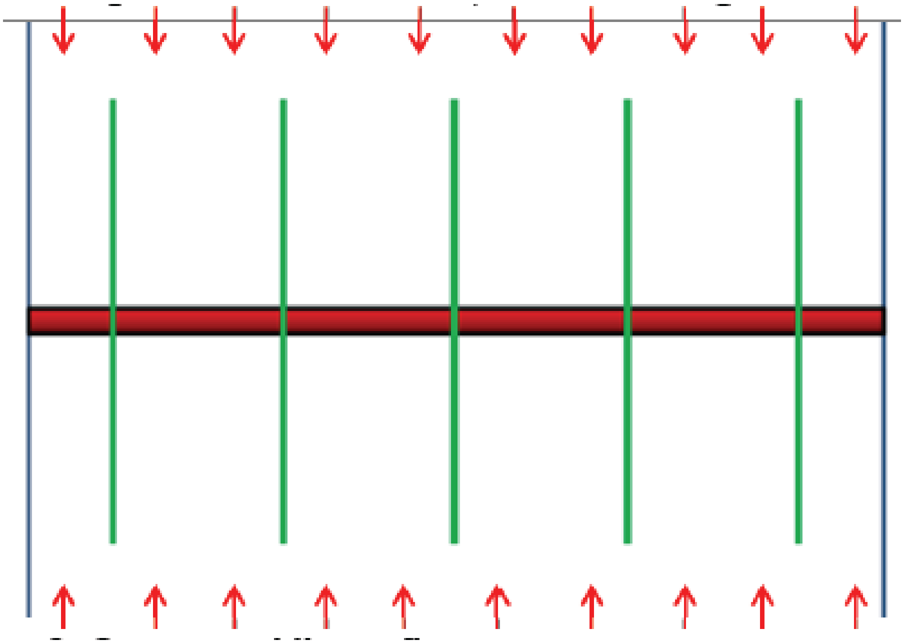
3. A new model that isn’t discussed in Monograph 4

