# Agenda

- Single phase simple model determination of $A\sqrt{k}$
- Single phase $A\sqrt{k}$ and EUR correlations
- A(Area) and k (permeability) assumptions and the impact on EUR
- How water saturation affects $A\sqrt{k}$
- How to estimate water saturation when you don't know what saturation is
- Common Assumptions on Complex Models (Multiphase Flowback and Production with Enhanced Fracture Region)
    - How Data extraction periods can influence false flow regimes
    - How choke changes affect an interpretation
    - How choke changes and stimulation fluid affect an interpretation
- Permian Well Example Using EFR Assumption
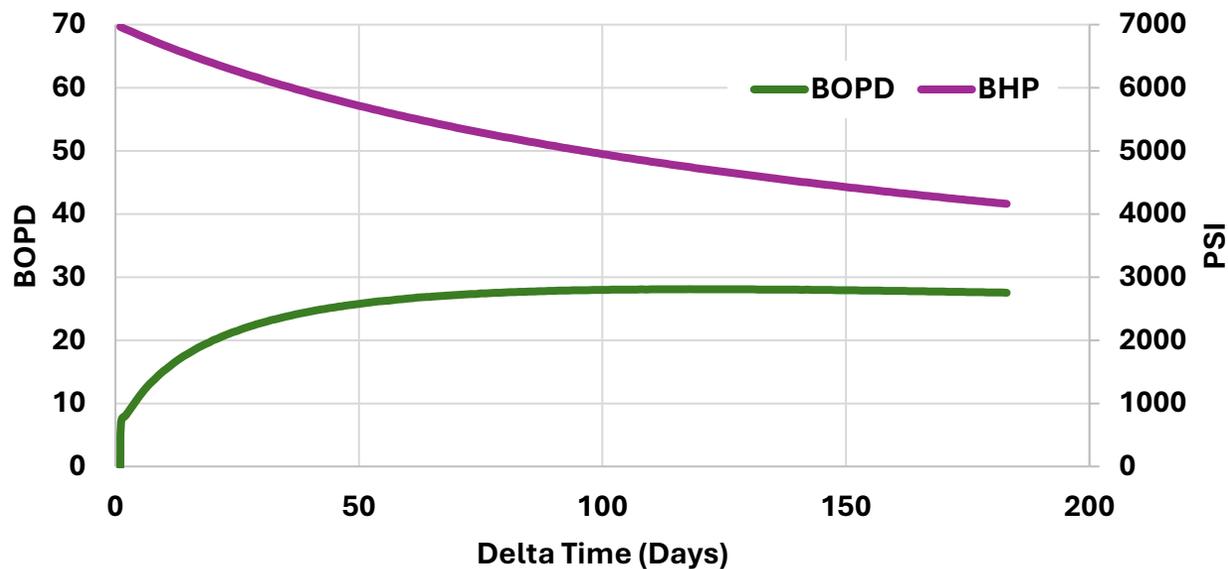   - How much data do you need to assess a well using numerical models?
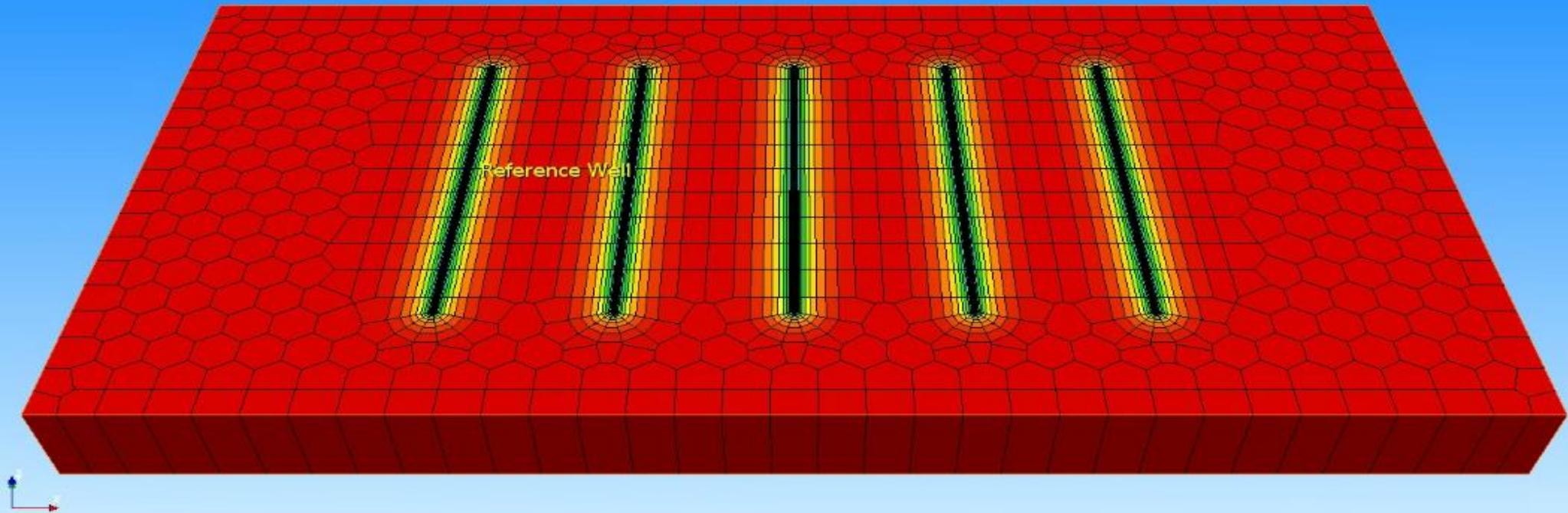
- Formation Height: 150ft.
- GOR: 1200 scf/bbl.
- *Total* Permeability: 0.0005md
- Porosity: 7%
- Fracture Half Length: 300ft.

- #Fractures: 5
- Lateral Length: 1000ft.
- TVD: 10000ft
- Oil API: 45°
- Bubble Point: 3450 psi.

- Gas Gravity: 0.7
- Chlorides: 30000 ppm
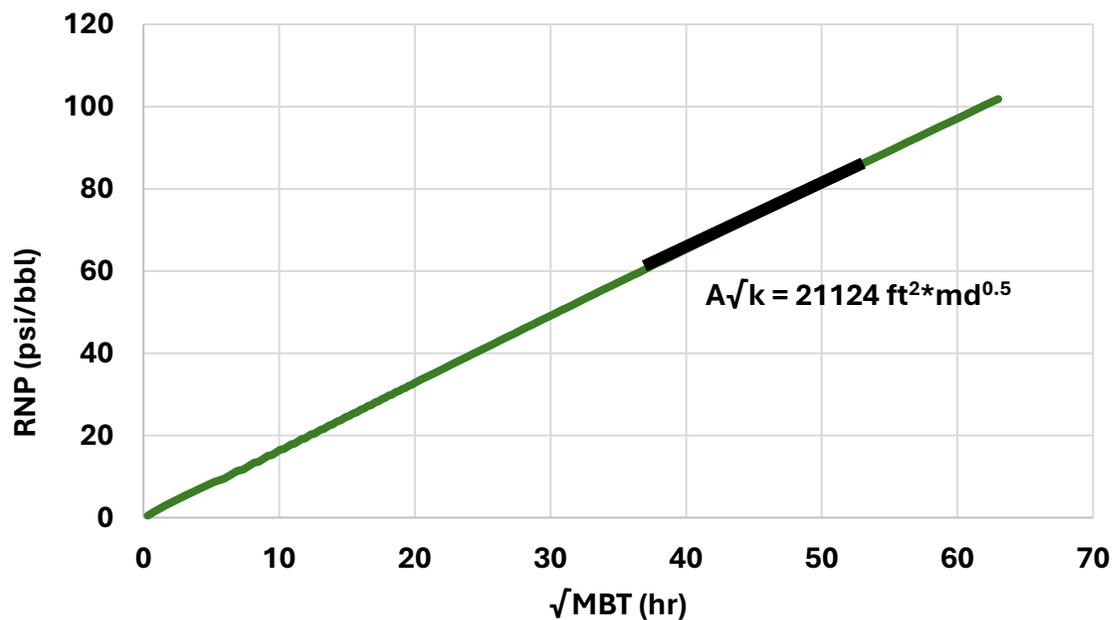- BHT: 180 °F
- Water Saturation: 65%

6 Month Production History

Single Phase Oil Log-Log Plot

Slope = 0.5

Single Phase Oil Linear Flow Plot

$A\sqrt{k}$ = 21124 ft^2*md$^{0.5}$
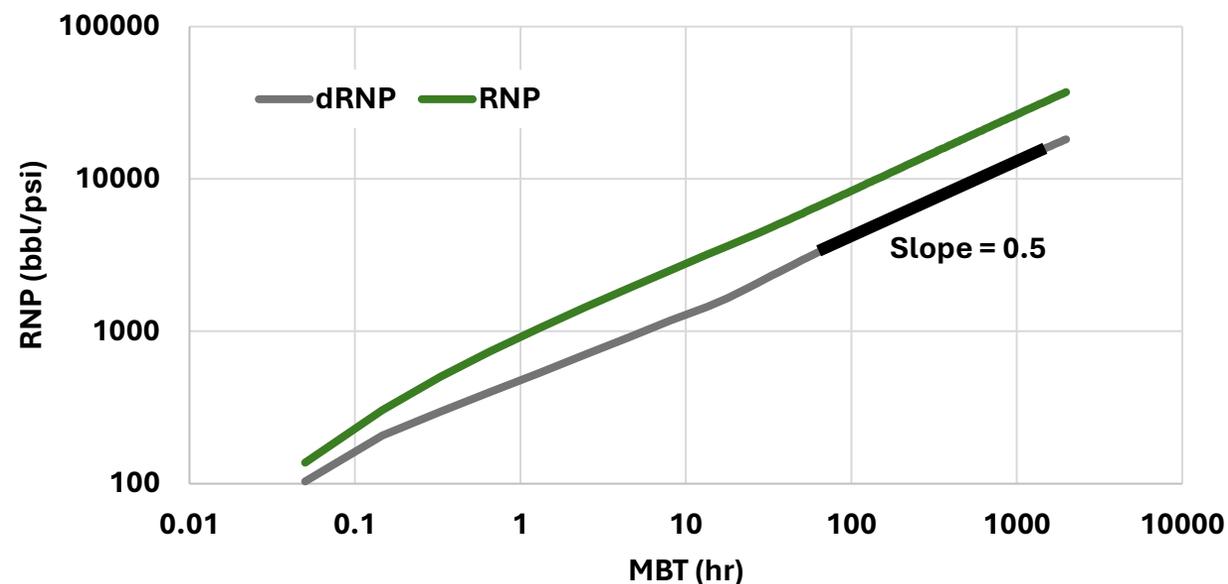
- $A\sqrt{k}$ is a measure of well performance obtained from the slope of the straight-line trend on a RNP vs $\sqrt{\text{MBT}}$ when a fractured well is in linear flow

