Keys to Achieving a Successful Waterflood and Estimating Waterflood Reserves

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Dr. William M. Cobb

William M. Cobb & Associates, Inc.

Petroleum Engineering & Geological Consultants

Dallas, Texas

PRIMARY RECOVERY VS WF

- **Primary Recovery**

  Requires the <u>Reservoir Pressure be Constantly Declining</u>

- **Waterflooding is**

  1. A Displacement Process
  2. Most Efficient When Reservoir Pressure is Maintained or Increased

PRIMARY RECOVERY VS WF

- **When converting from primary to waterflooding**

1. The reservoir recovery mechanism changes.

2. Consequently reservoir evaluation and reservoir management procedures generally need to be changed

WHAT ARE THE KEY FACTORS THAT DRIVE THE OUTCOME OF A WATER INJECTION PROJECT?

$$Np \propto N * E_A * E_V * E_D$$

N_P = Cumulative Waterflood Recovery, BBL.

N = Oil in Place at Start of Injection, BBL.

E_A = Areal Sweep Efficiency, Fraction

E_V = Vertical Sweep Efficiency, Fraction

E_D = Displacement Efficiency, Fraction

WATERFLOOD RECOVERY FACTOR

$$\frac{N_p}{N} = RF$$

$$RF \propto \underbrace{E_A * E_V}_{E_{VOL}} * E_D$$

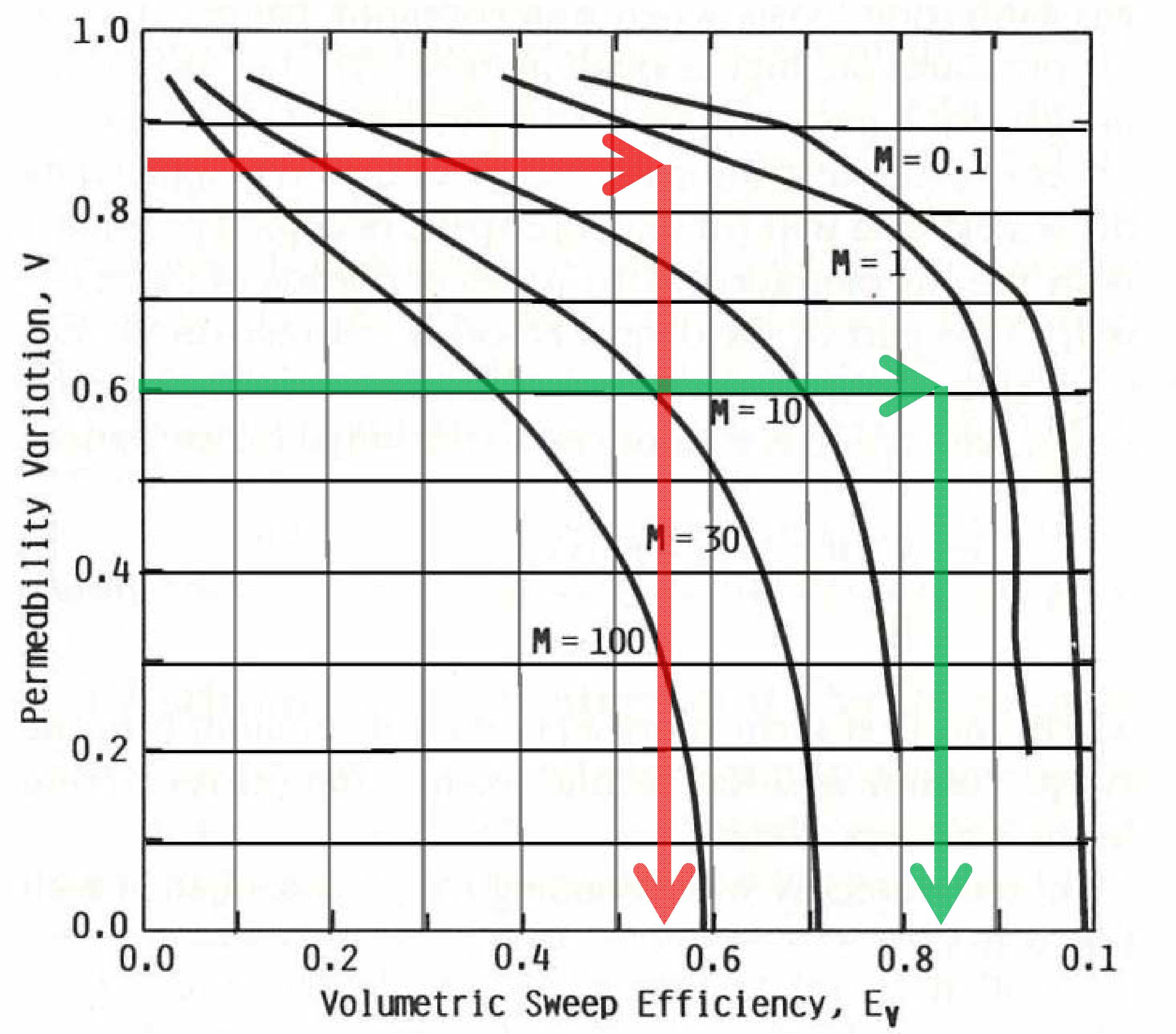
E_A = f (MR, Pattern, Directional Permeability, Pressure Distribution, Cumulative Injection & Operations)

E_V = f (Rock Property variation between different flow units, Cross-flow, MR)

E_{VOL} = Volumetric Sweep of the Reservoir by Injected Water

E_D = f (Primary Depletion, S_o, $\bar{S}_o$, K_{rw} & K_{ro}, μ_o & μ_w)

Willhite's Correlation for Five Spot Volumetric Sweep Efficiency with WOR = 50.



THE QUARTERBACK OF ALL INJECTION PROJECTS IS THE INJECTION WELL

Properly Locate Injection Wells:

- ✓ **They provide appropriate areal distribution of the injected water**
- ✓ **They deliver the water at the correct time**
- ✓ **They deliver the water in the proper volume**
- ✓ **Effective utilization of injection wells is the important key to optimizing the WF by allowing EA and EV values and RF to be maximized**

Quarterback Continued…

- ✓Injectors and producers are located to form confined patterns
- ✓Patterns take advantage of K_X/K_Y
- ✓Injection profiles are monitored and effectively managed
- ✓The most efficient waterfloods are when the injection to production well count ratio is near 1:1 (I/P > 1.0 not always bad)
- ✓Good producers make good injectors - bad producers make bad injectors

Waterflood Reserve Forecasting

1. Numerical simulation
   - ✓Detailed geological description
   - ✓Reliable PVT and relative permeability
   - ✓Accurate history matching of production and pressure on a <u>well by well basis</u>