Compound Linear Flow Model considers flow from native reservoir into the SRV



SRV = Stimulated Reservoir Volume

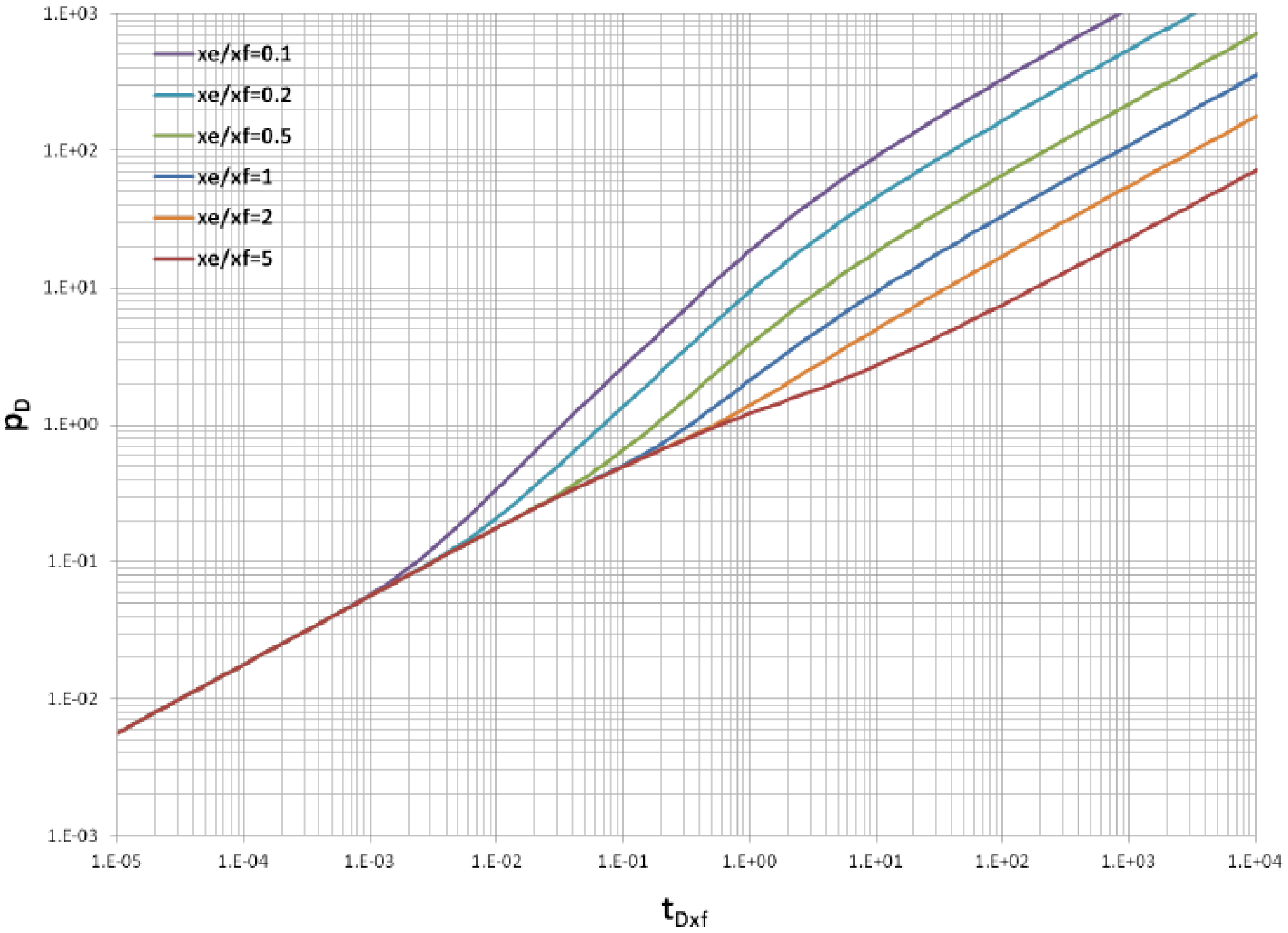
Primary linear flow

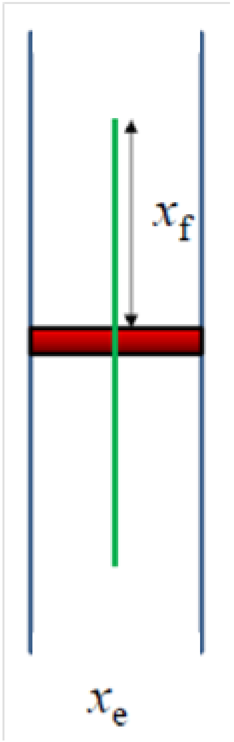


Compound linear flow

Ref: Liang, 2012, SPE 162646

Compound Linear Flow type curves





Ref: Liang, SPE 162646

Compound Linear Flow equations

Primary linear flow

$$t_{Dxf} = \frac{0.00633kt}{\phi\mu c_t x_f^2}$$

$$p_D = \sqrt{\pi t_{Dxf}}$$

Compound linear flow

$$p_D = \frac{kh\left(p_i - p_{wf}\right)}{141.2qB_o\mu_o}$$

$$p_D = \frac{2x_f}{x_e}\sqrt{\pi t_{Dxf}} + s'$$

Ref: Liang, SPE 162646

Two important times for Compound Linear Flow

Time to end of primary linear flow

$$t = \frac{1896\phi\mu c_t d_i^2}{k}$$

t = time, hours

Time to start of compound linear flow

$$t = \frac{316\phi\mu c_t x_f^2}{k}$$

t = time, days

Ref: Liang, SPE 162646

Will a well reach compound linear flow or boundary dominated flow?