- For the 5 Fracture model with x_f = 300 ft (x_{mf} = $N_f x_f$ = (5)(300ft.) = 1500ft.) and a height of 150 ft. the $A\sqrt{k}$ should be:

- $A\sqrt{k}$ = $4x_{mf}h\sqrt{k}$ = (4)(1500 ft.)(150 ft.) $\sqrt{(0.0005)}$ = 21124 ft^2*md$^{0.5}$

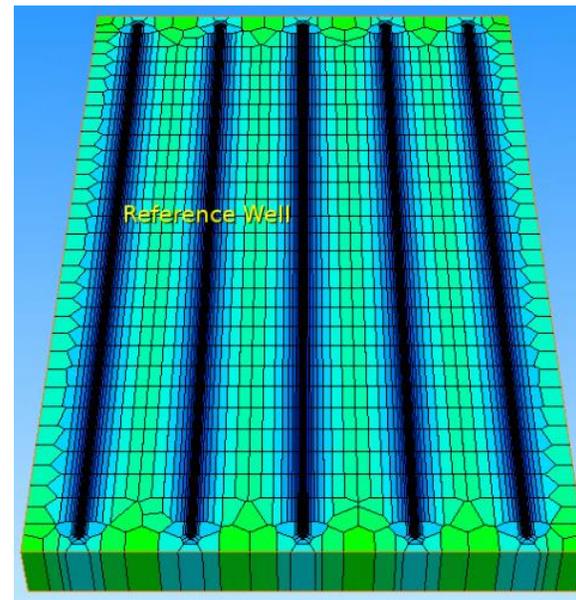- **Model production history's will all be 6 months because that is often all you get on an oil well!**

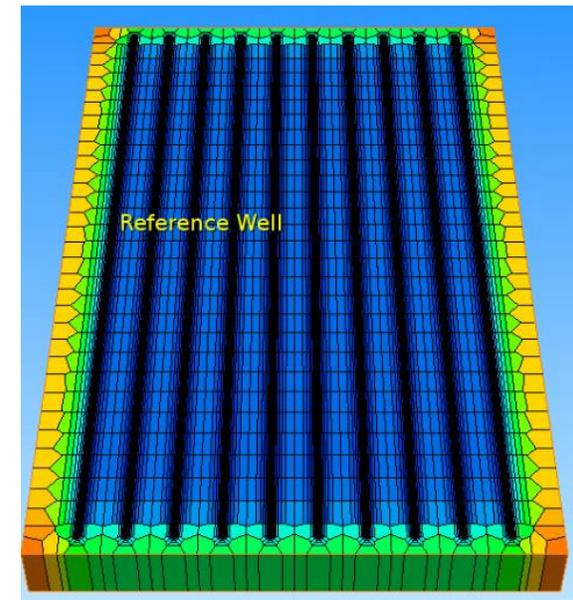# Is There a Correlation Between $A\sqrt{k}$ and EUR?
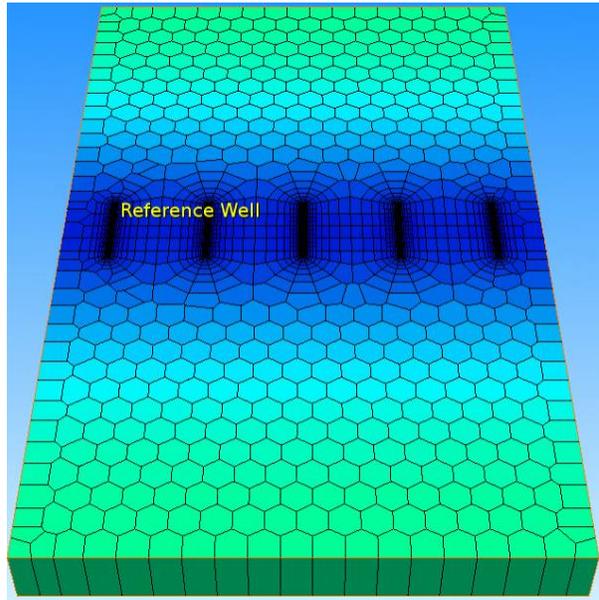
x_f = 95 ft.
N_f = 5
k = 0.005 md.
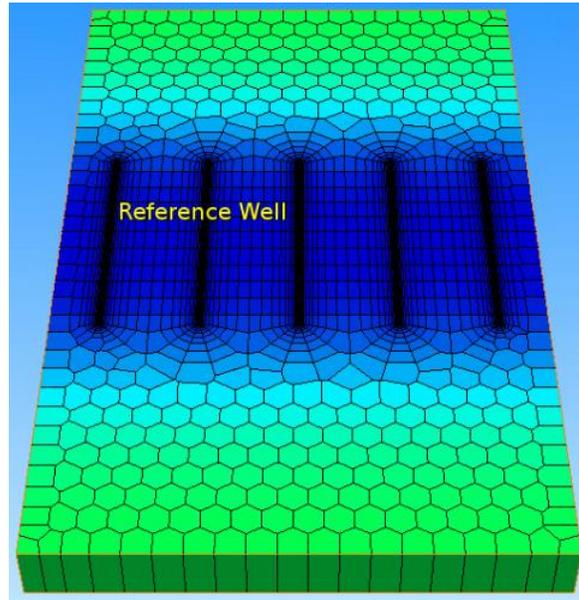
X_f = 300 ft.
N_f = 5
k = 0.0005 md.

X_f = 950 ft.
N_f = 5
k = 0.00005 md.

X_f = 950 ft.
N_f = 10
k = 0.00005 md.

	x_f (ft.)	N_f	k (md.)	$A\sqrt{k}$ (ft^2*$\sqrt{md}$)	EUR (bbl)	Unbounded EUR (bbl)
Case 1	95	5	0.005	20124	95219	366974
Case 2	300	5	0.0005	20124	95263	113004
Case 3	950	5	0.00005	20124	93535	109867
Case 4	950	10	0.00005	40249	95057	114542

Is There a Correlation Between A√k and EUR?

$x_f = 950$ ft.
$N_f = 1$
$k = 0.00005$ md.

$X_f = 950$ ft.
$N_f = 3$
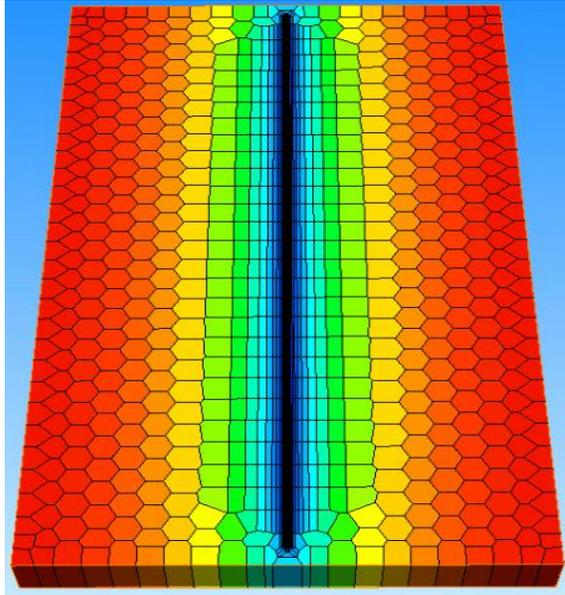$k = 0.00005$ md.

$X_f = 950$ ft.
$N_f = 5$
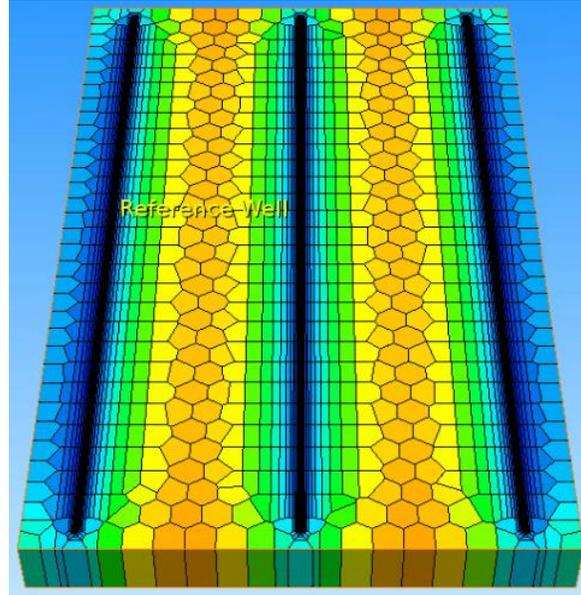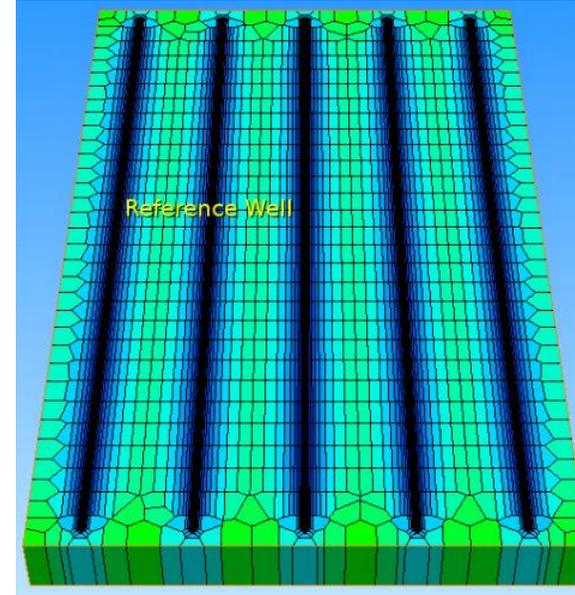$k = 0.00005$ md.
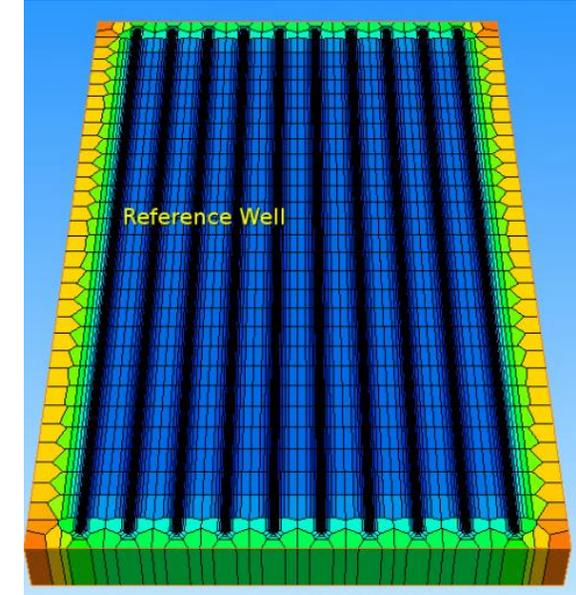
$X_f = 950$ ft.
$N_f = 10$
$k = 0.00005$ md.

