Knowledge Integrity Service

GEO INDIA 2022

Estimation of Recoverable Resources

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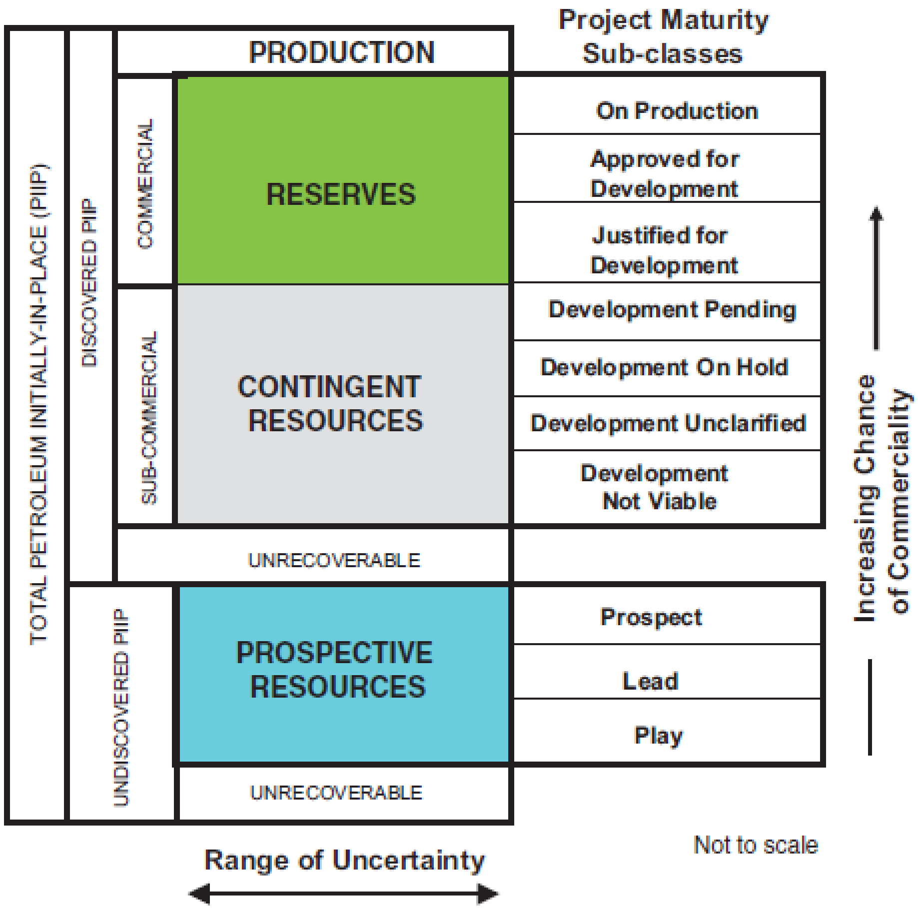
Worldwide Petroleum Consulting

Estimation of Hydrocarbons In-Place

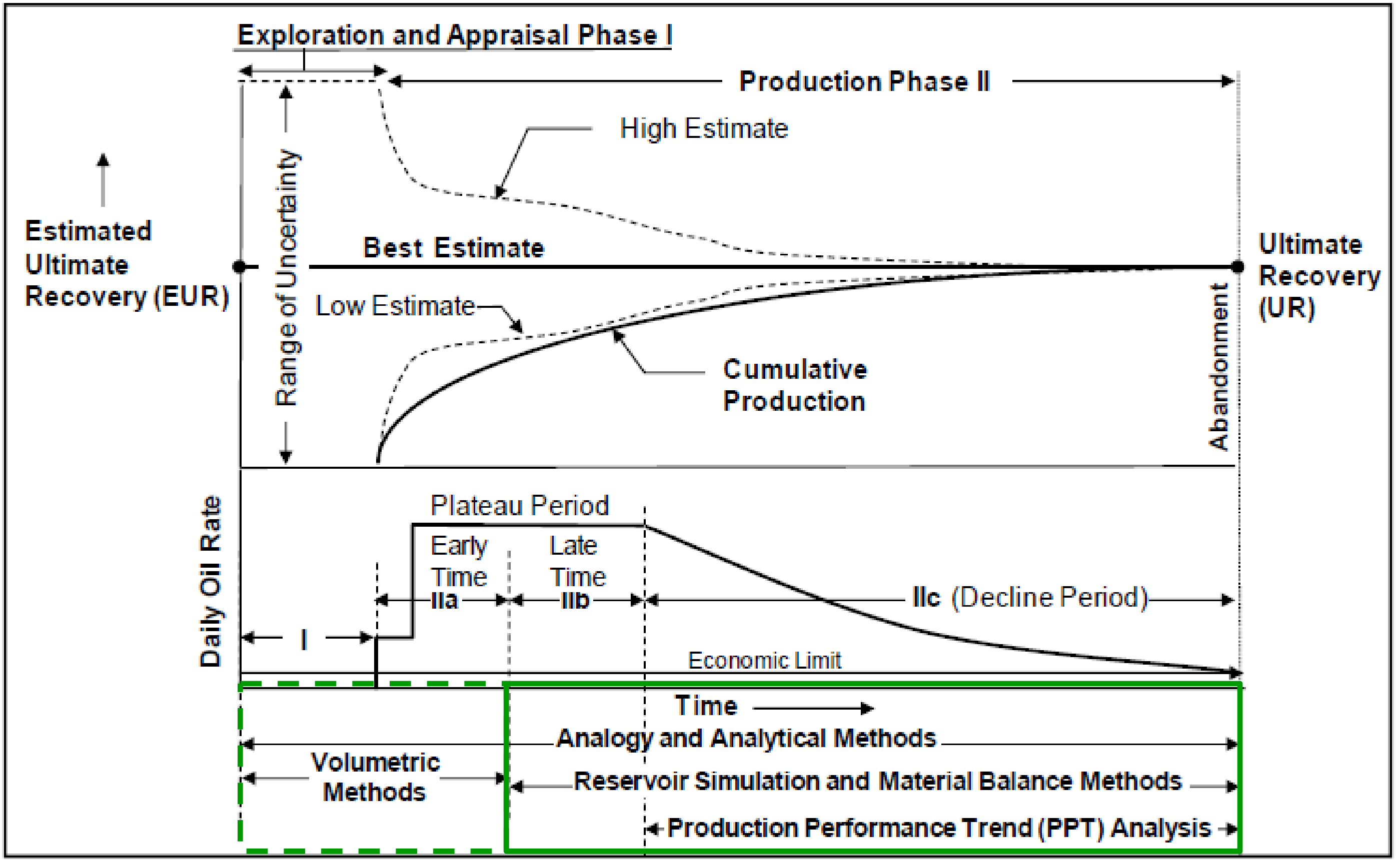
Reserve Assignment Example

- **Discovery**
  - A petroleum accumulation where one or several exploratory wells through testing, sampling, and/or logging have demonstrated the existence of a significant quantity of potentially recoverable hydrocarbons and thus have established a known accumulation. In this context, “significant” implies that there is evidence of sufficient quantity of petroleum to justify estimating the in-place volume demonstrated by the well(s) and for evaluating the potential for technical recovery.
- **Justified for Development**
  - Are agreed upon by the managing entity and partners as commercially viable and have support to advance the project, which includes a firm intent to proceed with development. All participating entities have agreed to the project and there are no known contingencies to the project from any official entity that will have to formally approve the project.
- **Approved for Development**
  - Justified for Development Reserves are reclassified to Approved for Development after a FID has been made.



Estimation of Recoverable Quantities

Uncertainty in Assessment Method Over Project Life



Change in uncertainty and assessment methods over the project's E&P life cycle.