Waterflood Reserve Forecasting

2. Decline curve analysis by well

   ✓Rate versus time should be used with caution

   ✓Rate versus cumulative oil should be used with caution

   ✓Log WOR versus cumulative oil when WOR > 2.0 is probably best

   ✓Reliable forecast require accurate well tests

PRODUCTION RATE DEPENDS ON INJECTION RATE

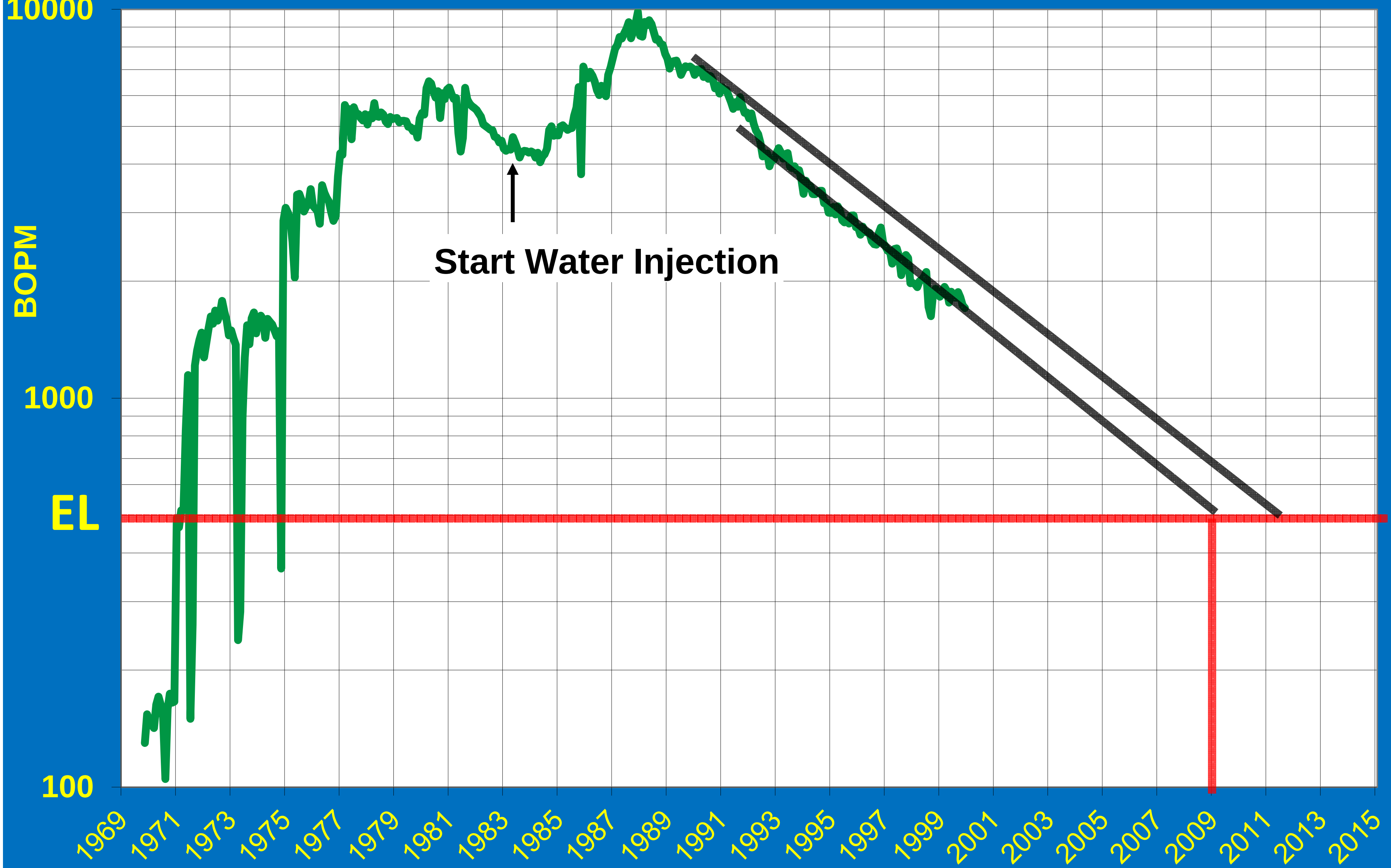
$$q_o = \frac{i_w * f_o}{B_o} = \frac{i_w(1 - f_w)}{B_o}$$

$$q_W = \frac{i_w \ * \ f_o}{B_W}$$

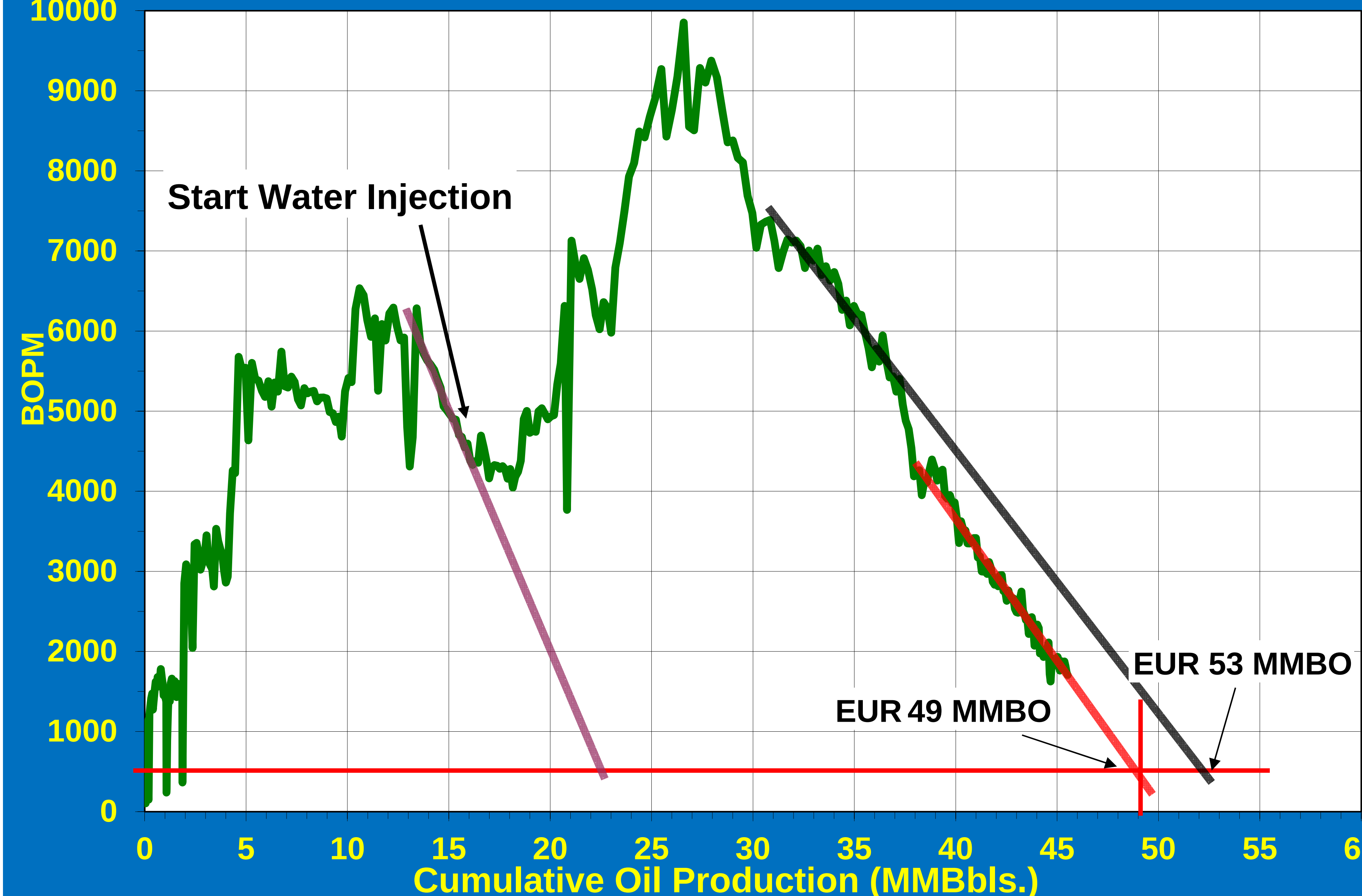
Conclusion

Oil and water production rates are directly related to injection rates. Therefore, DCA of q_o vs t or q_o vs N_P must be evaluated only after giving consideration to historical and projected water injection rates.