	x_f (ft.)	N_f	k (md.)	$A\sqrt{k}$ (ft²*√md)	EUR (bbl)	Unbounded EUR (bbl)
Case 1	950	1	0.00005	4024	27933	28988
Case 2	950	3	0.00005	12074	72817	86426
Case 3	950	5	0.00005	20124	93535	109867
Case 4	950	10	0.00005	40249	95057	114542

Affects of Common Assumptions on Simple Fracture Systems
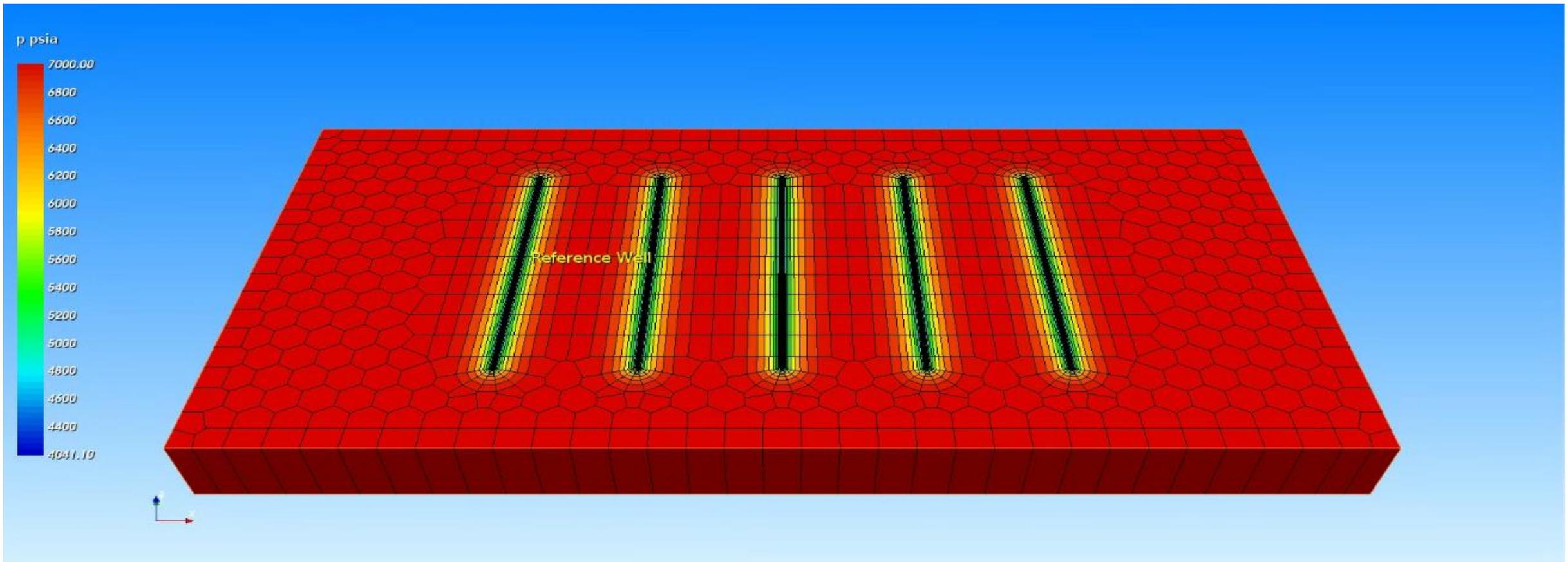
Assumption	x_f (ft)	N_f	$A\sqrt{k_t}$	k_o (md)	Oil EUR (STB)	Gas EUR (MMSCF)	Water EUR (STB)
Actual	300	5	20125	3.04E-05	56989	211	236803
1 Fracture / Stage	500	5	20125	1.10E-05	53699	230	230427
50% Cluster Efficiency	500	25	20125	4.38E-07	50799	206	221947
100% Cluster Efficiency	500	50	20125	1.10E-07	50211	210	222083

N$_f$ vs. EUR (x$_f$ = 300ft and k = 0.0005 md.)

Eventually adding more fractures does not increase the EUR

EUR (bbl)

Number of Fractures
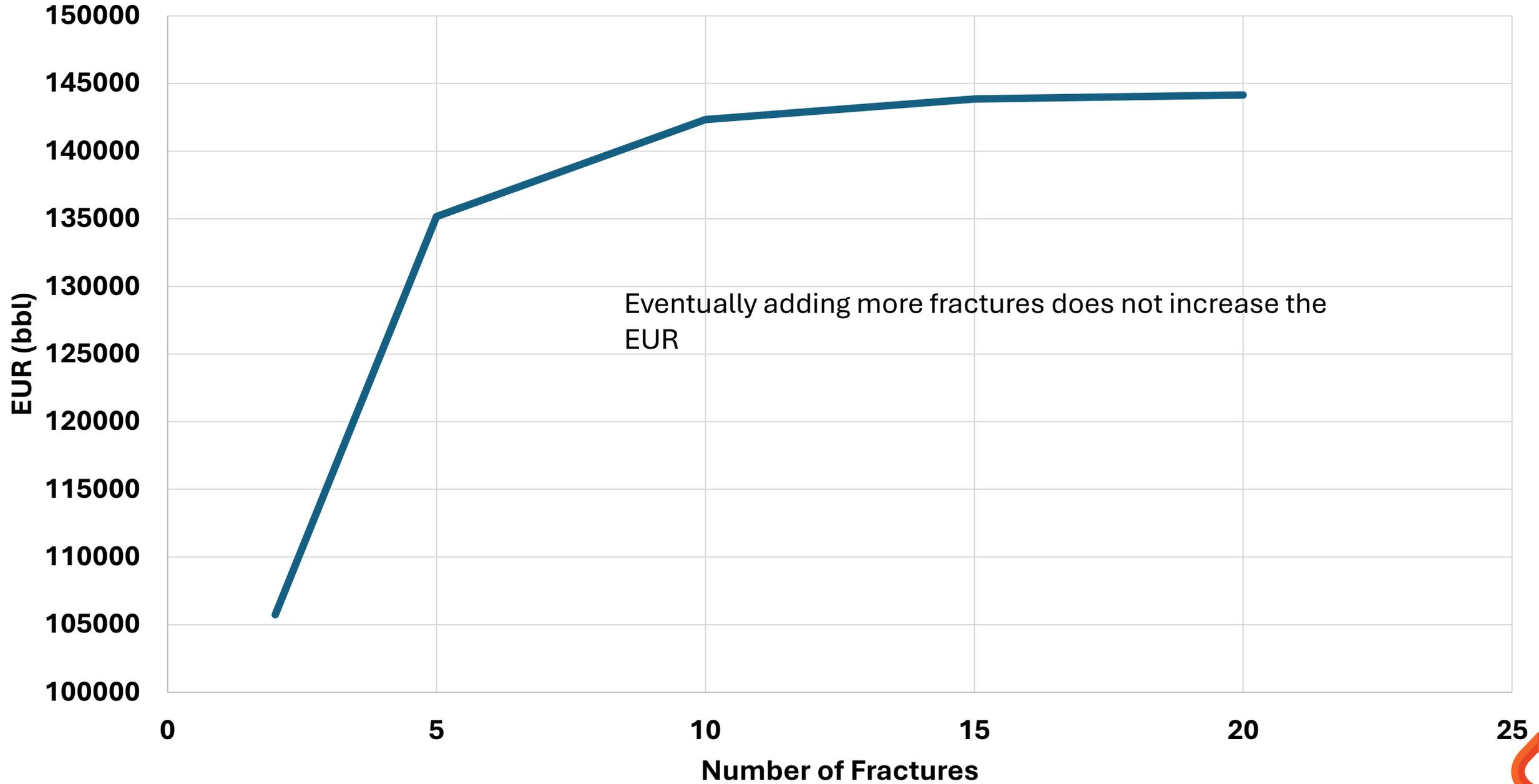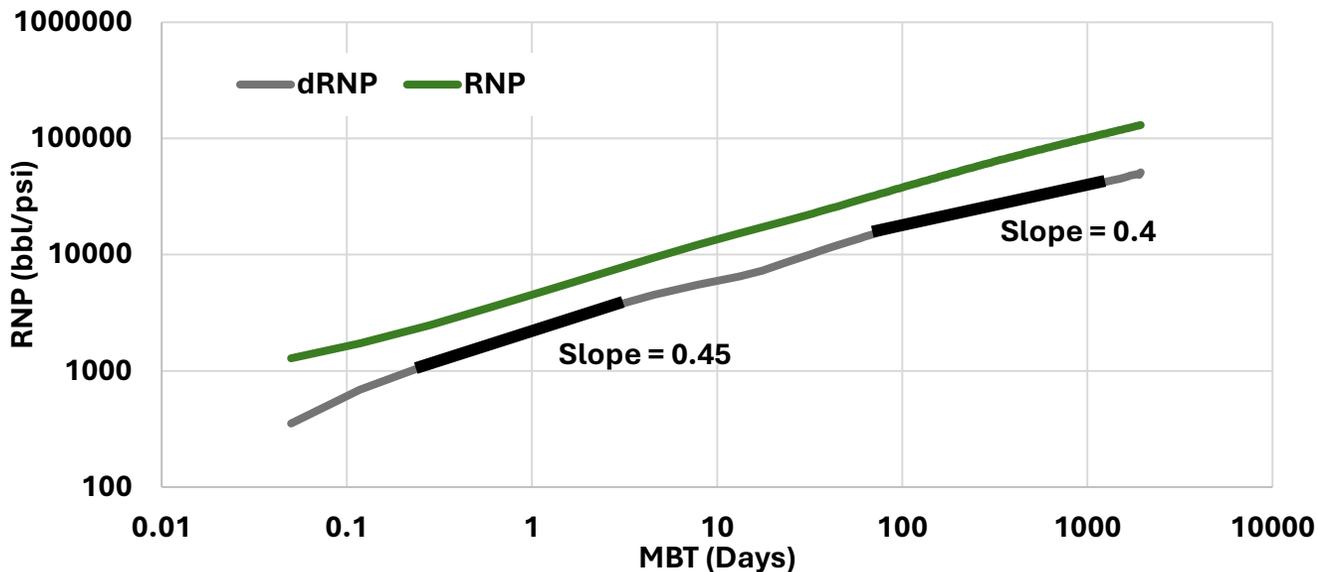
What does this tell us?

- $A\sqrt{k}$ can different for wells with the same drainage volume but have different permeability (k) and fracture area and the EUR will be the same if the well is sufficiently stimulated to drain the available volume within an economic time frame. Increasing $A\sqrt{k}$ will only accelerate production

- $A\sqrt{k}$ can be the same for wells with different drainage volumes and the EUR will be different. The well with the highest perm will have the fastest recovery and highest EUR.