Figure 4.2: SPE, Guidelines for Application of the Petroleum Resources Management System, November 2011

Estimation of Recoverable Quantities

Different ways of estimating recoverable quantities

- Recoverable estimates
  - Material balance
  - Decline curve analysis
  - Reservoir simulation
  - Analogy
  - Recovery factors
  - Forecasting reserves

Estimation of Recoverable Quantities

Material Balance: In-Place and Recoverable Quantities

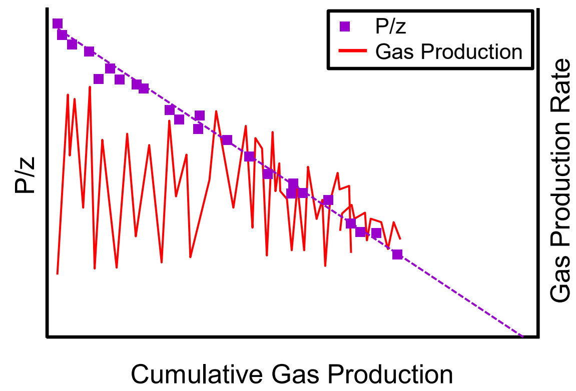
- Can be…
  - Used to estimate gas and/or oil in-place estimates
  - Compared to volumetric estimate of in-place to confirm and increase confidence
- Gas material balance plots
  - P/z vs. cumulative production (P/z plot)
  - Several others
- Can be used to estimate recoverable quantities
  - For gas reservoirs, abandonment pressure (P_a) is estimated from economic rate (limit)

Estimation of Recoverable Quantities

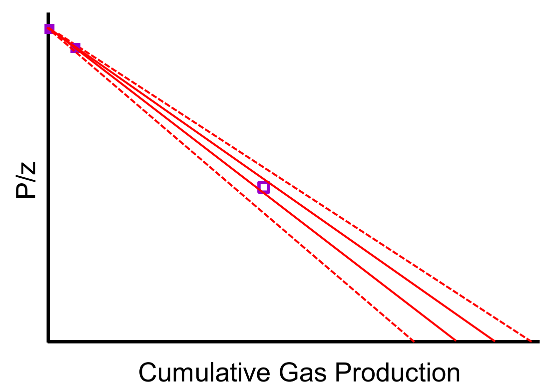
Gas Material Balance: P/z plot

- **Useful when…**
  - When data is sufficient and consistent
  - >30% of OGIP has been produced
  - Production is constrained by operational issues
  - Production performance is not reliable
- **Weak when…**
  - Production is less than 10% of OGIP
  - Water (aquifer) influx; may overstate OGIP estimates
  - Water in wells; may effect accuracy of pressure measurements
  - Reservoir pressure on reservoir flanks is not well known