WATERFLOOD EXPONENTIAL DECLINE



OIL RATE VS CUMULATIVE OIL PRODUCED



OIL RATE VS CUMULATIVE OIL PRODUCED

WOR IS INDEPENDENT OF INJECTION RATE BUT DEPENDENT ON STRATIFICATION

$$WOR = \frac{q_w}{q_o}$$

$$\text{WOR} = \frac{i_w \ * \ f_w}{i_w \ * \ (1 - f_w)}$$

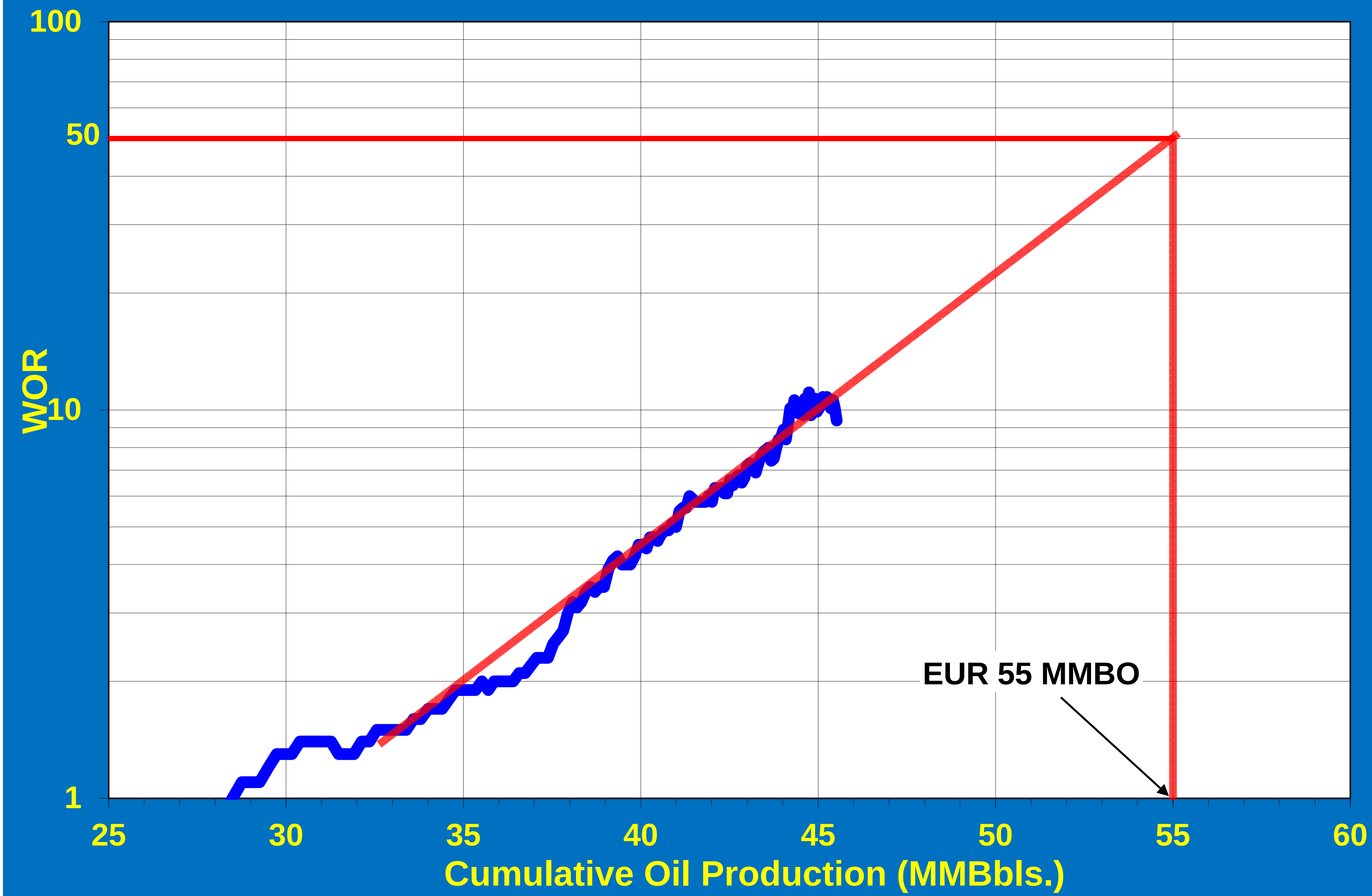
$$\text{WOR} = \frac{f_w}{(1 - f_w)}$$

$$(WOR)_{STD.\,COND.} = \frac{f_w}{(1-f_w)} * \frac{B_o}{B_w}$$

<u>Conclusion</u>

- ✓ **WOR is independent of injection rate**
- ✓ **WOR should be applied to individual wells and not field**
- ✓ **WOR should be applied using values greater than 2.0**

WATER OIL RATIO VS CUMULATIVE OIL



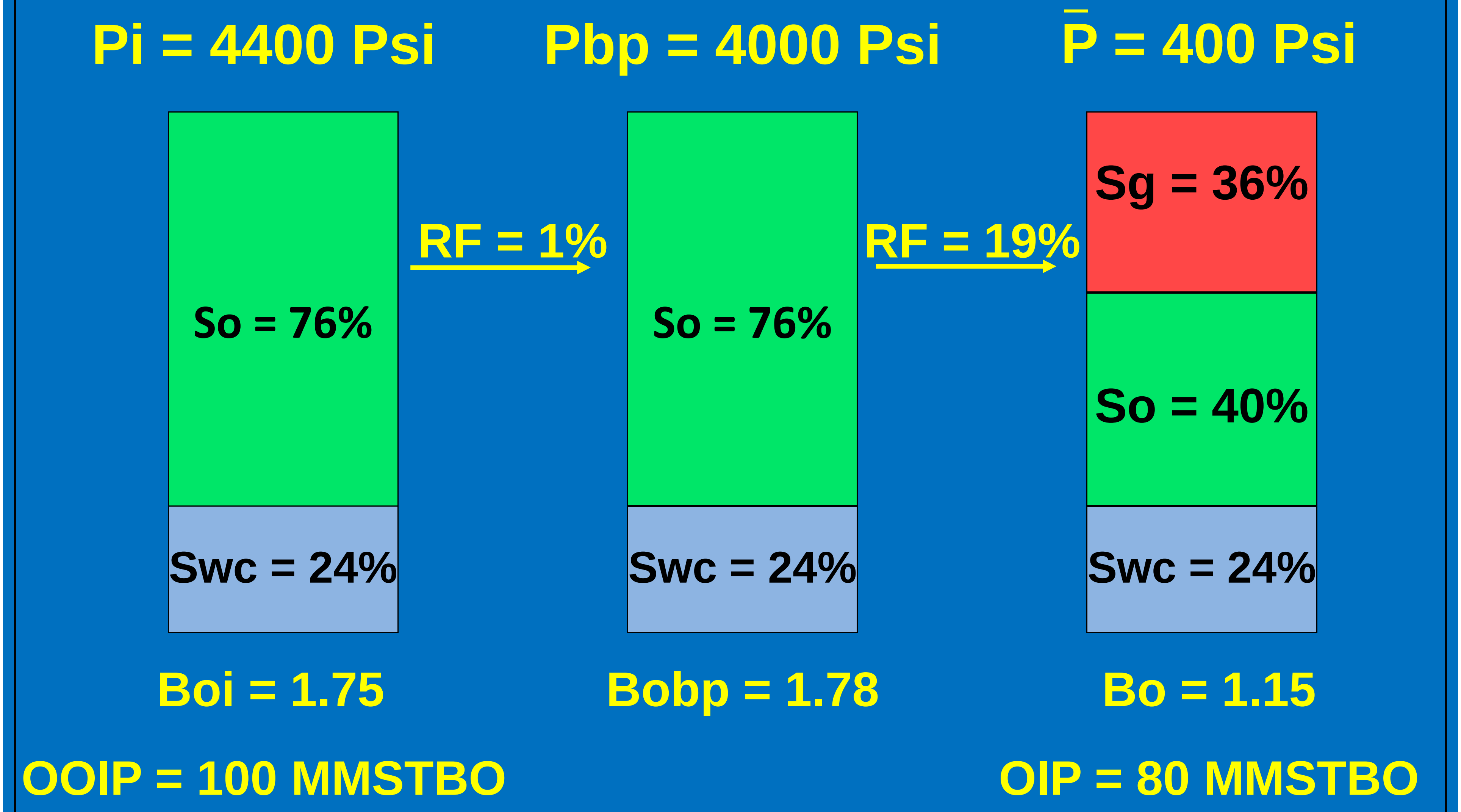
3) Analogy Requires:

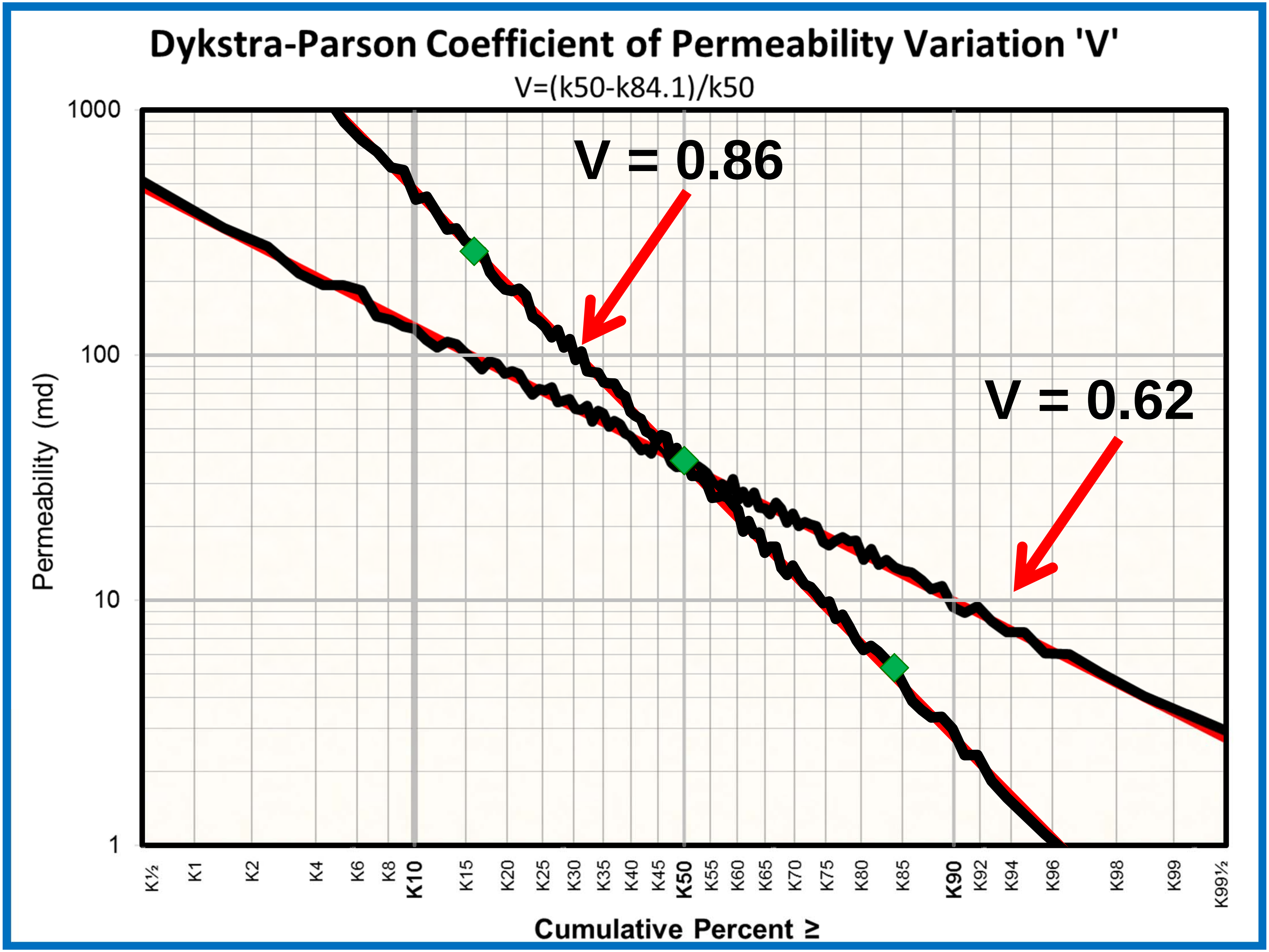
- ✓ ***Saturations similar at start of injection, So, Swc, & Sg***

- ✓ ***Rock Properties are similar***
  - ***Relative permeability***
  - ***Dykstra-Parson V factor***

- ✓ ***Fluid Properties, viscosity (μ_o)***

NORTH AMERICA
LIQUID EXPANSION - SOLUTION GAS DRIVE





Dykstra-Parson Coefficient of Permeability Variation 'V'
V=(k50-k84.1)/k50
V = 0.86
V = 0.62
1000
100
10
1
Permeability (md)
K½
K1
K2
K4
K6
K8
K10
K15
K20
K25
K30
K35
K40
K45
K50
K55
K60
K65
K70
K75
K80
K85
K90
K92
K94
K96
K98
K99
K99½
Cumulative Percent ≥

4) Secondary to Primary Ratio (S/P):

- ✓ ***Projects must be analogous***
- ✓ ***Use with extreme caution because most projects are not analogous***

Voidage Replacement Ratio Analysis (VRR)

Desired Ratio 1.1 to 1.2

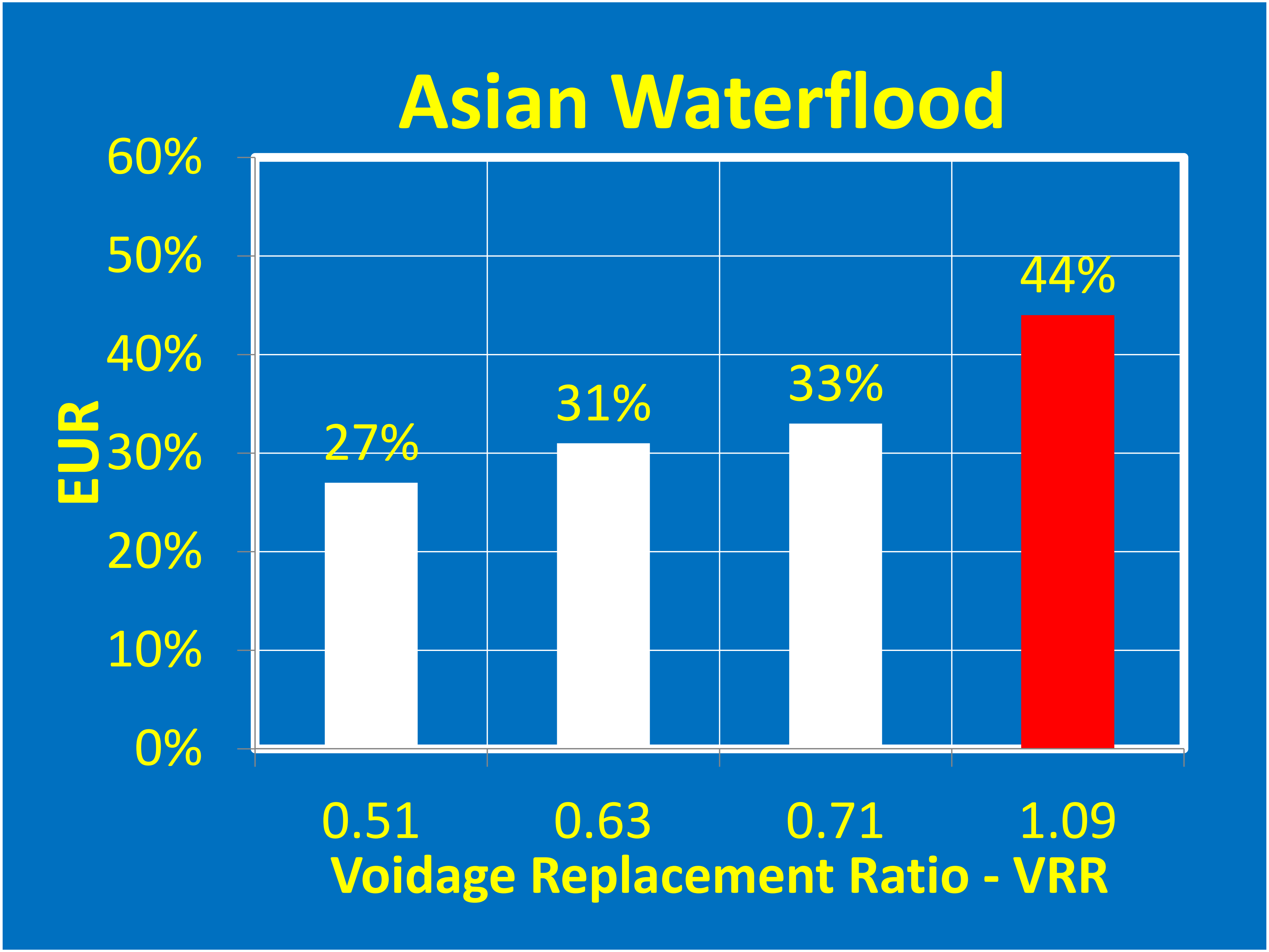
- ***Calculated at reservoir conditions***
- ***Includes:***
  - ✓ ***Oil***
  - ✓ ***Water***
  - ✓ ***Gas (solution and free)***