For a well to reach compound linear flow

$$\frac{y_e}{x_f} > 2\sqrt{2\pi} = 5.01$$

ye = interwell spacing, feet

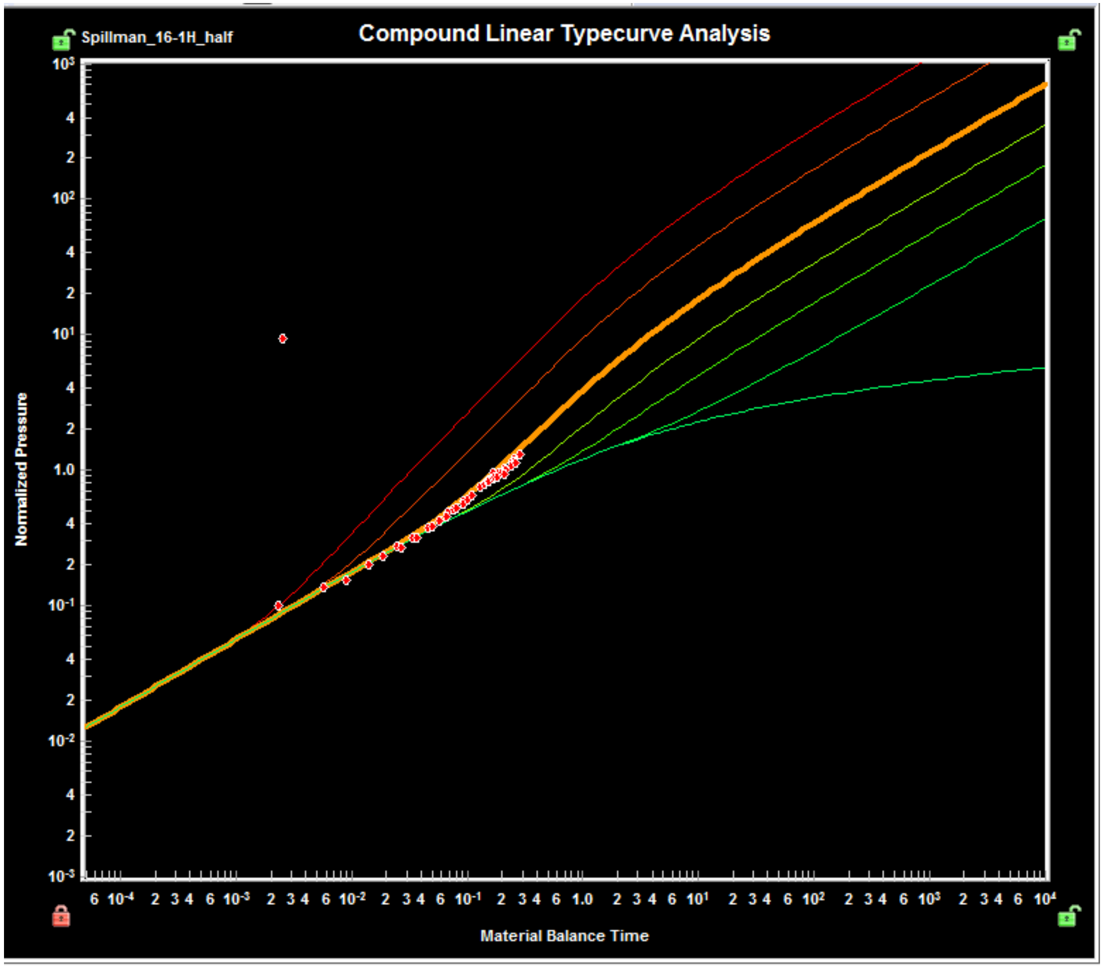
Assume ye = 1,000 ft and xf = 200 feet

Then ye/xf = 5

Well will probably transition from primary
linear flow to BDF, unlikely that CL flow
will be observed

Ref: Liang, SPE 162646

Spillman 16-1H analyzed with CL model



CL analysis of Spillman 16-1H assumed

- **Oil = 42 API**
- **GOR = 750 scf/stb**
- **Initial reservoir pressure = 6500 psia**
- **Bottomhole flowing pressure = 3000 psia**
- **Net pay = 100 ft**
- **Porosity = 10%**

Better estimates of rock, fluid, and wellbore properties required to refine analysis and predict future performance