- Curtailed production



- Uncertainty with time

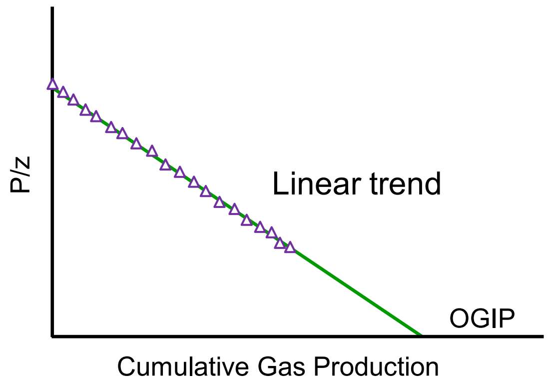


Estimation of Recoverable Quantities

Gas Material Balance: Uncertainty from Drive Type

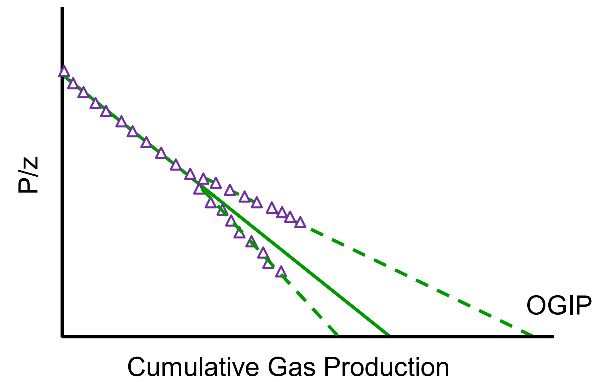
- Example – Reliable trend

P/z Plot



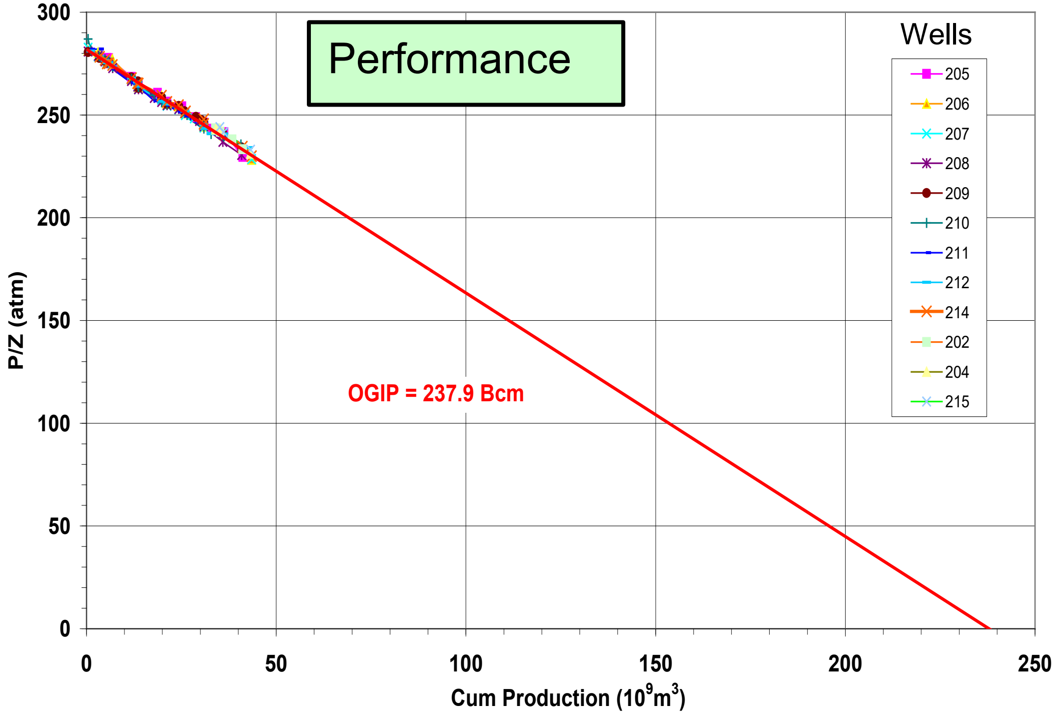
- Example – Unreliable trends

P/z Plot



Engineering Upgrade Prerequisites and Examples

Gas Material Balance: Example – Performance vs. Volumetrics



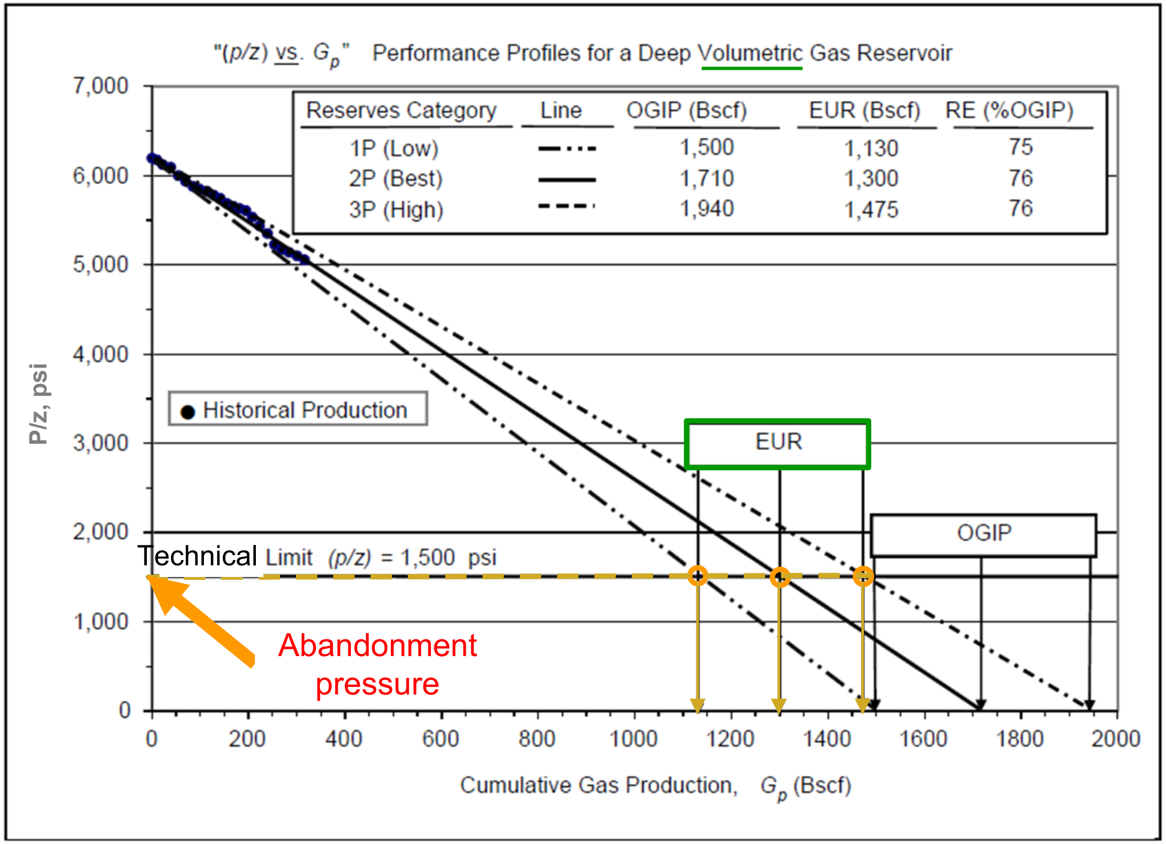
- **Material Balance**
  - Supported by volumetrics
- **OGIP**
  - Volumetric 249.3 10^9m^3
  - P/z 237.9 10^9m^3
  - Difference 4.6%
- **Is the P/z OGIP:**
  - Proved?
  - 2P? or 3P?
  - Do we need another type of performance plot?

Volumetrics (3P = Proved + Probable + Possible)

Reservoir Area and Volume				Average Reservoir Parameters					
Surface Area (km^2)	Net Volume (10^6m^3)	Pore Volume (10^6m^3)	Hydrocarbon Pore Volume (10^6m^3)	Net Thickness (m)	Porosity (%)	Gas Saturation (%)	Formation Volume Factor (SC/RC)	OGIP (10^9m^3)	OGIP (10^9ft^3)
136.67	5,971.99	1,254.12	965.67	43.70	21.0	77.0	258.20	249,336	8,805,219

Estimation of Recoverable Quantities

Gas Material Balance: P/z plot – Example Estimating EUR



Gas reserves assessment by material balance methods (Late-Production Stage).

Figure 4.8: SPE, Guidelines for Application of the Petroleum Resources Management System, November 2011

Estimation of Recoverable Quantities

Gas Material Balance: Summary

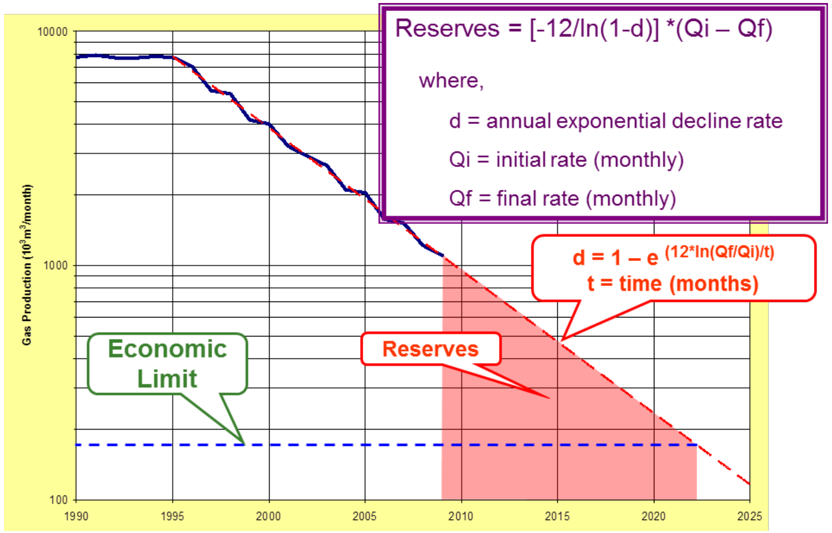
- Be aware of potential sources of uncertainty
  - Level of maturity in the life cycle
  - Potential drive mechanisms
  - Amount and quality of available data
- Reconcile with volumetric estimates for initial in-place
- Consider appropriate abandonment pressure
- Assign appropriate level of certainty

Estimation of Recoverable Quantities

- Recoverable estimates
  - Material balance
  - Decline curve analysis
  - Reservoir simulation
  - Analogy
  - Recovery factors
  - Forecasting reserves

- Decline curve analysis
  - Analysis of change in production rates with time
  - Reliable only…
    - Mid- to late-life
    - If operating conditions are stable
    - If production is not constrained
    - If there is an established trend
  - Considerations
    - Variable reservoir and fluid properties
    - Transient versus stabilized flow
    - Changes in operating conditions
    - Interference effects
    - Reservoir drive mechanisms

- Example rate-time graph
  - exponential decline

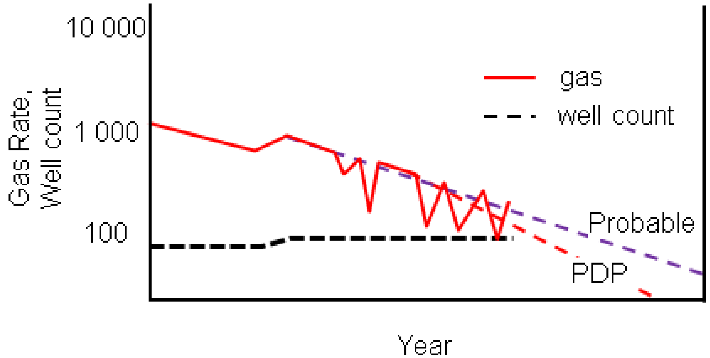


Estimation of Recoverable Quantities

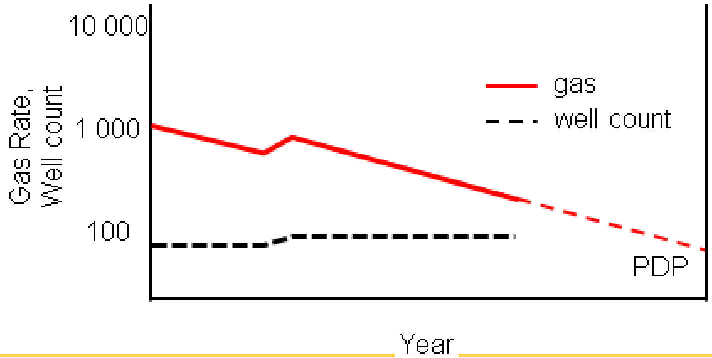
Decline Curve Analysis

- Decline curve analysis can be used…
  - for oil or gas
  - when there is a stable decline trend
  - when operating conditions are stable (example: chokes are not changed)
  - when demand is at or above capacity
  - when well count is stable
- PDP reserves are the total production from the "as of" date to the economic rate limit
  - Assuming that the trend is reasonably certain (90%)