ASIAN WATERFLOOD

SOLUTION GAS DRIVE (WEAK WATER INFLUX)	
Pi = Pbp = 2250 Psi	P = 2100 Psi - At Start Of Injection
Rsi = 550 SCF/STBO	Swc = 29%
Boi = 1.39 RB/STB	Sg = 3%
μ_{oi} = 0.44 CP	MR = 0.30

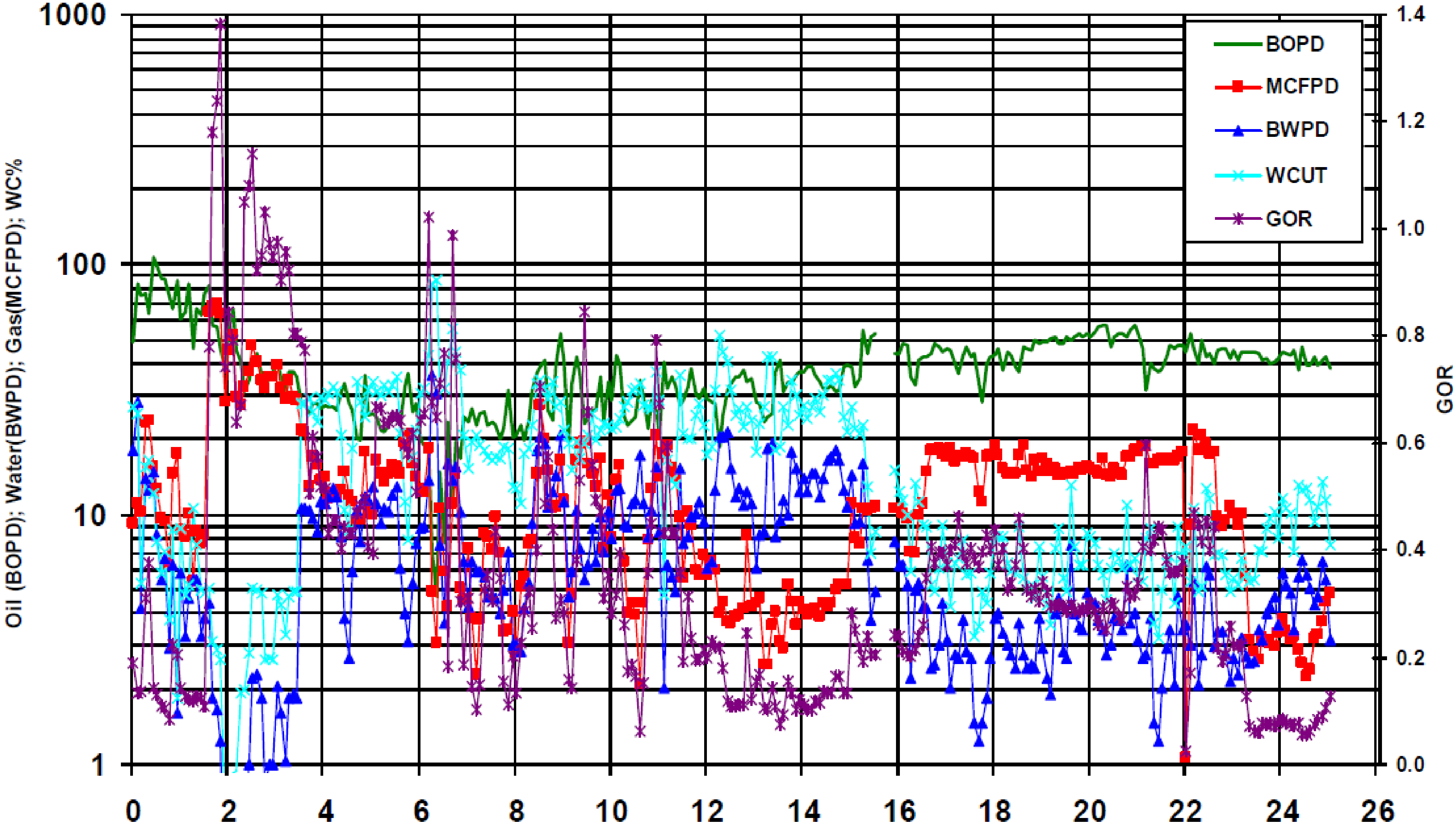
ASIAN WATERFLOOD RESPONSE

AREA	PRF W/O H2O %	Current RF %	**EUR %**	**VRR Since Start of Inj.**
1	15-18	18	27	0.51
2	15-18	21	31	0.63
3	15-18	25	33	0.71
4	15-18	31	***44***	***1.09***