- $A\sqrt{k}$ can correlate to EUR if a well is not sufficiently stimulated to drain the available reservoir volume.

- If a well is sufficiently stimulated to drain the available volume the assumption for permeability and Area does not need to be correct and the EUR will be reasonably accurate.
  - Can we assume wells in North America are sufficiently stimulated with a well defined volume (spacing)?
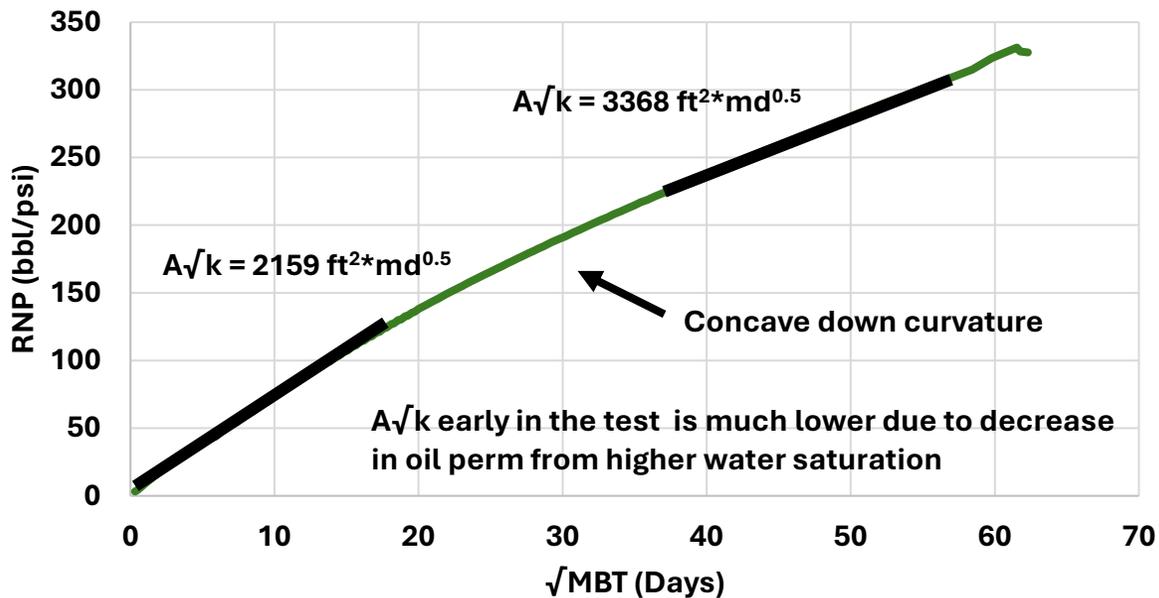
6 Month Production History
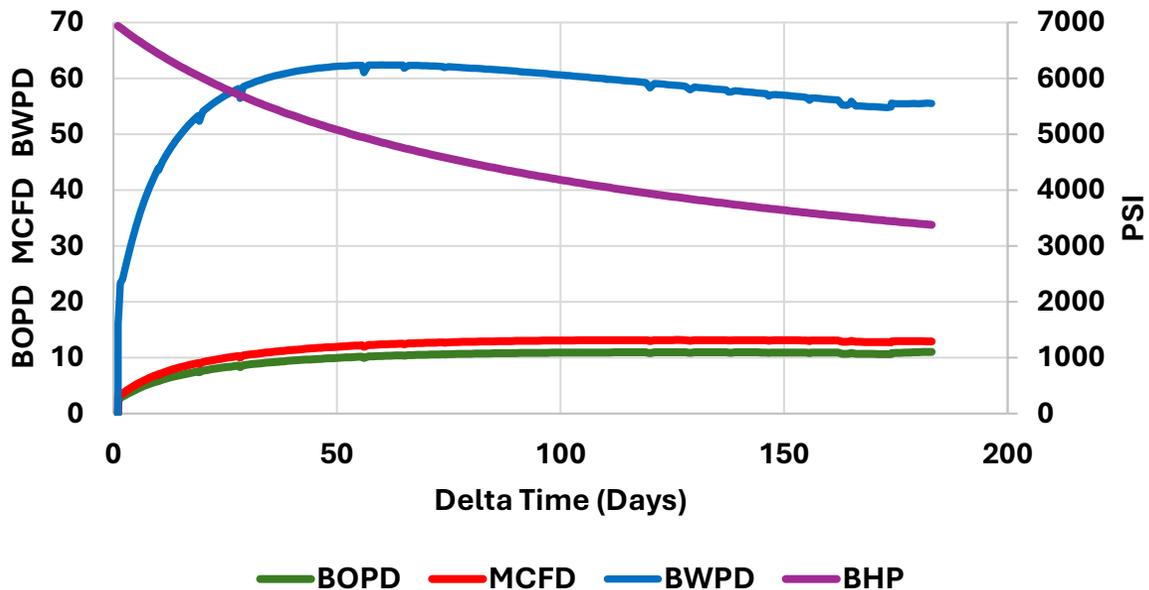
Oil Log-Log Plot (65% Sw)

Slope = 0.4

Slope = 0.45

Oil Linear Flow Plot (65% Sw)

$A\sqrt{k} = 3368 \text{ ft}^2 * md^{0.5}$

$A\sqrt{k} = 2159 \text{ ft}^2 * md^{0.5}$

Concave down curvature

$A\sqrt{k}$ early in the test is much lower due to decrease in oil perm from higher water saturation

Production Ratios

GWR & WOR diverging due to changing saturations
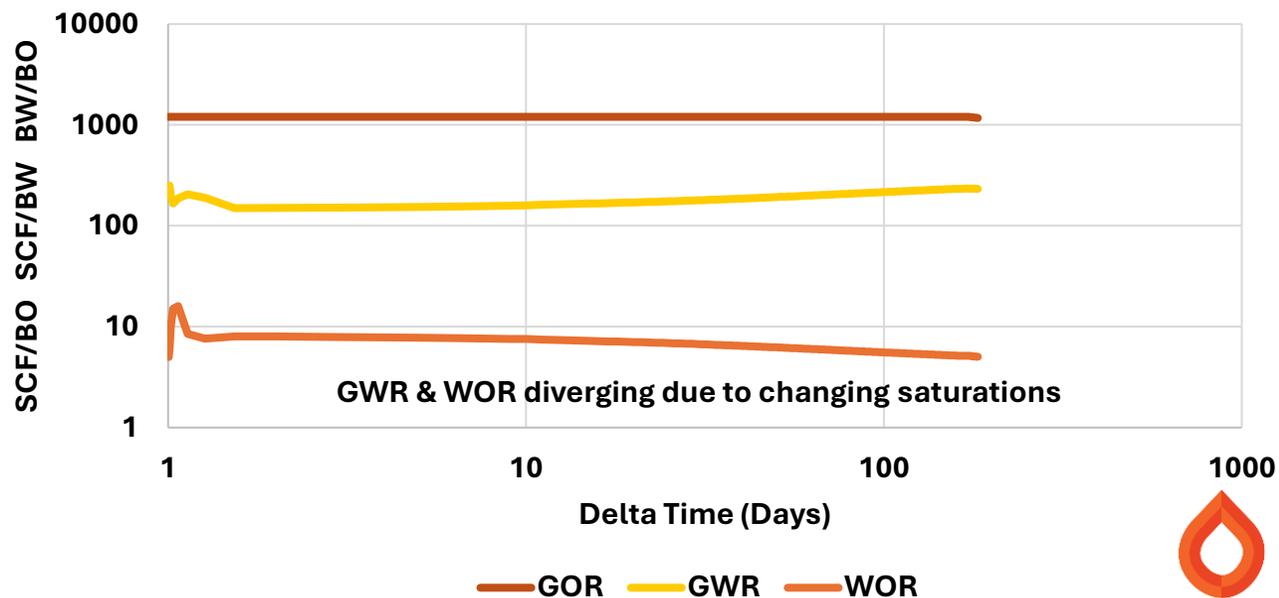
Oil - Water Relative Permeability
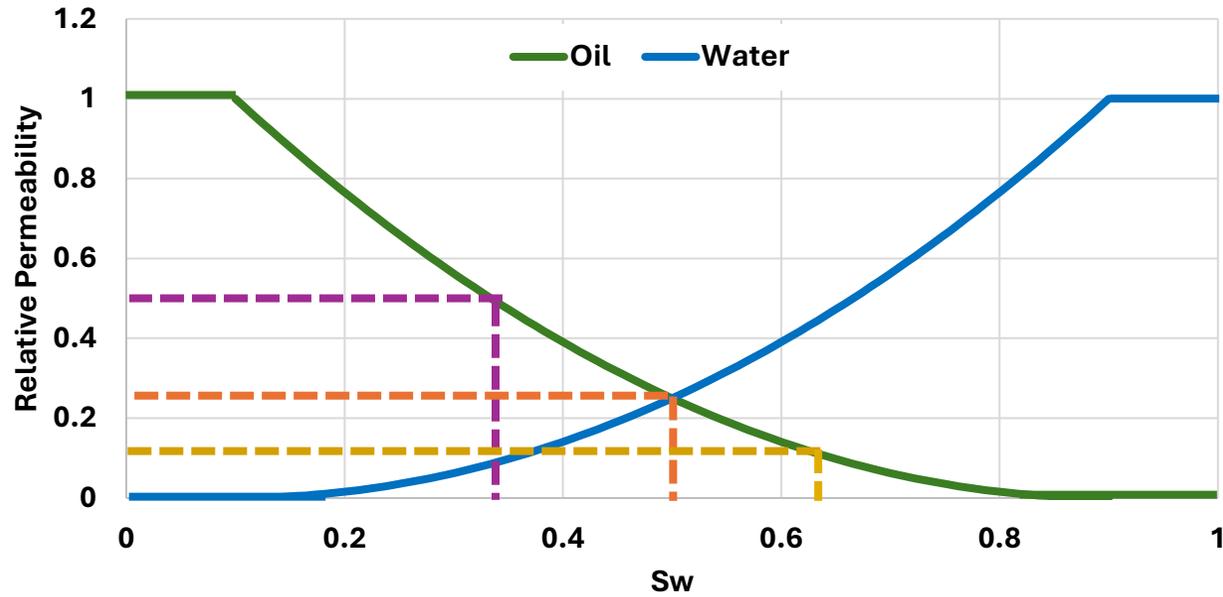
Water Sat. (%)	Krow	Krwo	$A\sqrt{k_o}$ (ft²*md$^{0.5}$)
35	0.47	0.09	12599
50	0.25	0.25	7083
65	0.09	0.47	2893