- Decline rate uncertain

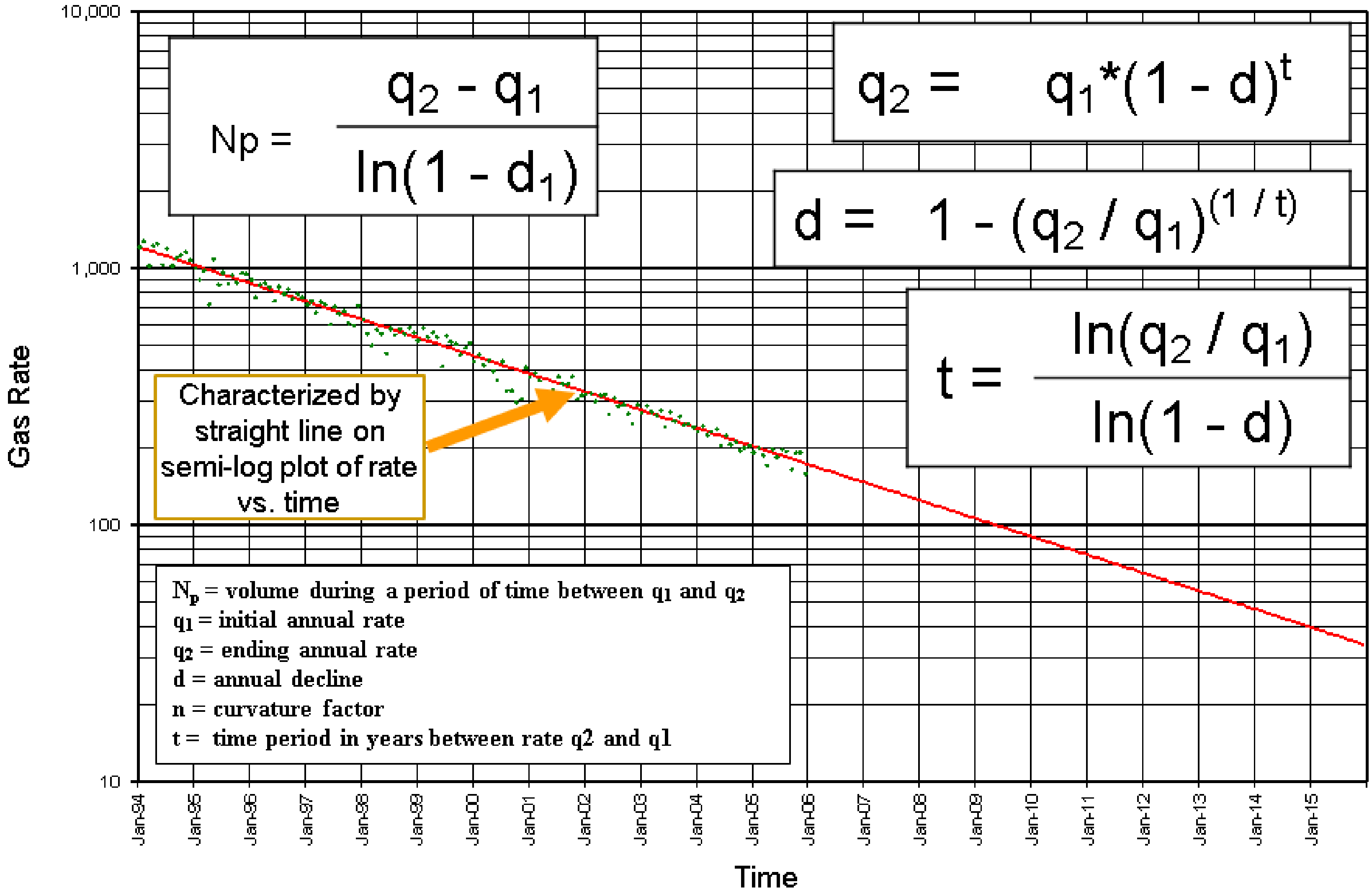


- Stable decline



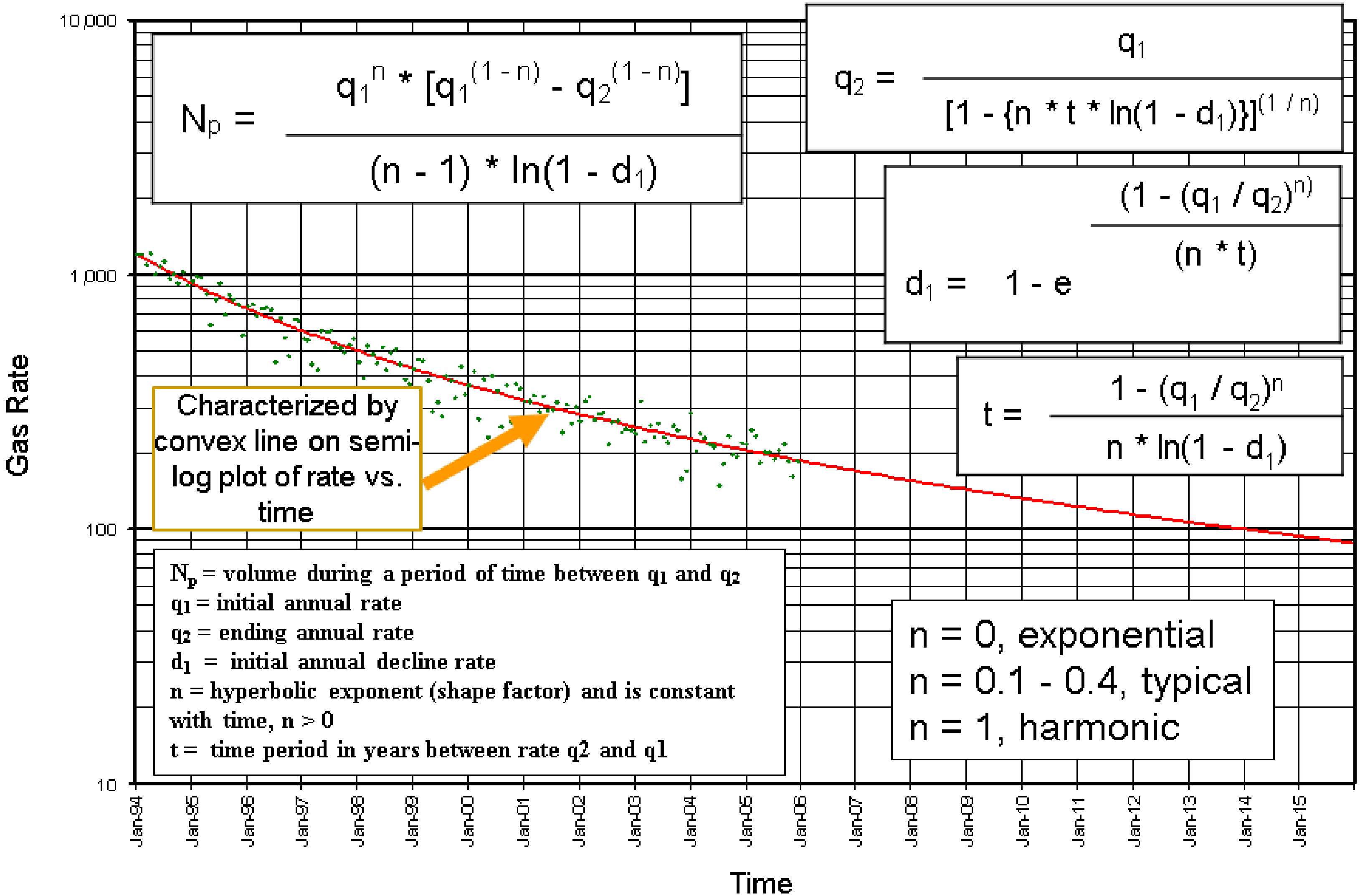
Estimation of Recoverable Quantities

Decline Curve Analysis: Exponential Decline



Estimation of Recoverable Quantities

Decline Curve Analysis: Hyperbolic Decline



$$N_p = \frac{q_1^{n} * [q_1^{(1-n)} - q_2^{(1-n)}]}{(n-1) * \ln(1-d_1)}$$

$$q_2 = \frac{q_1}{[1 - \{n * t * \ln(1-d_1)\}]^{(1/n)}}$$

$$d_1 = 1 - e^{\frac{(1 - (q_1 / q_2)^{n})}{(n * t)}}$$

$$t = \frac{1 - (q_1 / q_2)^{n}}{n * \ln(1-d_1)}$$

N_p = volume during a period of time between q_1 and q_2
q_1 = initial annual rate
q_2 = ending annual rate
d_1 = initial annual decline rate
n = hyperbolic exponent (shape factor) and is constant with time, $n > 0$
t = time period in years between rate q2 and q1

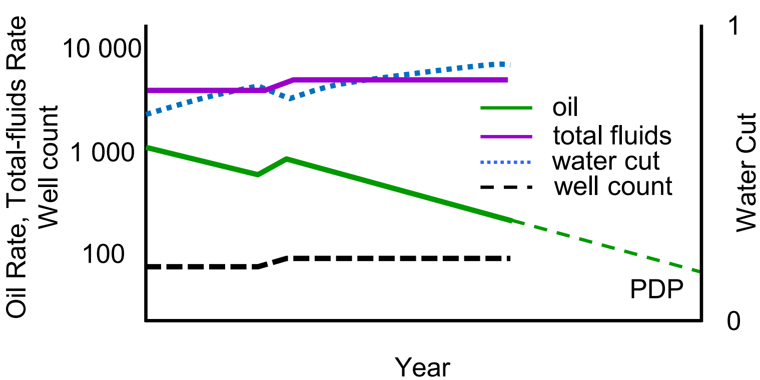
- $n = 0$, exponential
- $n = 0.1 - 0.4$, typical