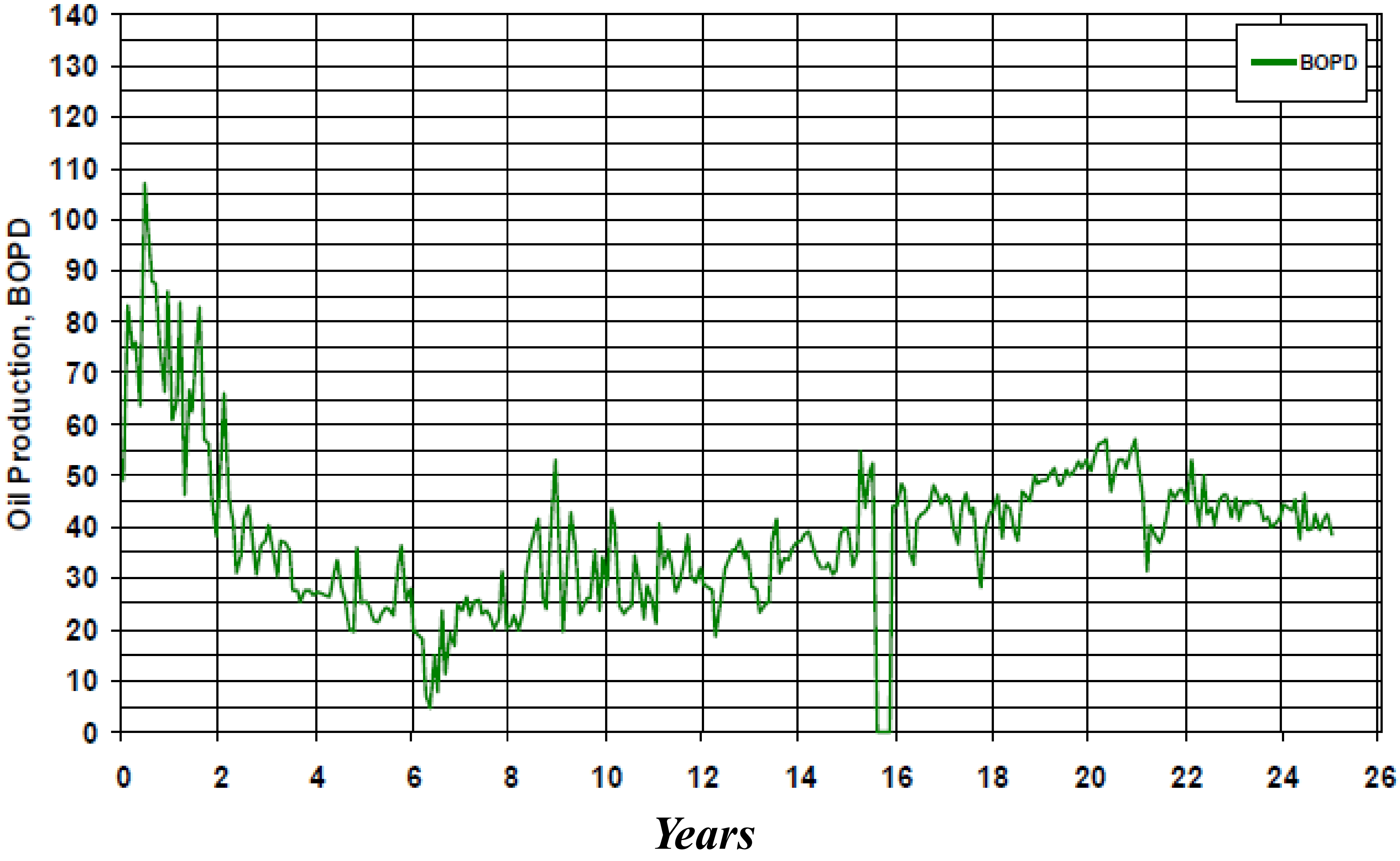
Asian Waterflood
60%
50%
40%
30%
20%
10%
0%
EUR
27%
31%
33%
44%
0.51
0.63
0.71
1.09
Voidage Replacement Ratio - VRR