** $A\sqrt{k}$ for our 5-fracture model should be 21124 ft²*md$^{0.5}$
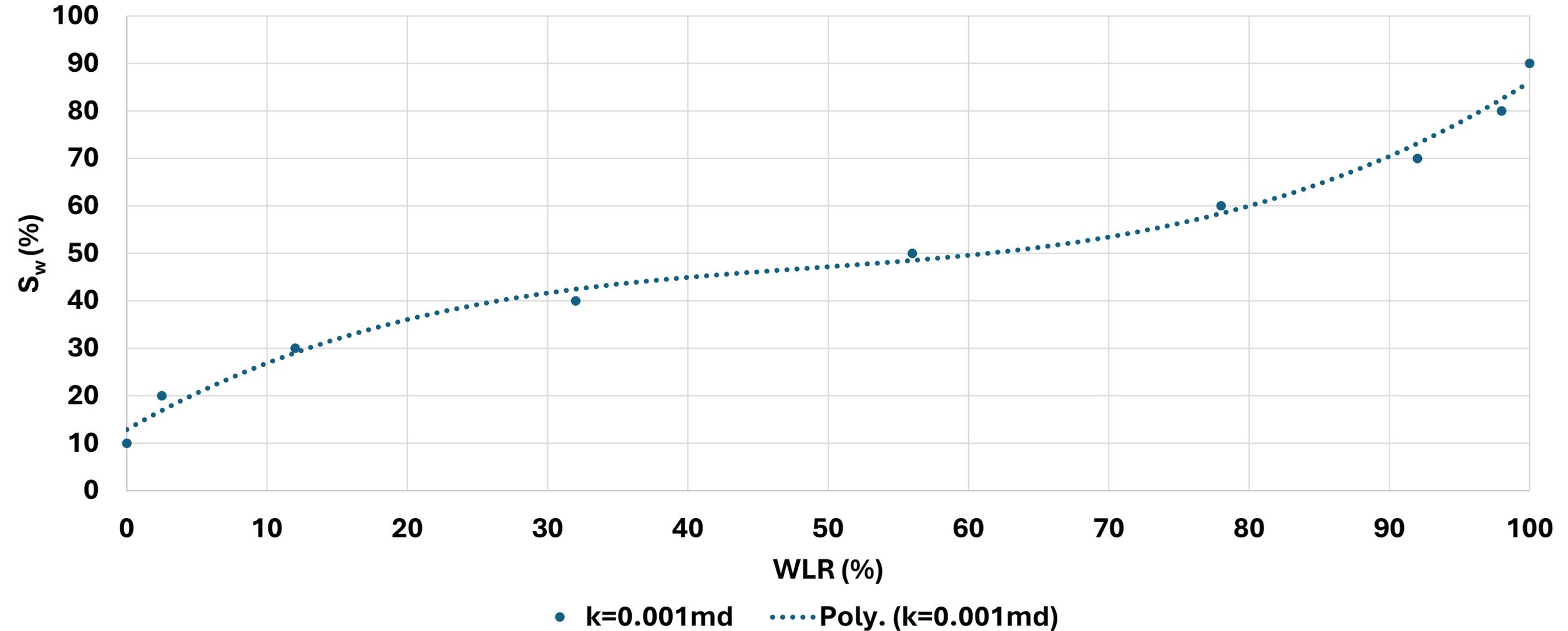
Oil Linear Flow Plot Comparison
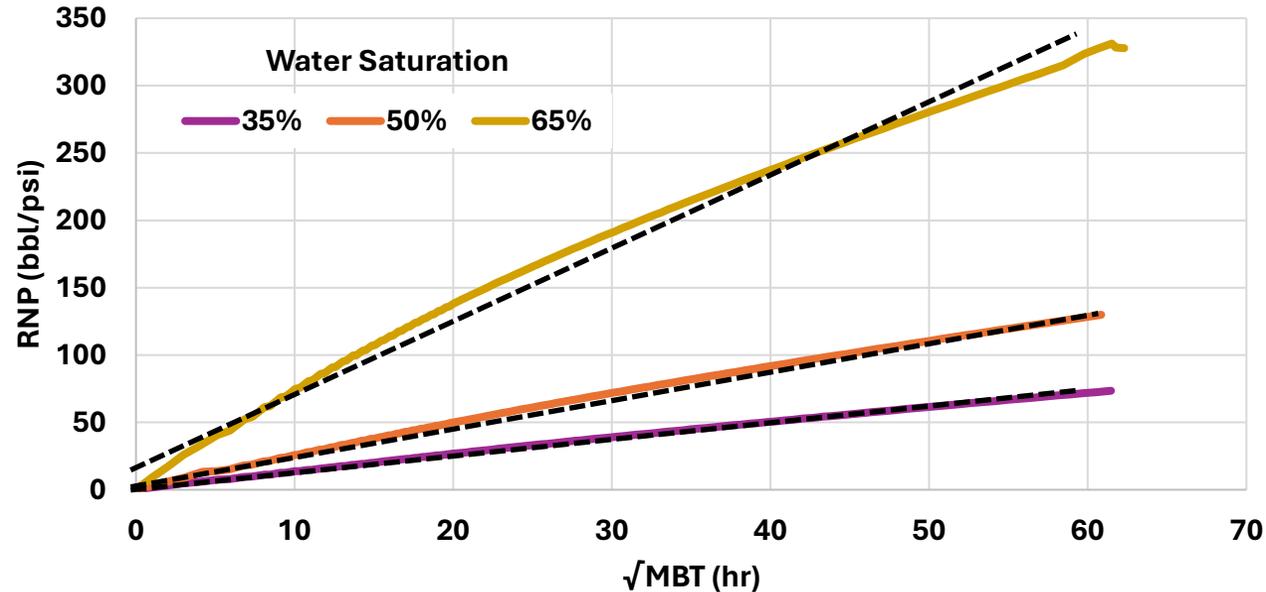
- As water saturation increases the relative permeability to oil decreases.

- As the relative permeability to oil decrease the $A\sqrt{k_o}$ decreases.

- If there is a higher water saturation in the pore space there is less oil but also less permeability to oil so it is harder for the oil to flow.

S$_w$ vs WLR

- k=0.001md ······ Poly. (k=0.001md)
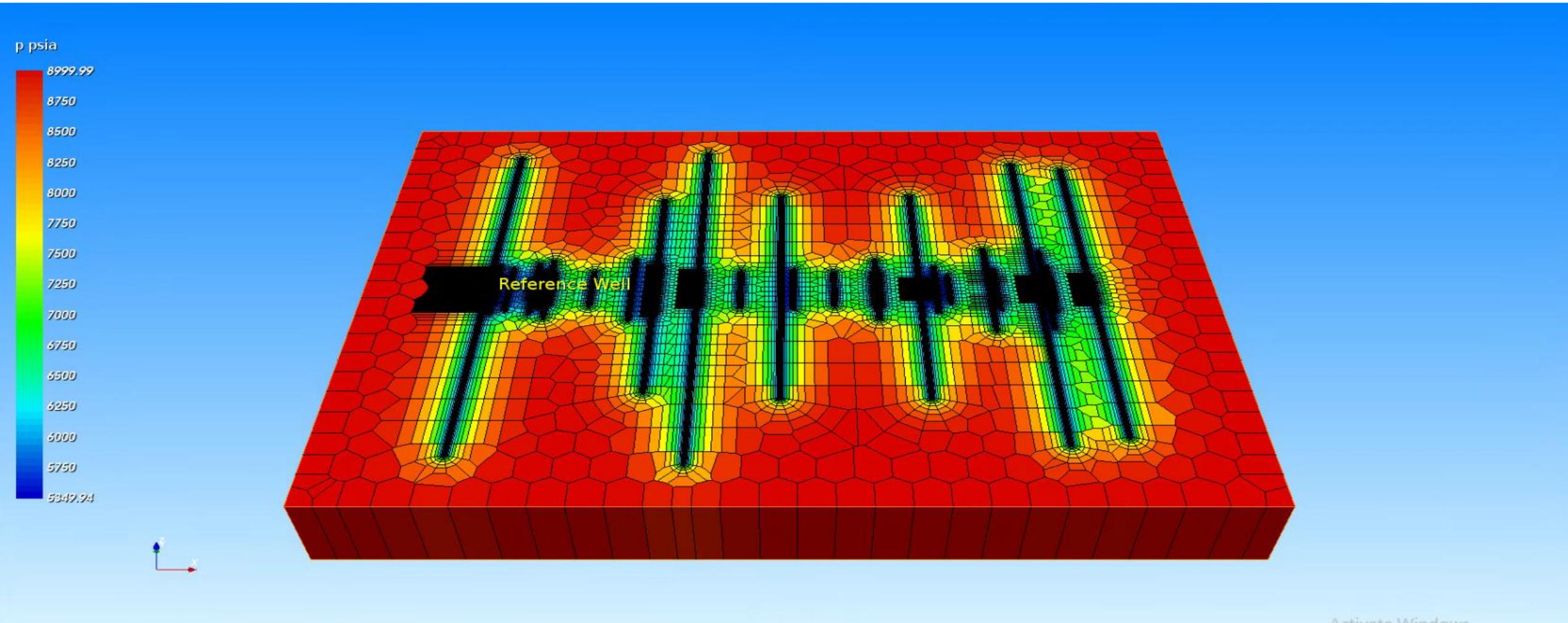
- If you are unsure about water saturation make a simple model with ball park parameters
- This example uses standard water/oil rel. perm. curve w/ 5% porosity and 0.001md total perm
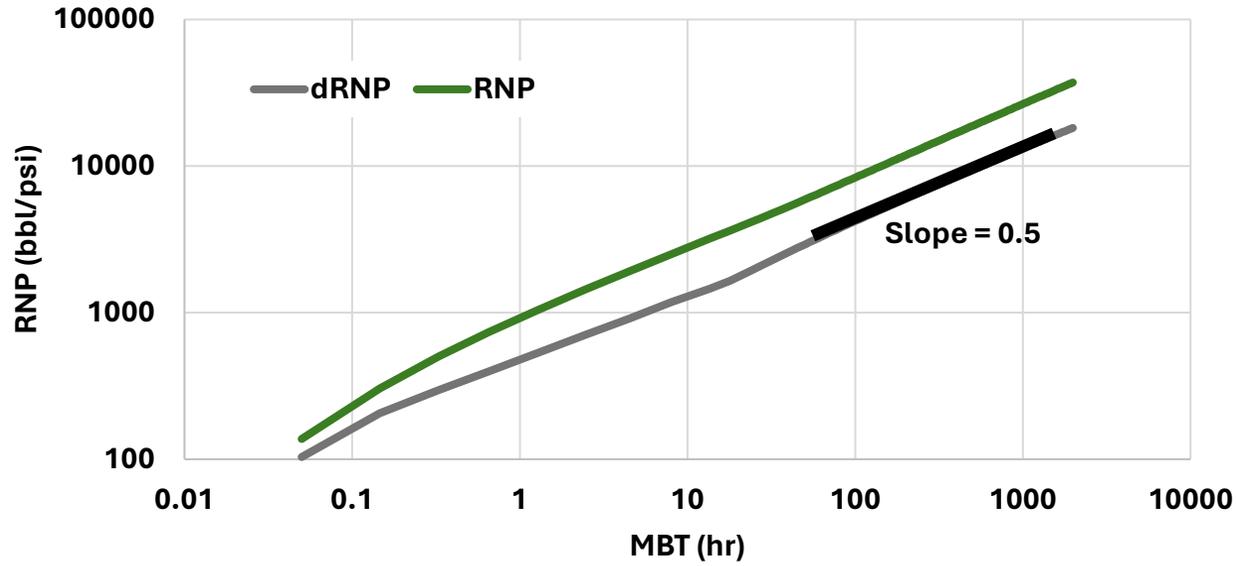- Helps us see if the water saturation estimate is close based on produced WLR.