Summary & Conclusions

- SPEE Monograph 4 focuses on predicting performance of developed wells in unconventional reservoirs
- Diagnostic plot constructed and three models applied to first half of Spillman 16-1H production data
- Comparison of model forecasts with second half of Spillman data indicates
  - All models acceptable for one year reserves cycle
  - No model accurately predicts long term recovery

Summary & Conclusions – 2

- **Frac hits introduced noise in diagnostic plot but did not change signature.**
- **Diagnostic plot of offending well showed no evidence of hit on offset wells.**
- **Compound linear (CL) model developed for multi-fractured horizontal wells.**
- **CL model requires rock and fluid properties and wellbore completion info.**

Thank you!

jseidle@mhausa.com

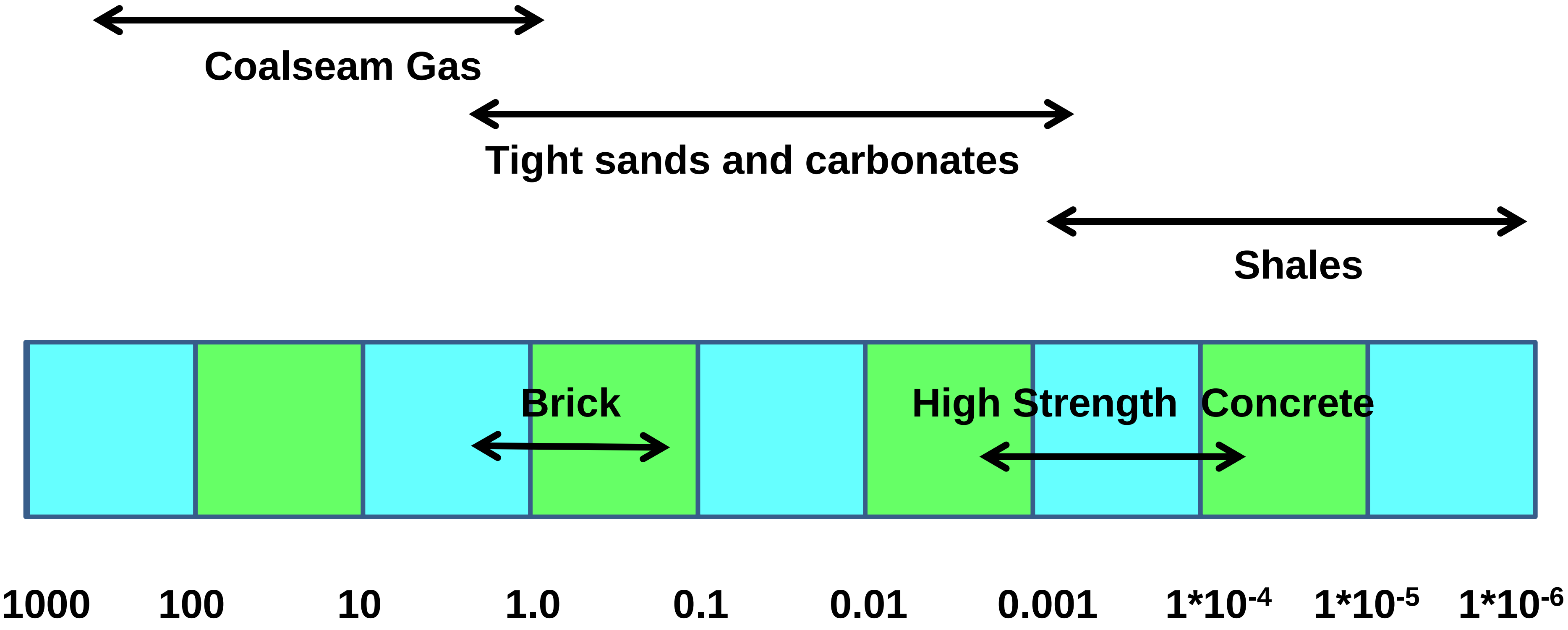