Ain't Acceptable
Spaghetti Graph for a Production Well

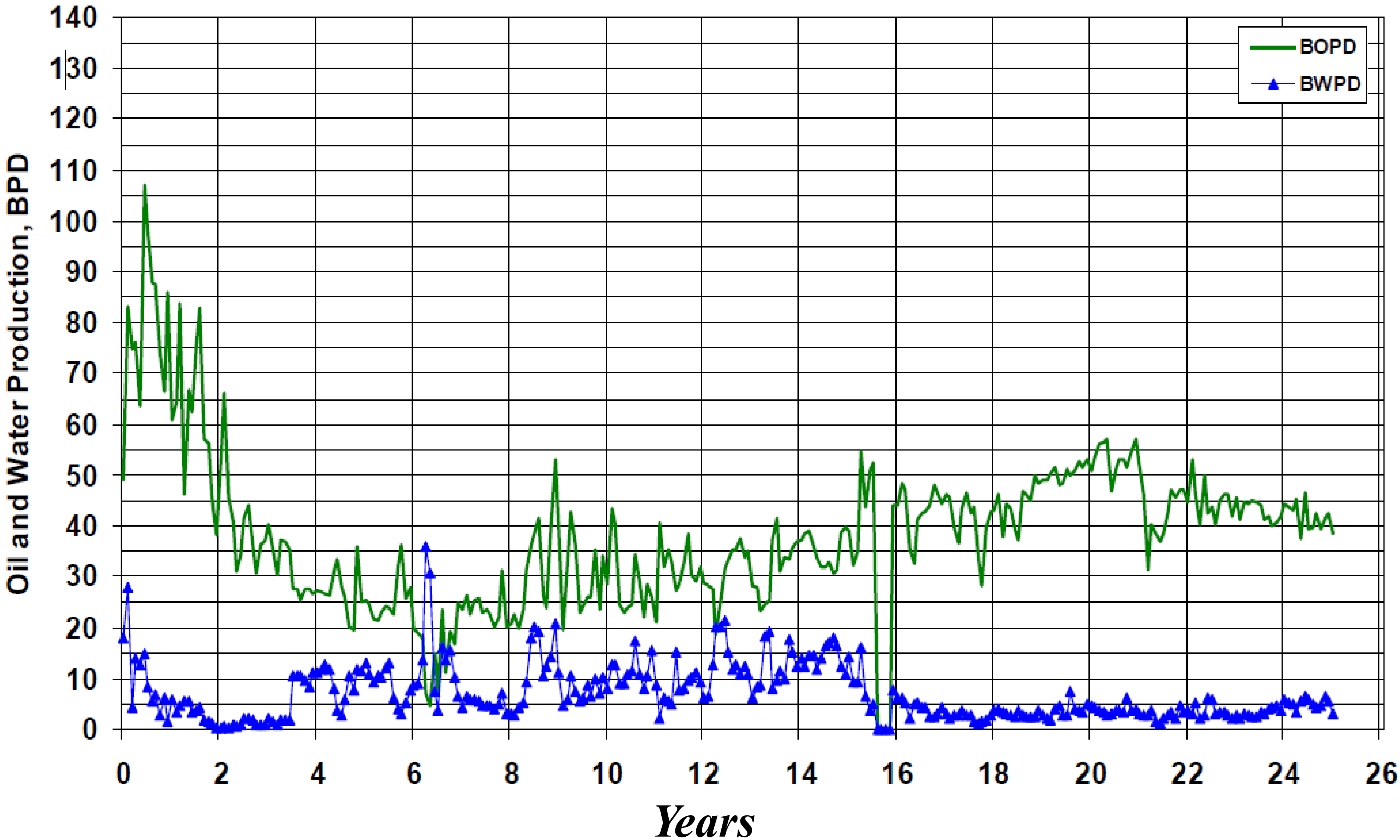


Years

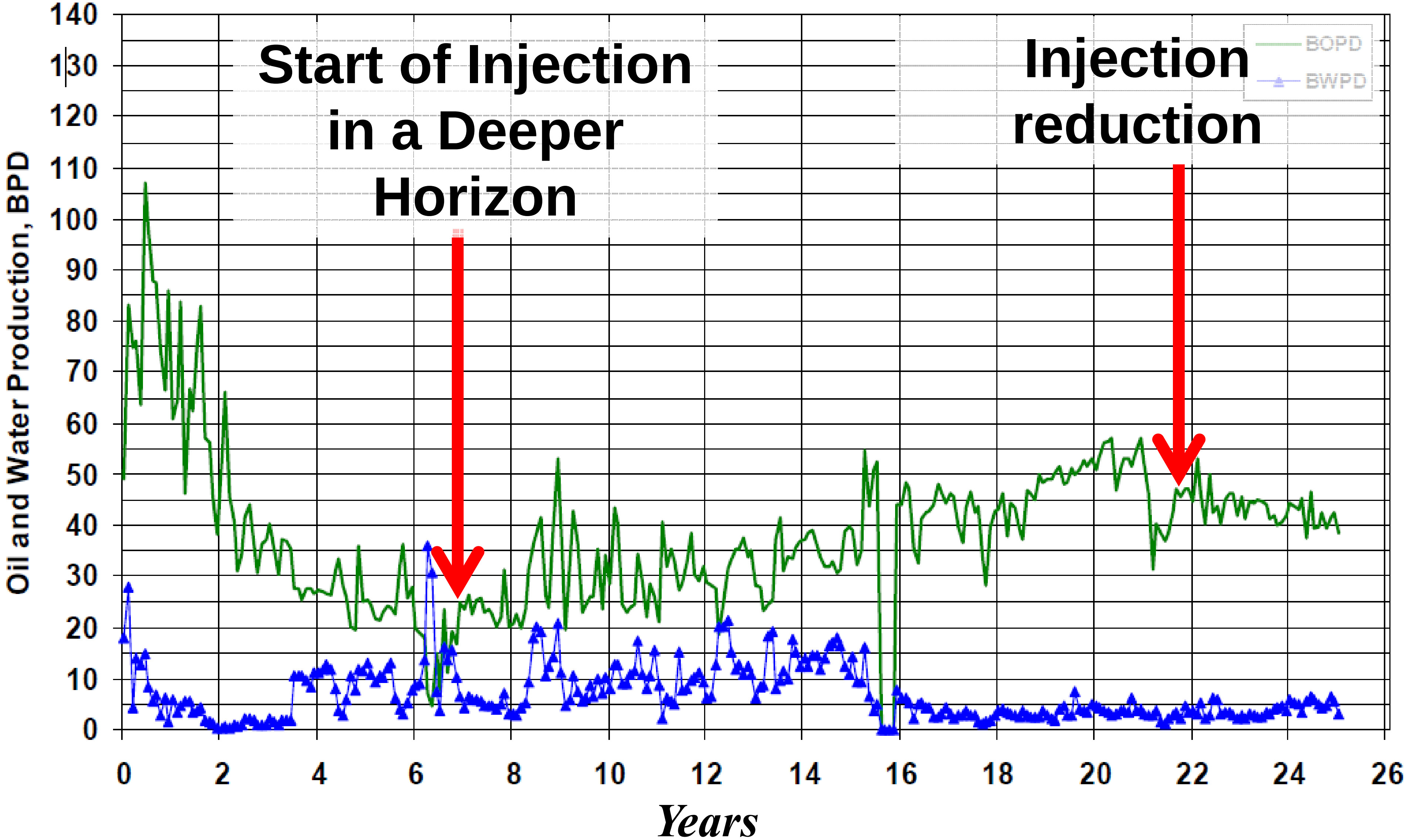
Single String of Spaghetti – Oil Rate vs Time



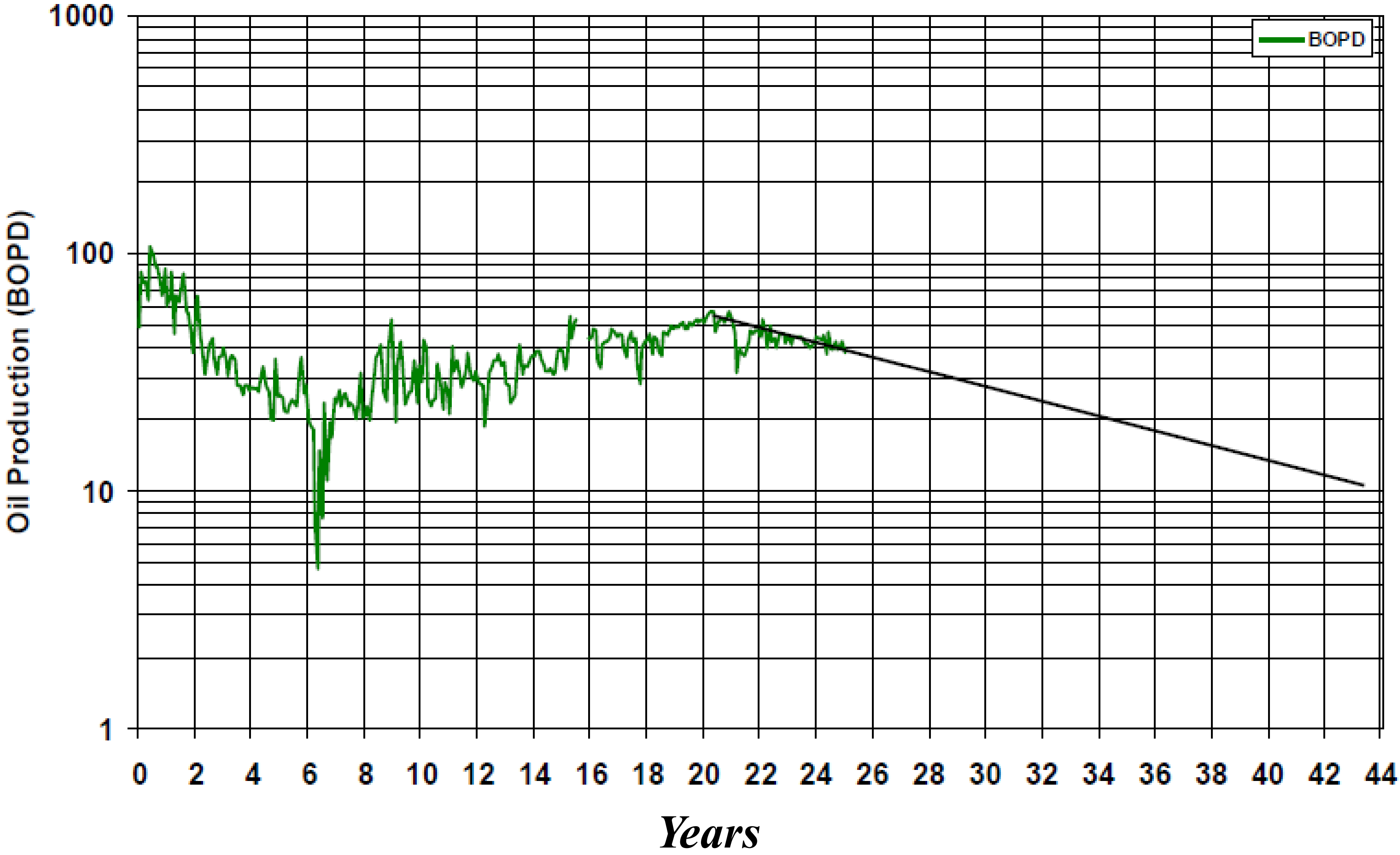
Two Strings of Spaghetti – Oil & Water Rate vs Time