Common Assumptions on Complex Fracture Systems

6 Month Single Phase Oil Production History

20 Day Initial Production ("Flowback") Period

BOPD

PSI

Delta Time (Days)

BOPD ——— BHP

Log-Log Plot

RNP (bbl/psi) vs MBT (hr)

Slope = 0.5

Linear Flow Plot

RNP vs √MBT (hr)

$A\sqrt{k} = 21124$ ft^2*md$^{0.5}$

Log-Log Plot (FB Excluded)

RNP (bbl/psi) vs MBT (hr)

Slope = 0.6

False Indication of Power Law Behavior
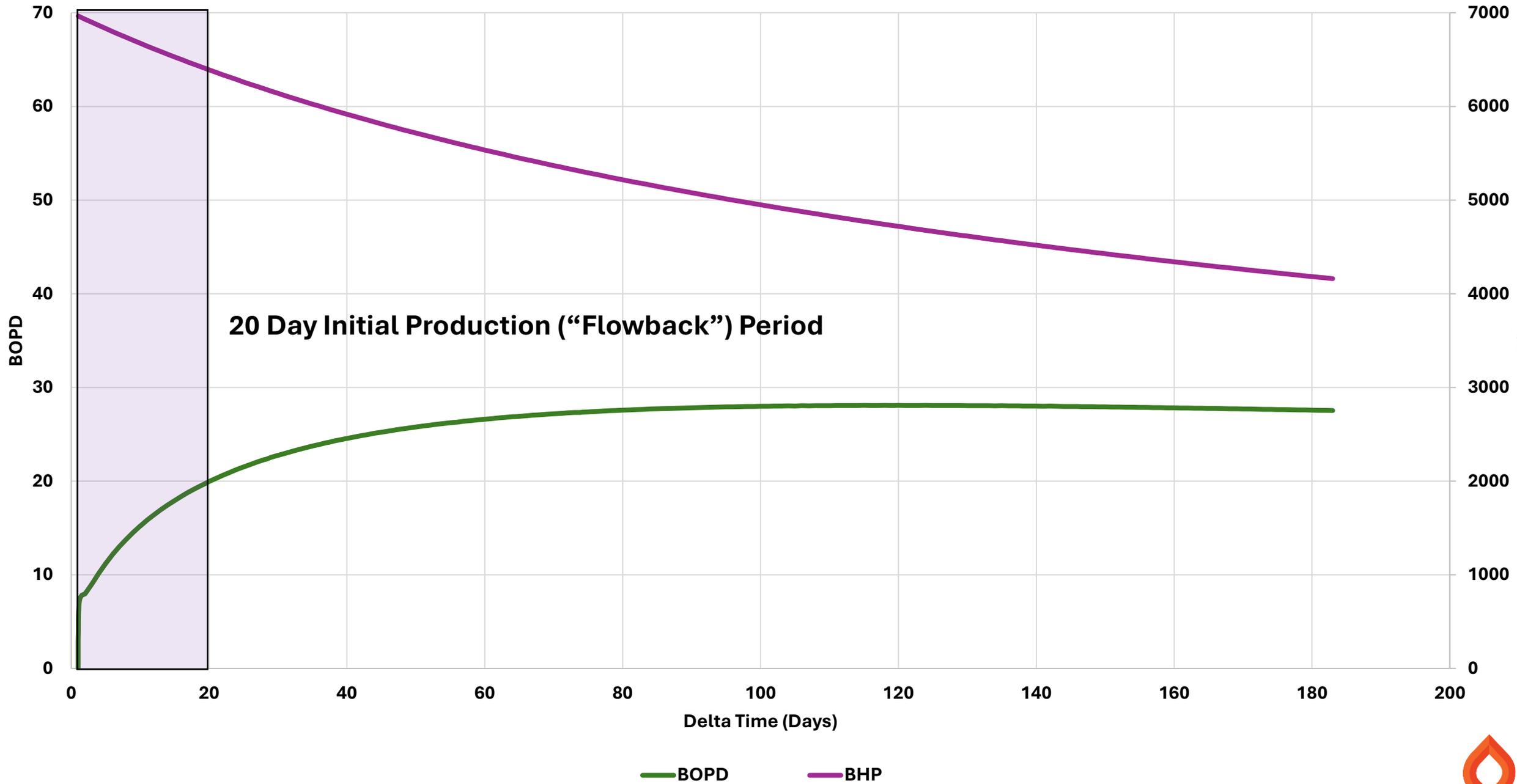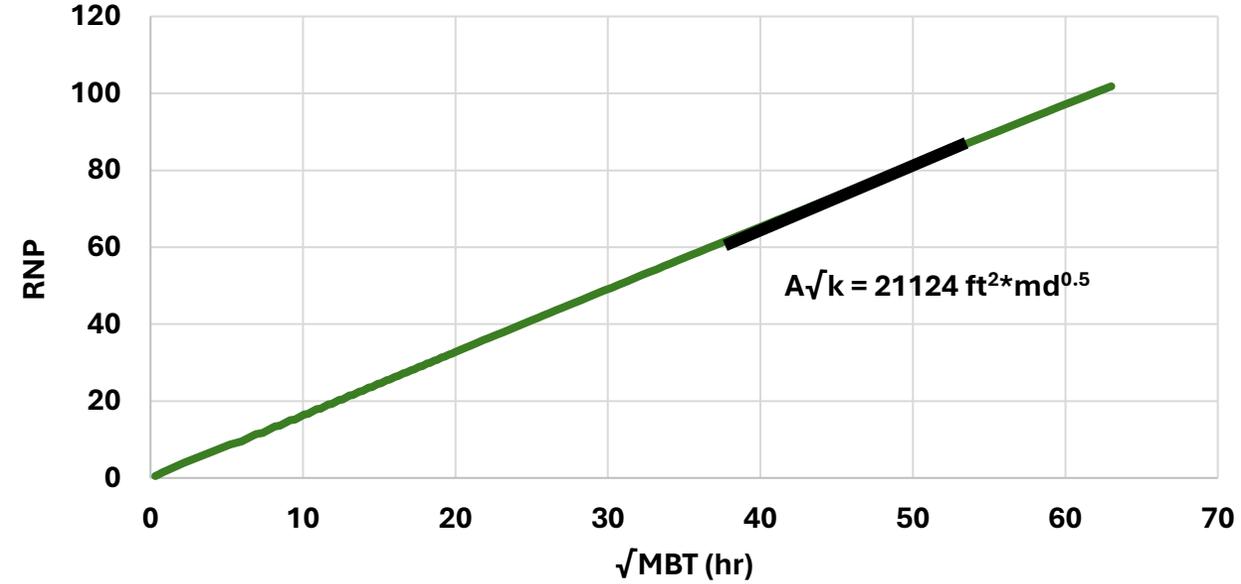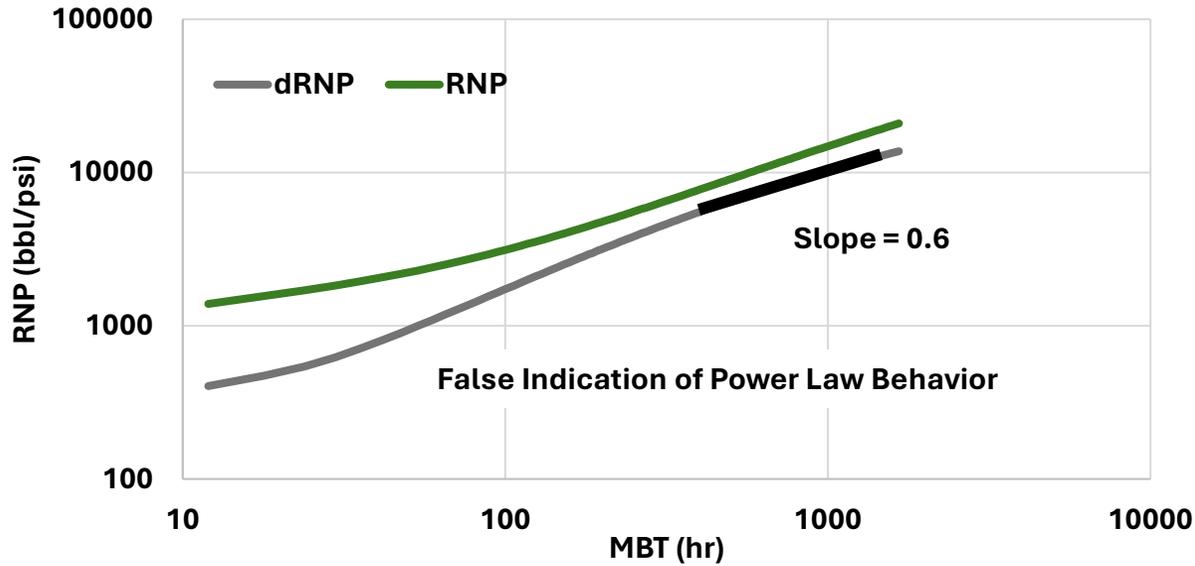
Linear Flow Plot (FB Excluded)

RNP vs √MBT (hr)

Concave up curvature

$A\sqrt{k} = 23468$ ft^2*md$^{0.5}$

A√k is over estimated!