- $n = 1$, harmonic

Estimation of Recoverable Quantities

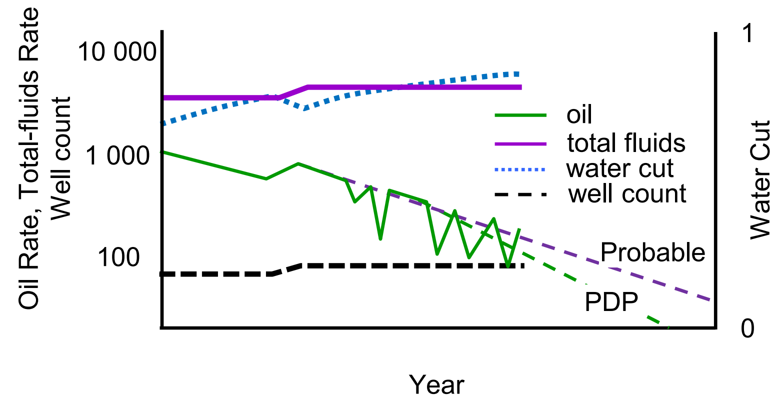
Decline Curve Analysis: Rate-Time Plot

- Rate-Time: Use
  - Can be used for oil and gas
  - When there is a stable decline trend
  - When well count is stable
  - When operating conditions are stable (example: chokes are not allowed)

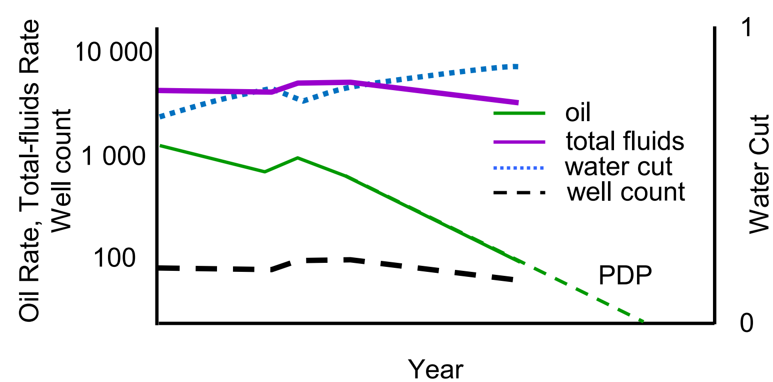
- Stable well count and oil decline



- Decline rate uncertain



- Well count decreasing

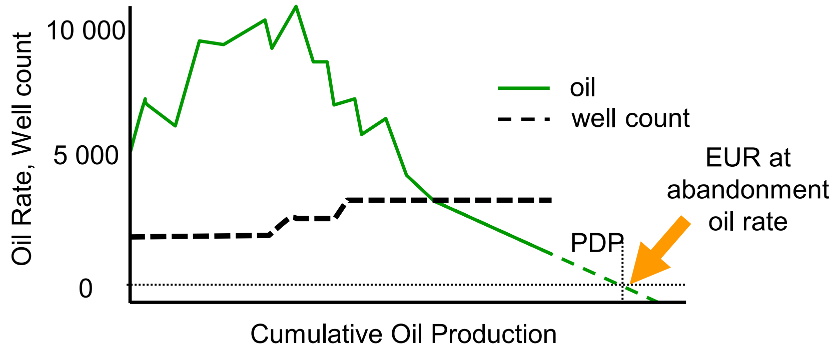


Estimation of Recoverable Quantities

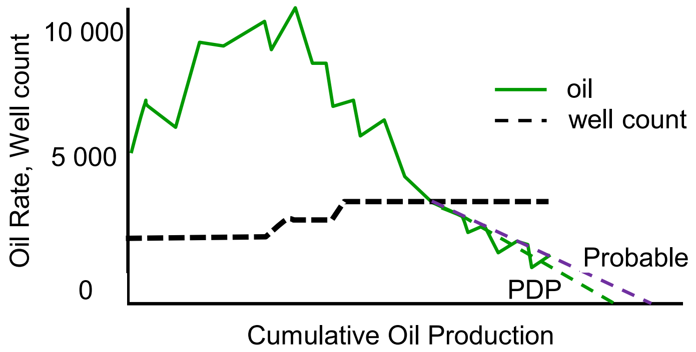
Decline Curve Analysis: Rate-Cumulative Production Plot - Example

- Rate-Cumulative Production: Use
  - Same constraints as Rate-Time plot

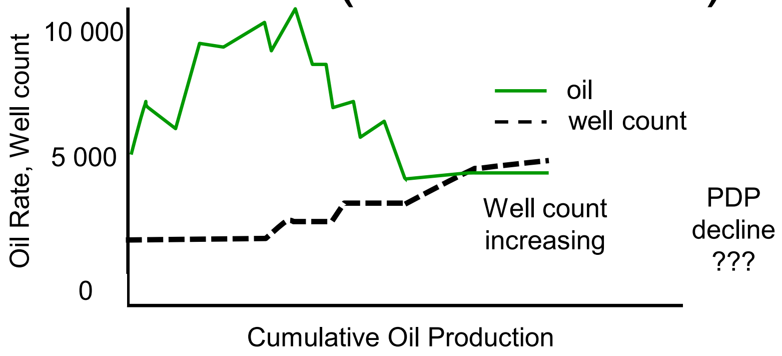
- Stable well count and oil decline



- Decline rate uncertain



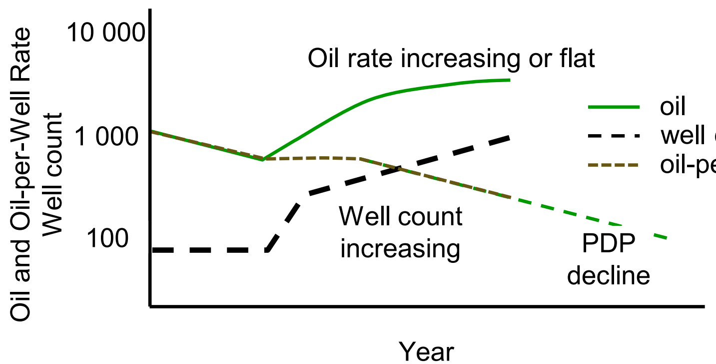
- No decline (inconclusive)