Two Strings of Spaghetti – Oil & Water Rate vs Time



Spaghetti String – Exponential Decline



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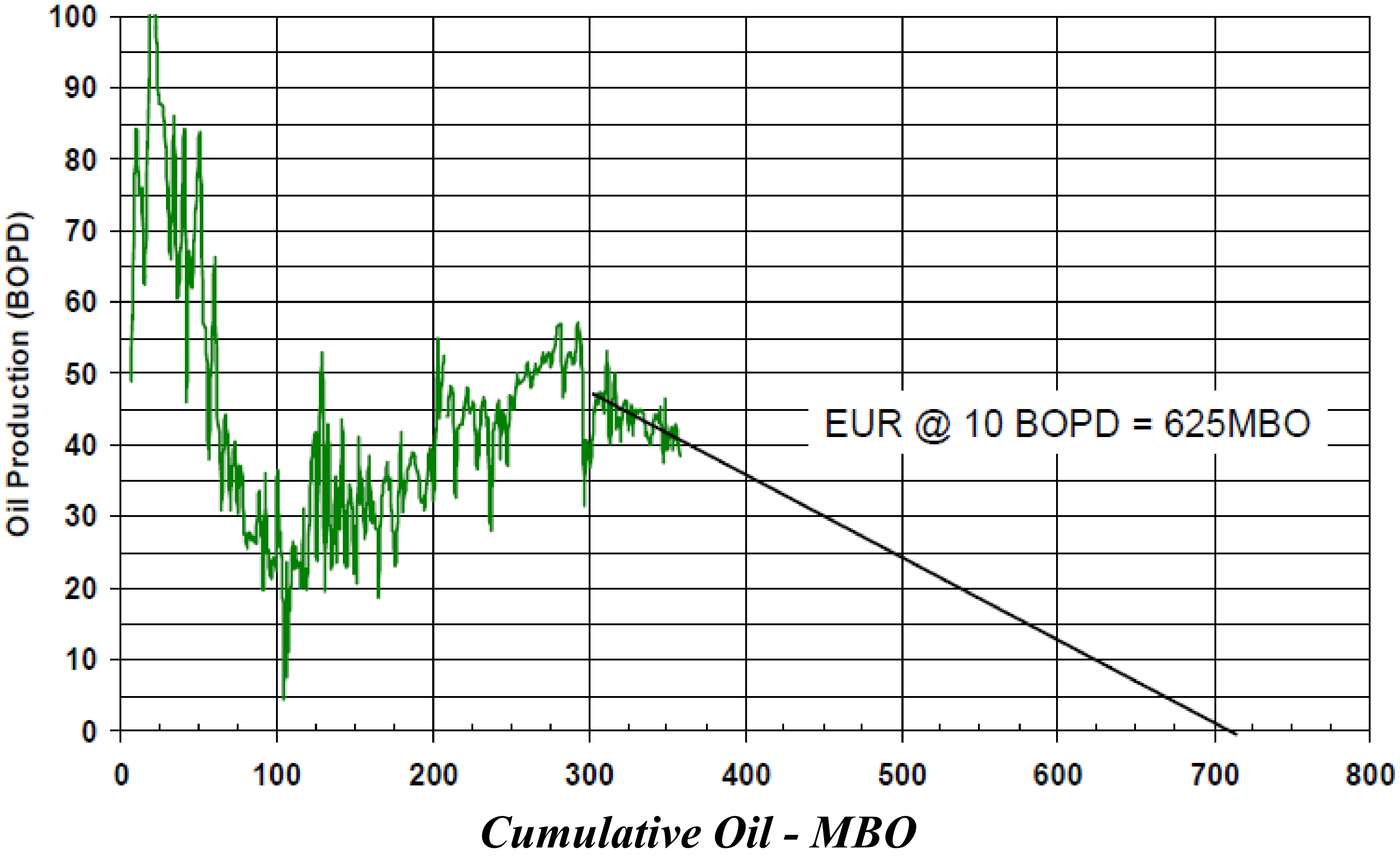
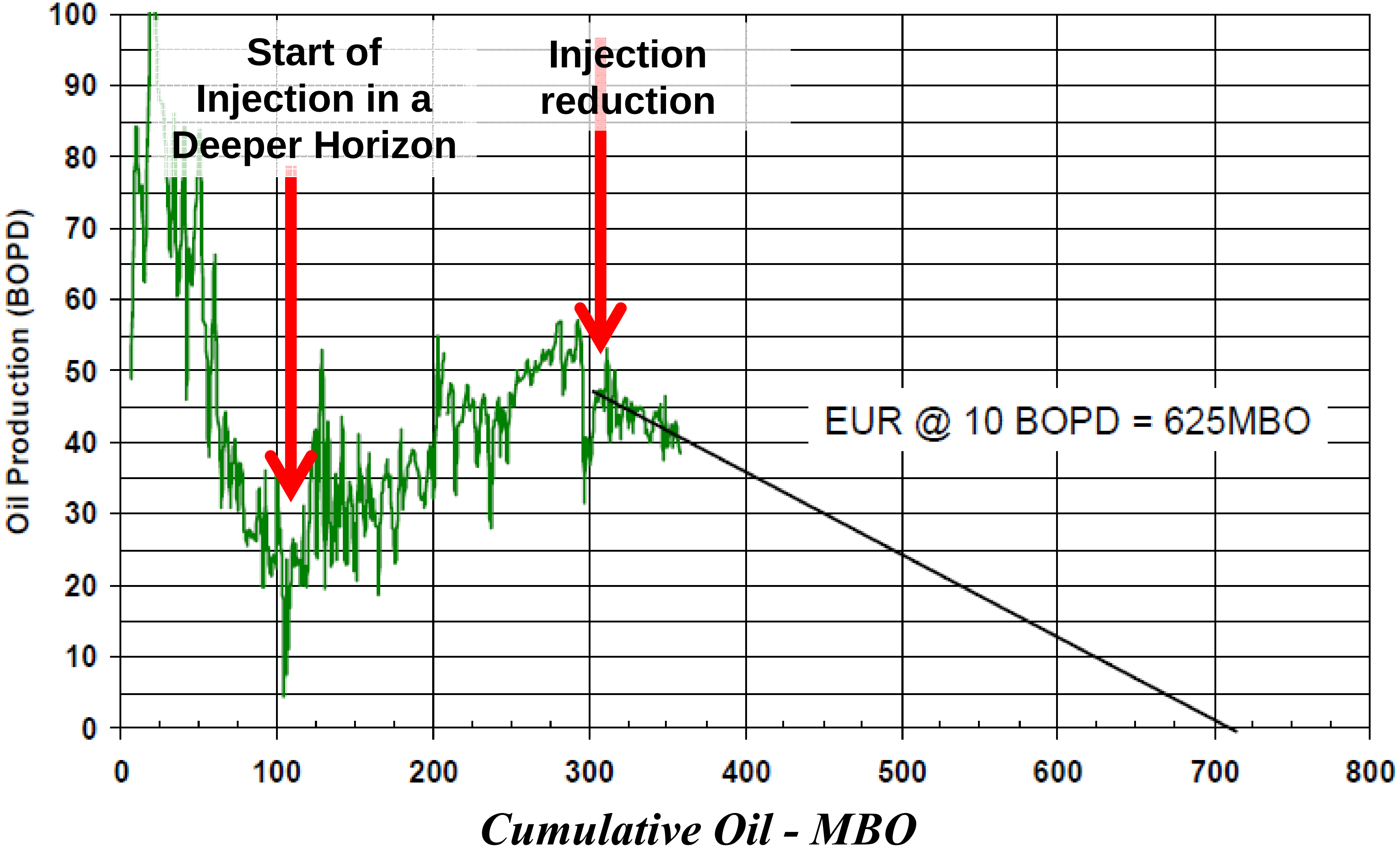


Spaghetti String – Exponential Decline



Take-a-way Points for Today:

1) *Waterflooding is very different from Primary Depletion*

2) *Test wells on a monthly basis (oil, H2O, gas)*

3) *Keep liquid levels in wells pumped off for*
   - ✓ *Consistency in monthly production tests*
   - ✓ *Maximize injection rate*
   - ✓ *Maximize primary production from intervals not receiving injection*

Take-a-way Points for Today:

4) *Maintain simple graphs: Oil, GOR, WOR by well (no spaghetti today)*

5) *Oil and Water Production Rates are directly related to injection rates and stratification.*

6) *Variable injection rates and stratification make traditional decline curve forecasts unreliable.*

Take-a-way Points for Today:

7) Voidage replacement ratio > 1.2

8) <u>Analogy</u> requires similarity of:

- ✓ *rock properties,*
- ✓ *fluid properties,*
- ✓ *fluid saturations*

<u>at the start of the injection</u>

Take-a-way Points for Today:

9. ***Reserve Forecasting in Waterfloods*** ***<u>is not for Sissies</u>***