Office = 303-277-0270

Cell = 303-949-3467

Backup images

Placeholder

Permeabilities of Unconventional Reservoirs



Coalseam Gas

Tight sands and carbonates

Shales

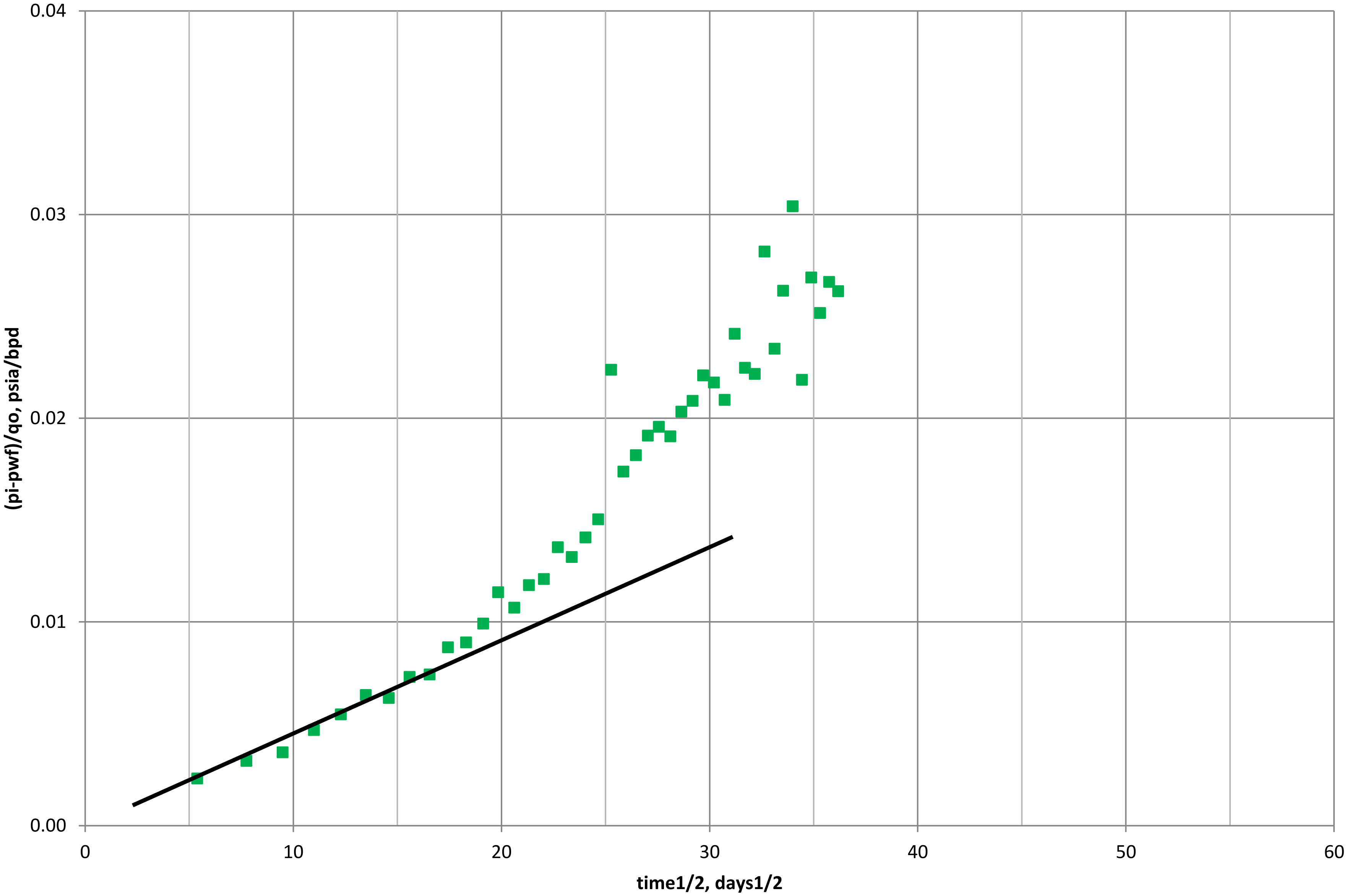
Brick

High Strength Concrete

1000 100 10 1.0 0.1 0.01 0.001 1*10^{-4} 1*10^{-5} 1*10^{-6}

Permeability in Millidarcies

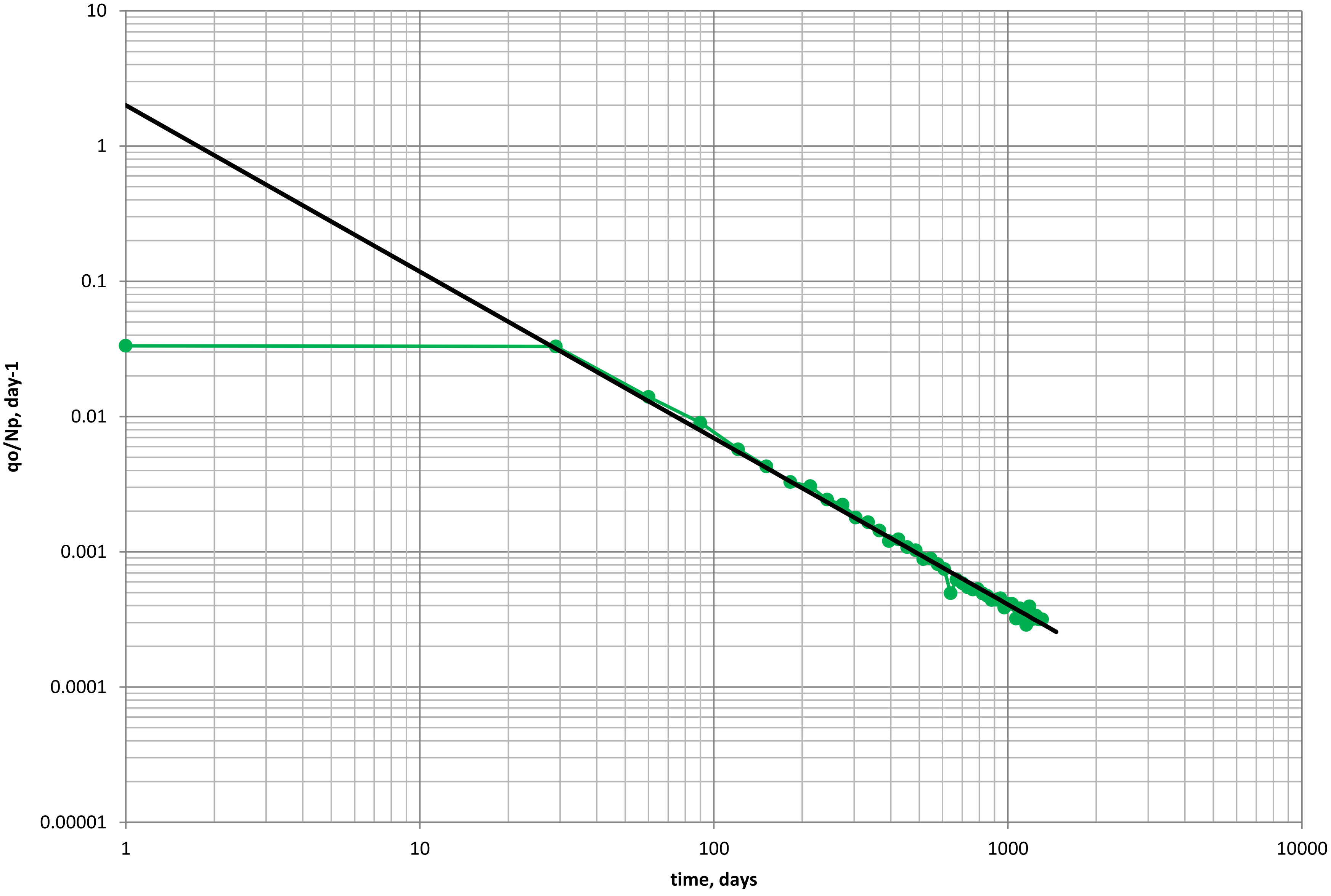
half Spillman 16-1 square root of time plot