Eagleford Well 1

500 hrs. Initial Production Data

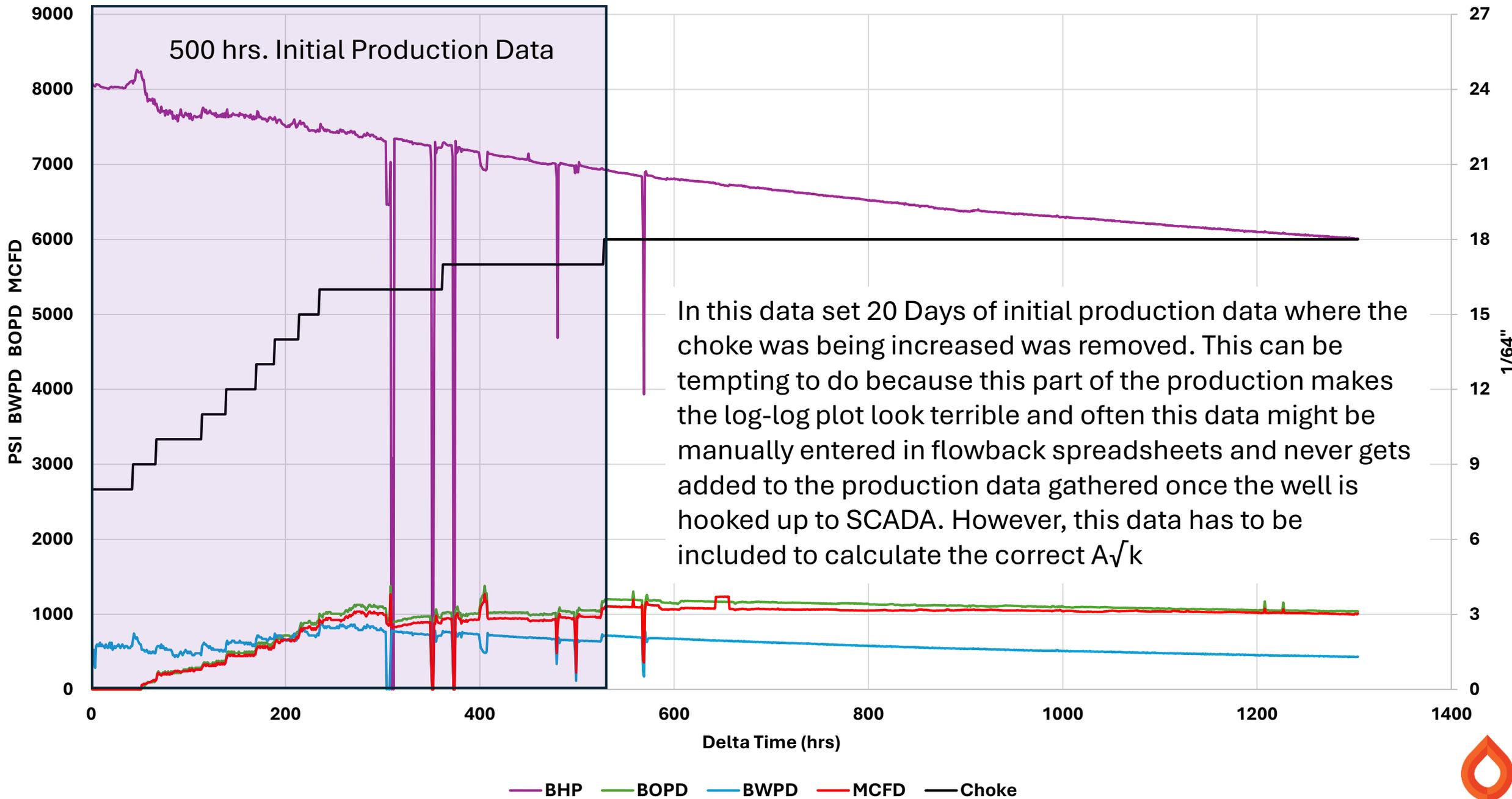In this data set 20 Days of initial production data where the choke was being increased was removed. This can be tempting to do because this part of the production makes the log-log plot look terrible and often this data might be manually entered in flowback spreadsheets and never gets added to the production data gathered once the well is hooked up to SCADA. However, this data has to be included to calculate the correct $A\sqrt{k}$

PSI BWPD BOPD MCFD

1/64"

Delta Time (hrs)

—— BHP —— BOPD —— BWPD —— MCFD —— Choke

Not Including Full Rate History: Field Example

Log-Log Plot

- dRNP - RNP

Slope = 0.5

RNP (bbl./psi) vs MBT (hr)

Linear Flow Plot

Nice straight linear trend correlates to when we see the 0.5 slope on the log-log plot

Correct A√k = 228629 ft^2*md^{½}

RNP (bbl./psi) vs √MBT (hr)

Log-Log Plot (500 hr. Initial Production Data Removed)
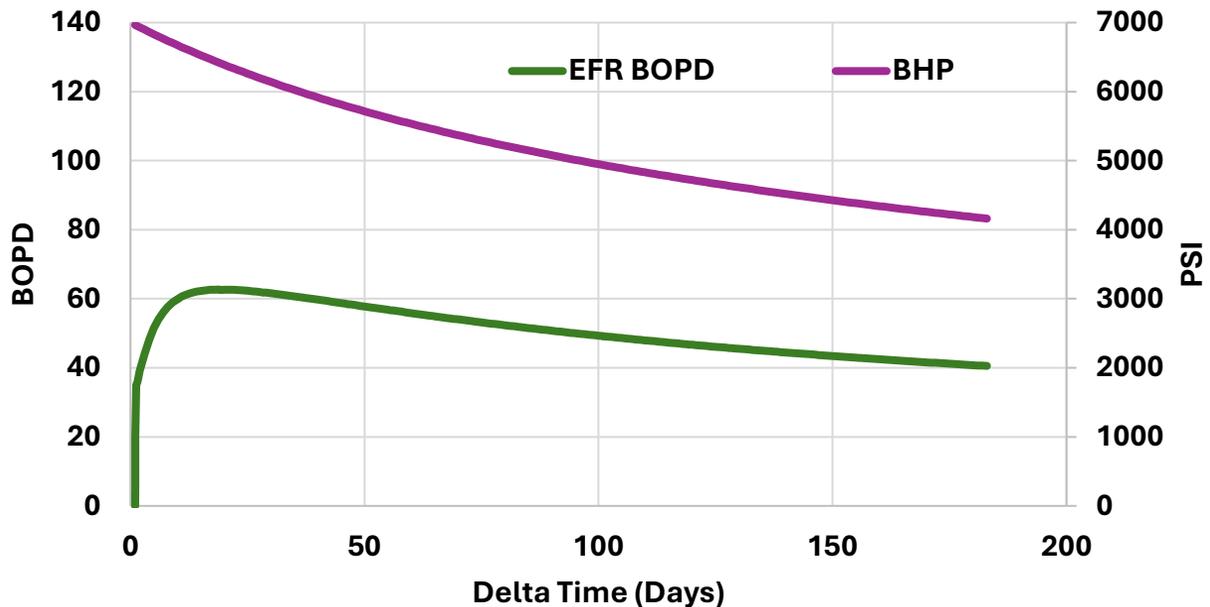
- dRNP - RNP

Slope = 1

False indication of boundary dominated behavior

RNP (bbl./psi) vs MBT (hr)

Linear Flow Plot (500 hr. Initial Production Data Removed

Not Including the Initial Production Data causes an over estimation of Linear Flow Parameter!!

Incorrect A√k = 335265 ft^2*md^{½}

Curvature not due to reservoir

Where do we pick a spot on here when we don't see linear flow on the log-log?

RNP (psi/bbl.) vs √MBT (hr)

EFR Production History

BOPD / PSI versus Delta Time (Days)

Legend: EFR BOPD, BHP

Single Phase EFR

RNP (psi/bbl) versus MBT(hr)

Legend: dRNP, RNP

Slope = 0.8

Slope = 0.5

Linear Flow Plot

RNP (bbl/psi) versus √MBT

Concave up curvature

$A\sqrt{k} = 47625 \ ft^2 \cdot md^{0.5}$

Correct $A\sqrt{k} = 21124 \ ft^2 \cdot md^{0.5}$

* $A\sqrt{k}$ is a combination of matrix and EFR

Matrix

EFR

Radius: 5ft.
Perm: 10x
Porosity: 5x

Wellbore

Multiphase EFR 6 Month Production History

Legend: BHP, BOPD, BWPD, MCFD, Choke

Axes: PSI BWPD / BOPD MCFD 1/64" vs Delta Time (hrs)

1 Pz Oil / 3Pz EFR No Stim. Fluid w Chokes

Legend: dRNP, RNP

Slope = 0.8

Axes: RNP (psi/bbl) vs MBT(hr)

Single Phase Oil Linear Flow Plot

A√k = 30456 ft^2*md$^{0.5}$

Correct A√k = 21124 ft^2*md$^{0.5}$

Axes: RNP (psi/bbl) vs √MBT (hr)

Production Ratios

GWR & WOR show gradual divergence early on

Legend: GOR, GWR, WOR

Axes: SCF/BO SCF/BW BW/BO vs Delta Time (hr)

Multiphase EFR 6 Month Production History

Legend: BHP, BOPD, BWPD, MCFD, Choke

Analysis Period

X-axis: Delta Time (hrs); Left Y-axis: PSI BWPD; Right Y-axis: BOPD MCFD 1/64"

1 Pz Oil/3Phz EFR Flowback Excluded

Legend: dRNP, RNP

Slope = 1 Boundary?

Y-axis: RNP (psi/bbl); X-axis: MBT(hr)

Single Phase Oil Linear Flow Plot

$A\sqrt{k} = 8446 \text{ ft}^2 * md^{0.5}$

Y-axis: RNP (psi/bbl); X-axis: $\sqrt{MBT}$ (hr)

Production Ratios

Y-axis: SCF/BO SCF/BW BW/BO; X-axis: Delta Time (hr)

Legend: GOR, GWR, WOR

Multiphase EFR 6 Month Production History

Legend: BHP, BOPD, BWPD, MCFD, Choke

Y-axis (left): PSI BWPD
Y-axis (right): BOPD MCFD 1/64"
X-axis: Delta Time (hrs)

1 Pz Oil / 3Pz EFR w Stim. Fluid & Chokes

Legend: dRNP, RNP
Slope = 0.65

Y-axis: RNP (psi/bbl)
X-axis: MBT (hr)

Single Phase Oil Linear Flow Plot

$A\sqrt{k} = 6689$ ft^2*md$^{0.5}$

Correct 1phz from 3phz $A\sqrt{k} \approx 3000$ ft^2*md$^{0.5}$
Correct Single Phase $A\sqrt{k} = 21124$ ft^2*md$^{0.5}$

Y-axis: RNP (psi/bbl)
X-axis: $\sqrt{MBT}$ (hr)

Production Ratios

GWR & WOR show fast divergence early on

Y-axis: SCF/BO SCF/BW BW/BO
X-axis: Delta Time (hr)

Legend: GOR, GWR, WOR

Permian Basin Well 1

Legend: WHP, BHP, BOPD, BWPD, MCFD, Choke

Axes: PSI BOPD MCFD BWPD (left), 1/64" (right), Delta Time (hr)

Single Phase Oil Log Log Plot

RNP, dRNP

Slope = 0.72

Axes: RNP (bbl/psi), MBT (hr)

Single Phase Oil Linear Flow Plot

Straight line trend identified after the well was online for 10 days

$A\sqrt{k_o} = 49908.7\ ft^2 * \sqrt{md}$

Axes: RNP (psi/bbl), $\sqrt{MBT}$ (hr)