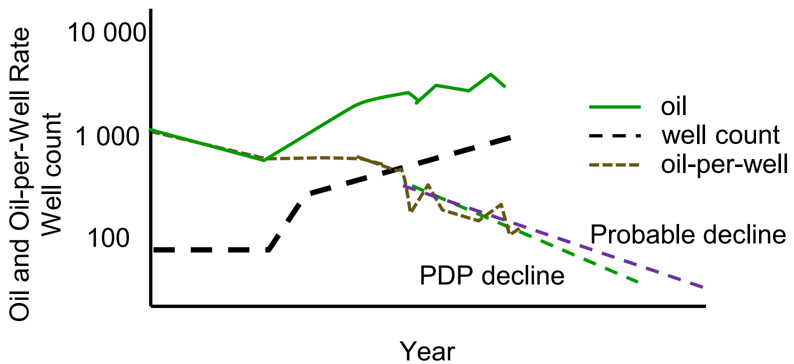
Estimation of Recoverable Quantities

Decline Curve Analysis: Oil-Rate per Well Plot - Example

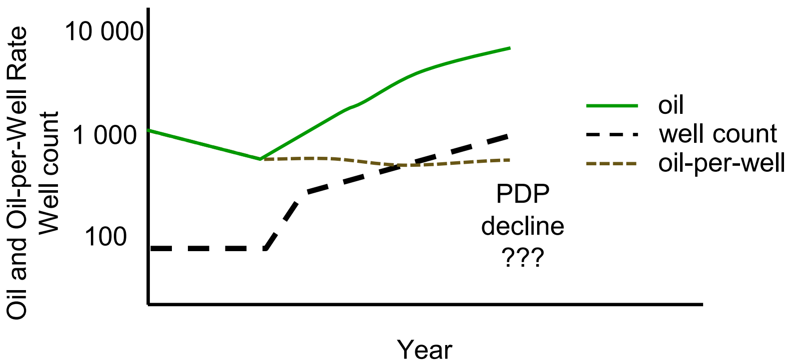
- Oil-Rate per Well : Use
  - Same constraints as Rate-Time plot
  - Oil rate divided by active number of producers
  - Oil-per-well decline may be indicative of true oil-rate base decline
  - Decline rate applied to oil Rate-Time
- Stable well count and decline



- Decline rate uncertain



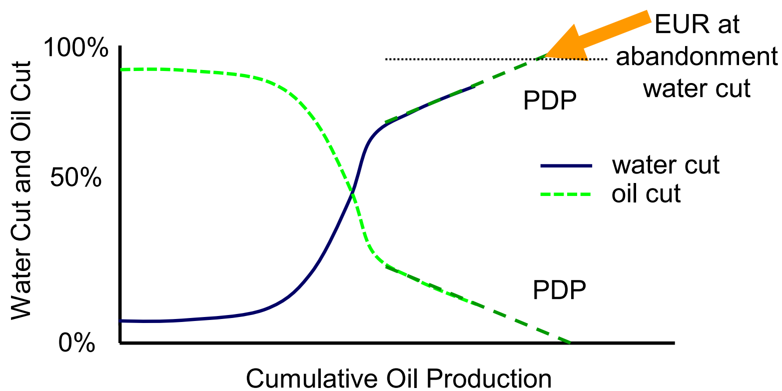
- No decline (inconclusive)



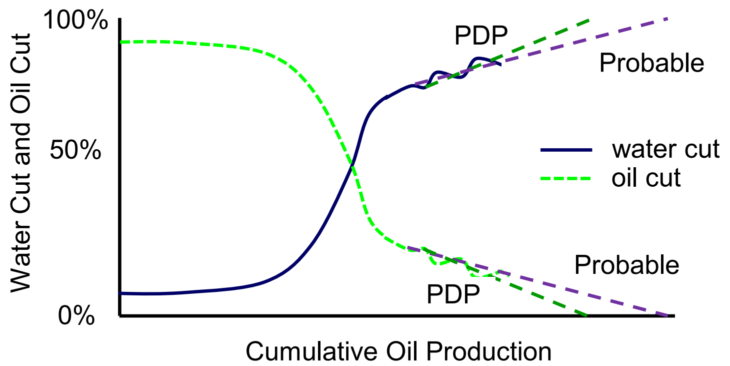
Estimation of Recoverable Quantities

Decline Curve Analysis: Oil or Water Cut vs. Cumulative Production Plot - Example

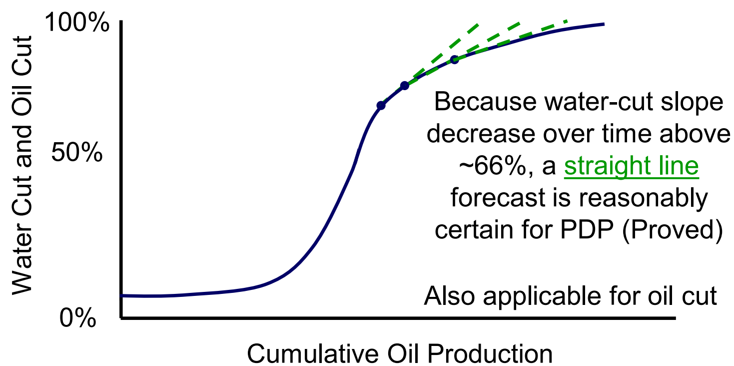
- Oil or Water Cut-Cumulative Production: Use
  - Oil cut = percent of oil produced versus total fluids
  - Same constraints as Rate-Time plot
  - Most applicable when water cut > 50%
  - The higher the water cut, the higher the certainty
- Stable well count and decline



- Trend uncertain



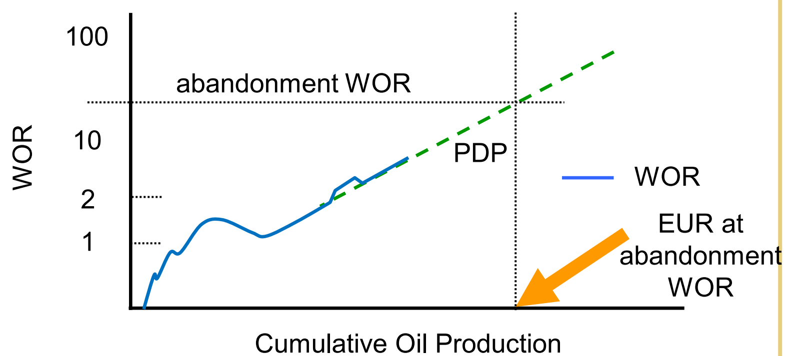
- Water cut starts bending at ~66%



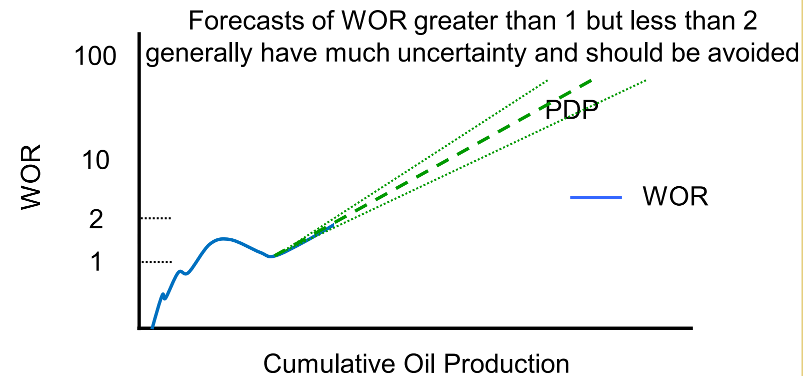
Estimation of Recoverable Quantities

Decline Curve Analysis: Water-Oil Ratio (WOR) vs. Cumulative Production Plot - Example