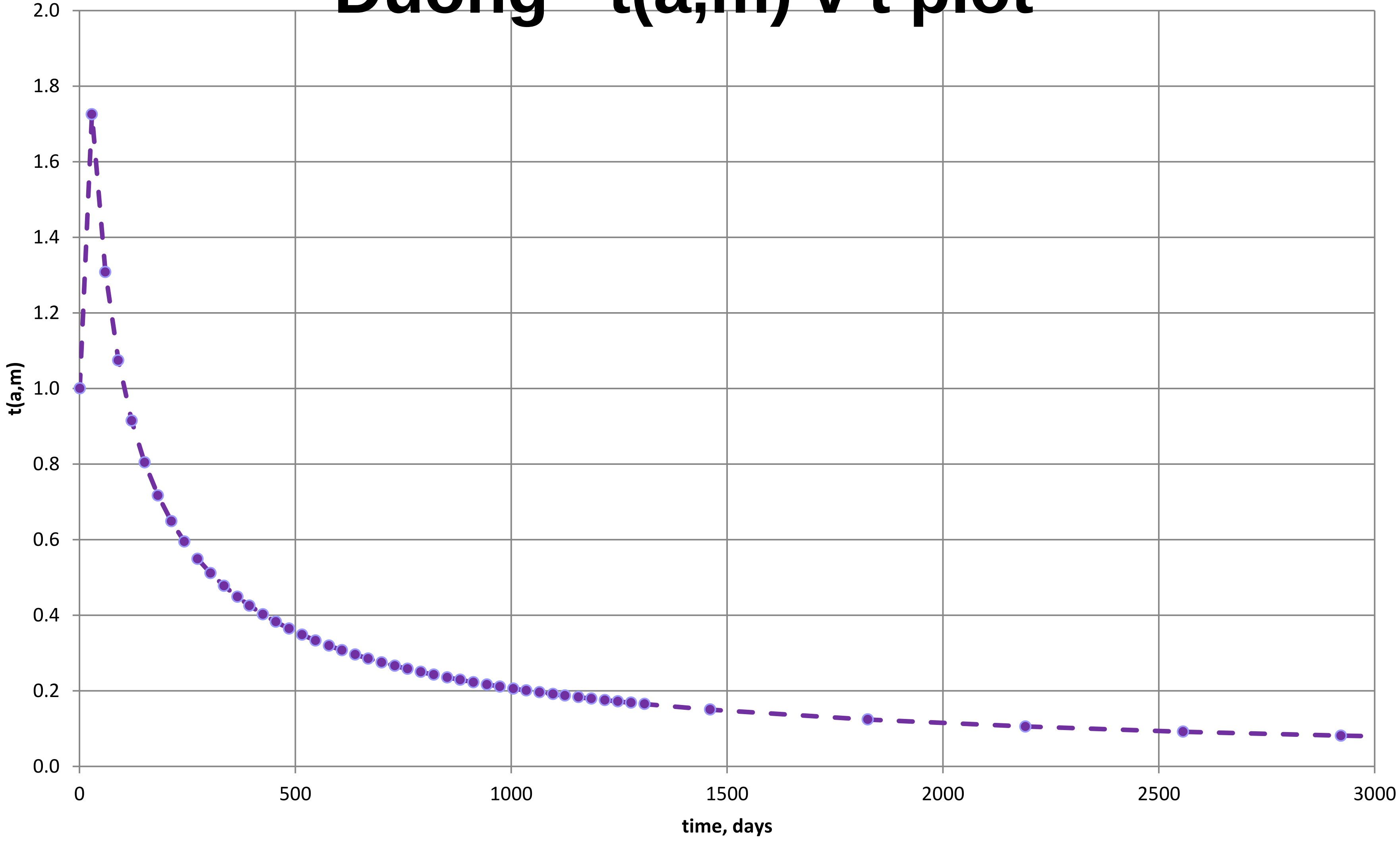
Modified Arps details

- Select a minimum terminal decline, Dmin
- Forecast follows hyperbolic decline until decline rate falls to the specified minimum
- Forecast follows exponential decline using specified minimum decline rate for remainder of well life