Production Ratios

GOR constant (BHP>Psat), GWR & WOR Diverging

Legend: GOR, GWR, WOR

Axes: SCF/BO SCF/BW BW/BO, Delta Time (hr)

Permian Basin Well 1

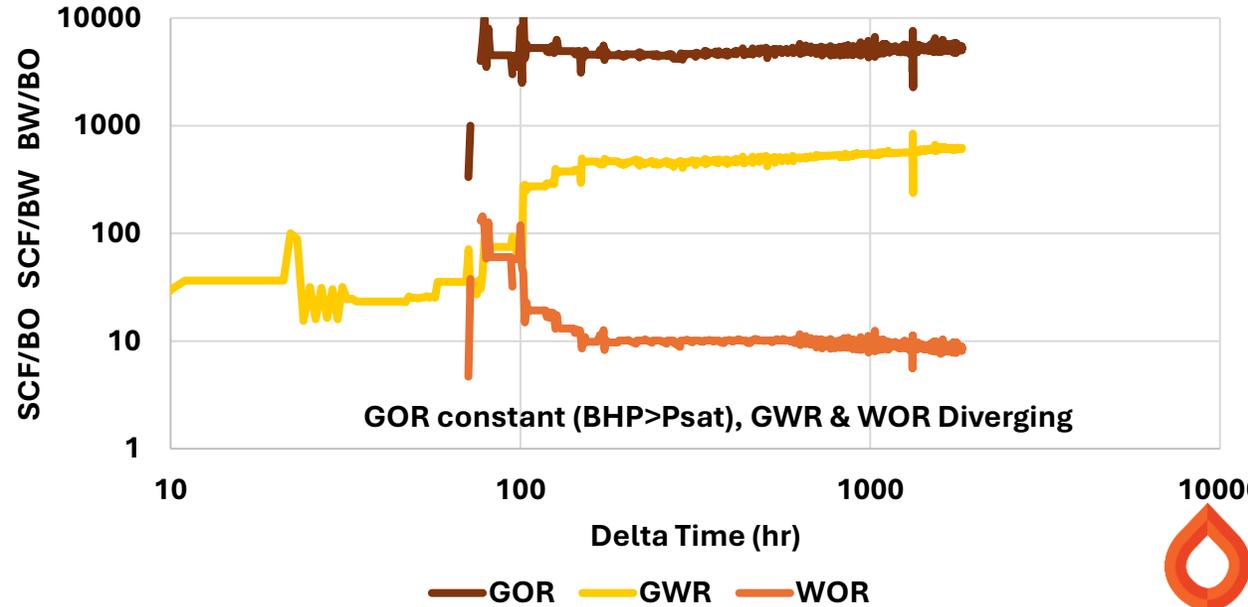Legend: WHP, BHP, BOPD, MCFD, MCFD (model), BOPD (model), BWPD (model), Res BOPD, Choke

Single Phase Oil Log Log Plot
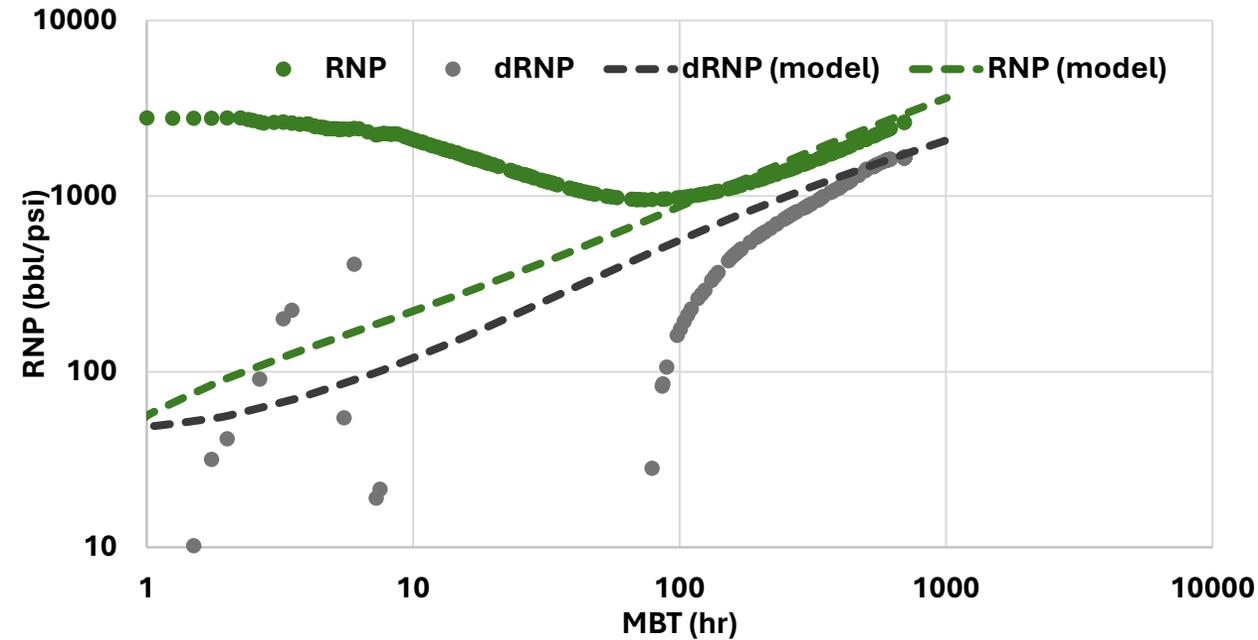
Single Phase Oil Linear Flow Plot

Cumulatives

50 Year EUR:
Oil: 503341 bbl
Gas: 4.08 BCF
Water : 1463218 bbl
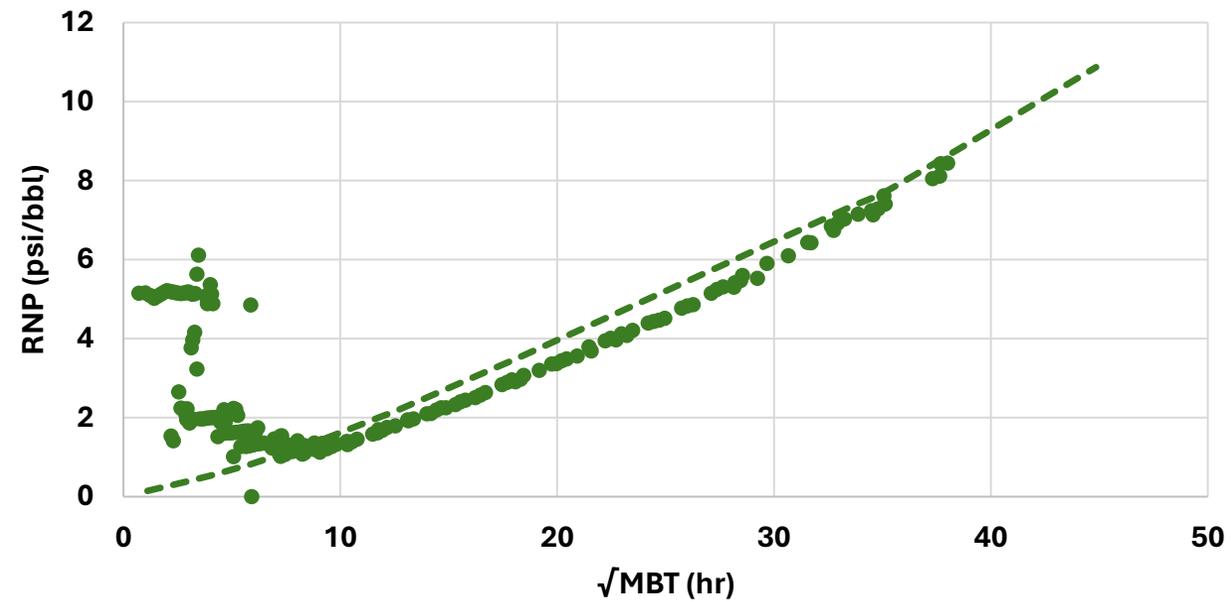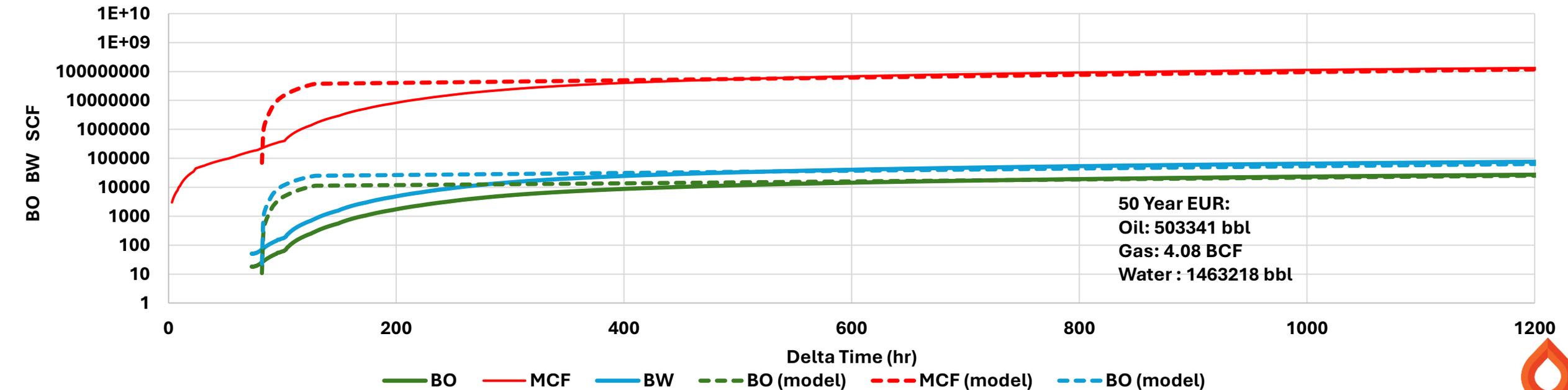
Conclusions

- A√k may or may not correlate with EUR. Simply assuming it does can lead to unrealistic expectations for EUR

- A√k along with assumptions for x_f / N_f or k can be used to seed numerical models and these parameters don't need to match the actual values for the EUR to be accurate.

- More complex fracture systems can be accurately modelled with less than a months worth of data.

- If you have no way of knowing water saturation or don't have that much confidence in the current estimates, simple models can be used to estimate water saturation from surface production ratios.

- Flowback data should be included in the analysis if the production period is short relative to the flowback period

- Choke changes do not affect flow regime identification

- Numerical EFR models applied to flowback/production data match the data very well when stimulation fluid is added in.

- EUR estimates using the EFR model are surprisingly accurate with a limited amount of data.

- Numerical models can have a considerable advantage over DCA for forecasting gas and forecasting in general when not a lot of data is available.