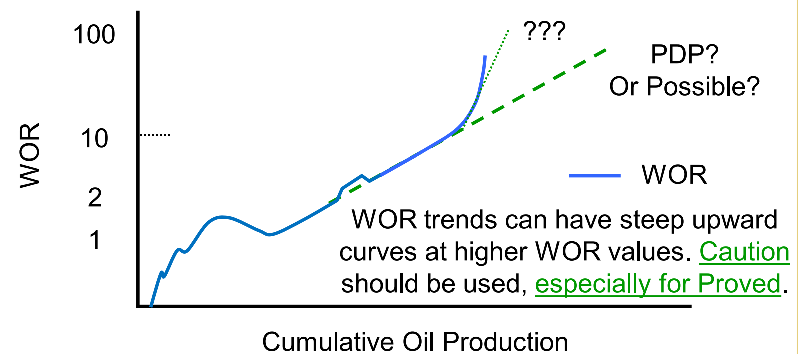
- **Water-Oil Ratio (WOR) - Cumulative Production: Use**
  - WOR= water to oil ratio
  - Same constraints as Rate-Time plot and Cut-Cumulative plots
  - May be applicable when WOR > 1; higher certainty when WOR > 2
  - Water cut = WOR/(WOR + 1)
- WOR above 2



- 1 < WOR < 2… use with caution



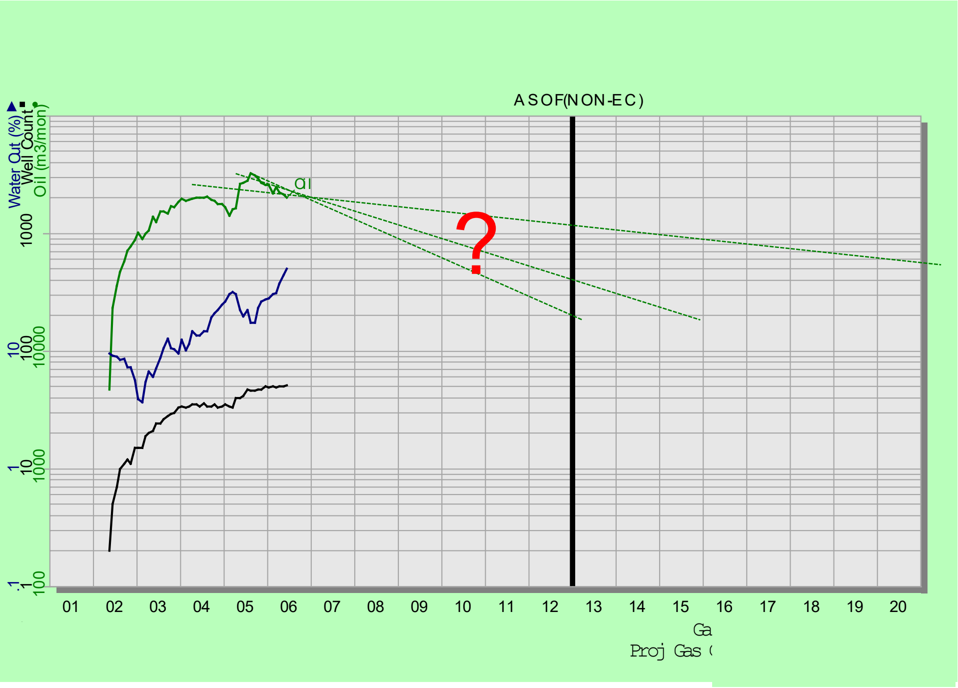
- WOR > 10: curve trends very steep



Estimation of Recoverable Quantities

Decline Curve Analysis: Example

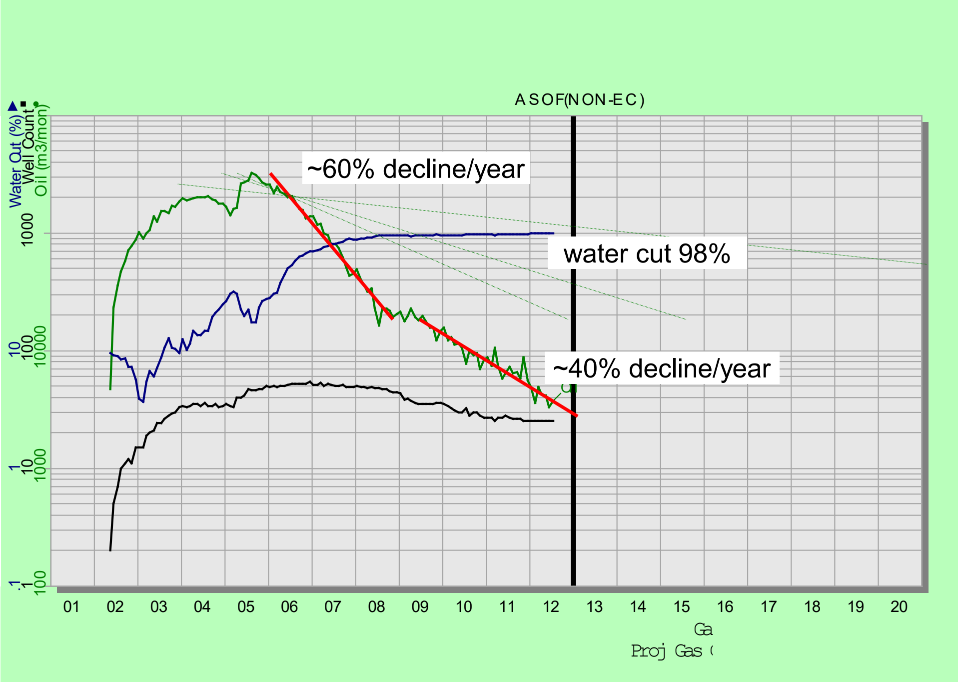
- Estimating proved developed producing (PDP) reserves
  - If we estimate a PDP forecast, which forecast would we use?
  - Remember, we have to use 90% certainty



Estimation of Recoverable Quantities

Decline Curve Analysis: Example - Answer

- What happened after peak production?
  - After peak production, there was a high degree of water breakthrough and oil rate indicated a ~60% decline rate. Current decline rate is ~40%.



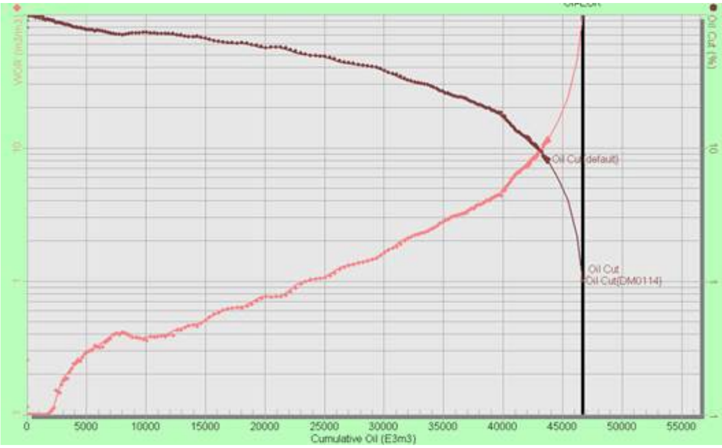
- Uncertainty
  - Did we understand the uncertainty of the reservoir?
  - Did we use appropriately risked forecast for the particular stage of development?
  - How can we avoid major write downs in proved?