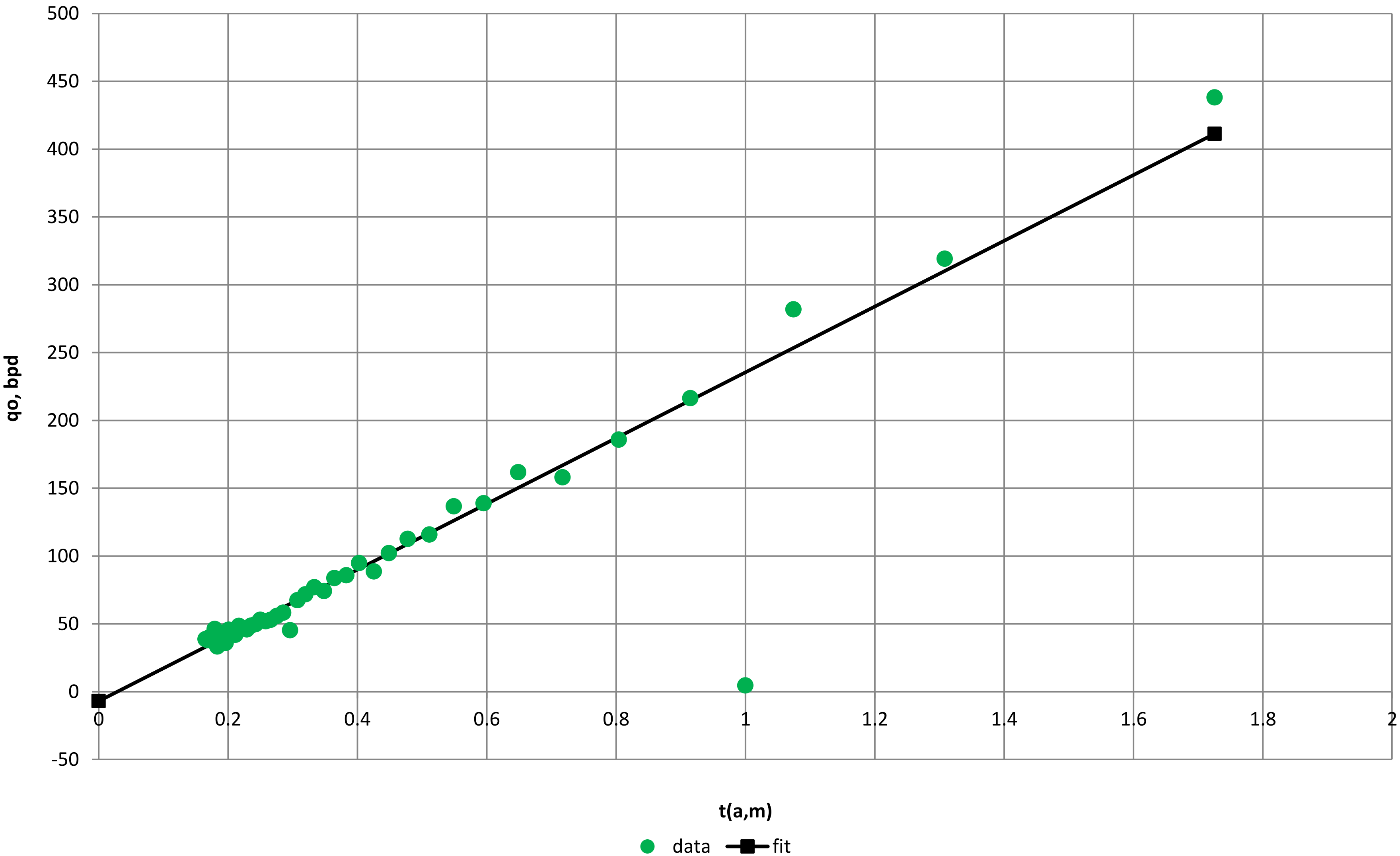
half Spillman 16-1H - Duong plot



Half Spillman 16-1H
Duong - t(a,m) v t plot



Half Spillman 16-1H
Duong - qo v t(a,m) plot



Half Spillman 16-1H
SEDM n & τ plot