Estimation of Recoverable Quantities

Decline Curve Analysis: Use Multiple Plots

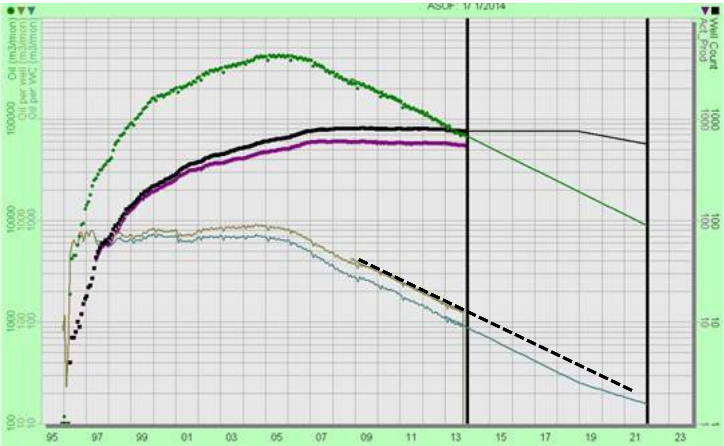
Rate vs. Time

Water Cut vs. Cumulative Oil



All plots should point to same answer for best results

Oil-per-well Rate vs. Time



WOR vs. Cumulative Oil

Estimation of Recoverable Quantities

Decline Curve Analysis: Summary

- Be aware of potential sources of uncertainty
  - Level of maturity in life cycle
  - Amount and quality of available data
  - Consistency and confidence in production trends
- Use more than one type of performance plots
- All plots should point to same answer
- Reconcile with volumetric estimates
- Assign appropriate level of certainty
- Decline curve analysis estimates do not replace material balance or volumetric estimates. They should support each other.

Estimation of Recoverable Quantities

- Recoverable estimates
  - Material balance
  - Decline curve analysis
  - Reservoir simulation
  - Analogy
  - Recovery factors
  - Forecasting reserves

Engineering Methodology

Reservoir Simulation

- Reservoir Simulation primary use is for development planning, NOT reserves determination
- However, reservoir simulation can be used for the assignment of reserves and falls under the “reliable technology” umbrella.
- Models are typically less heterogeneous than the reservoir
  - Tendency is to over predict recovery
  - Is considered to represent a 2P-3P case
  - To use for reserves the model must be thoroughly vetted
    - Established history match at the field, area, and well levels for all phases of production, injection, pressure etc.
    - Geologic model must be current using all available data
    - No anomalies such as flow barriers, high perm streaks, unusual adjustments of engineering parameters to gain the history match, turning of wells on and off (should match actual operational procedures) etc.
- More commonly reserves are assigned by volumetric estimates associated with recovery factors, analogues, and production performance analysis (decline curve analysis and material balance). These methods are combined and used together to increase confidence.
- Simulation models can be used in conjunction and cross checked with these other methodologies

Engineering Methodology

Example

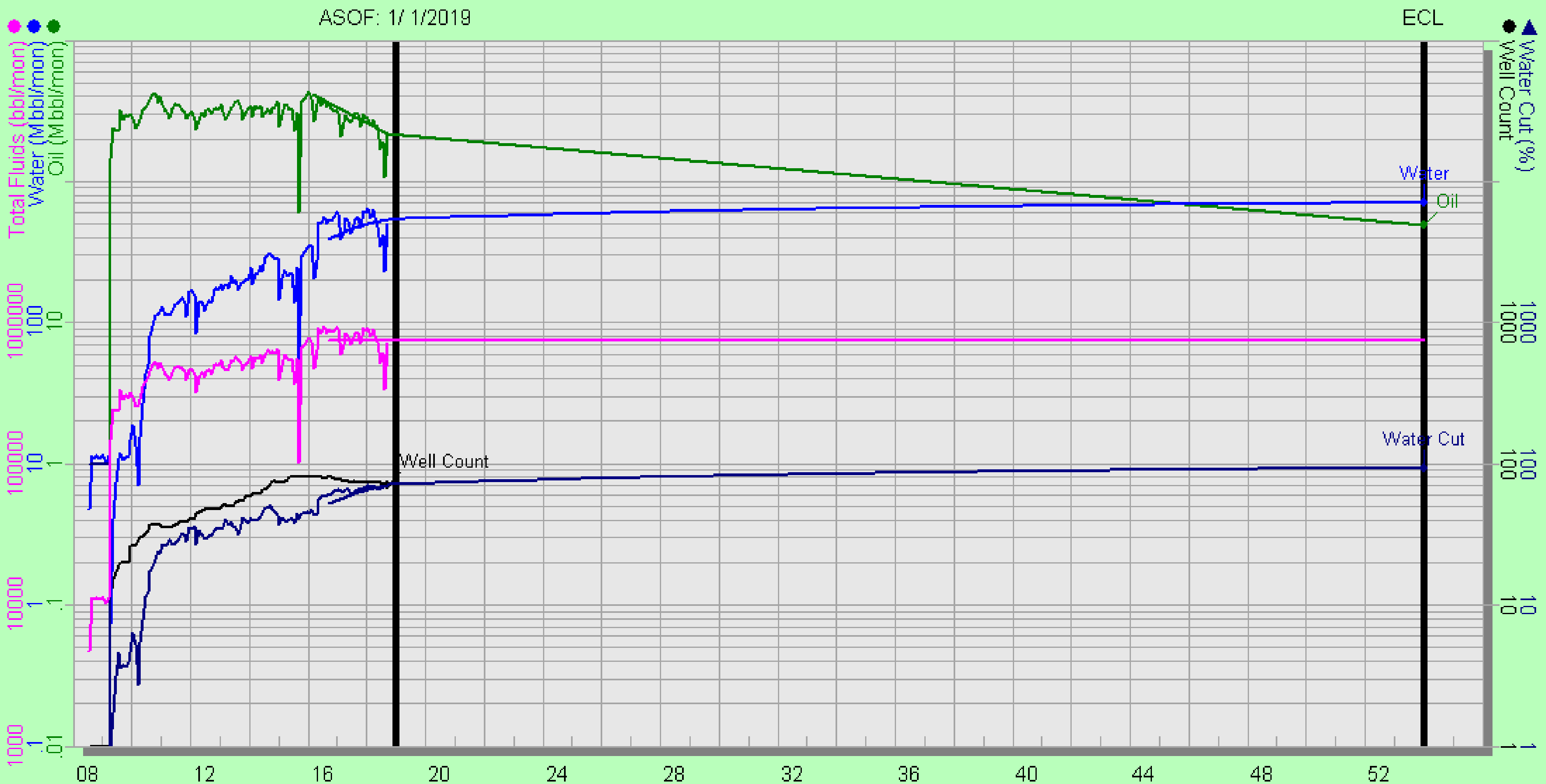
- West Africa Cretaceous Rift Lacustrine Sands
- 10 years of production
- Active Water Injection
- RF=18% Simulation “Do Nothing Case”
- History match (all phases and pressure) at the field level is good
- History match at many wells is good but not all
- Parameters (compressibility, Bo, Bg, viscosity etc.) in the model are reasonable
- Some surprises with water breakthrough

- As a litmus test look at the projection associated with the simulation model.

- Do you believe it? Why or why not?

Engineering Methodology

Single Reservoir - Reservoir Simulation “Do Nothing Case”

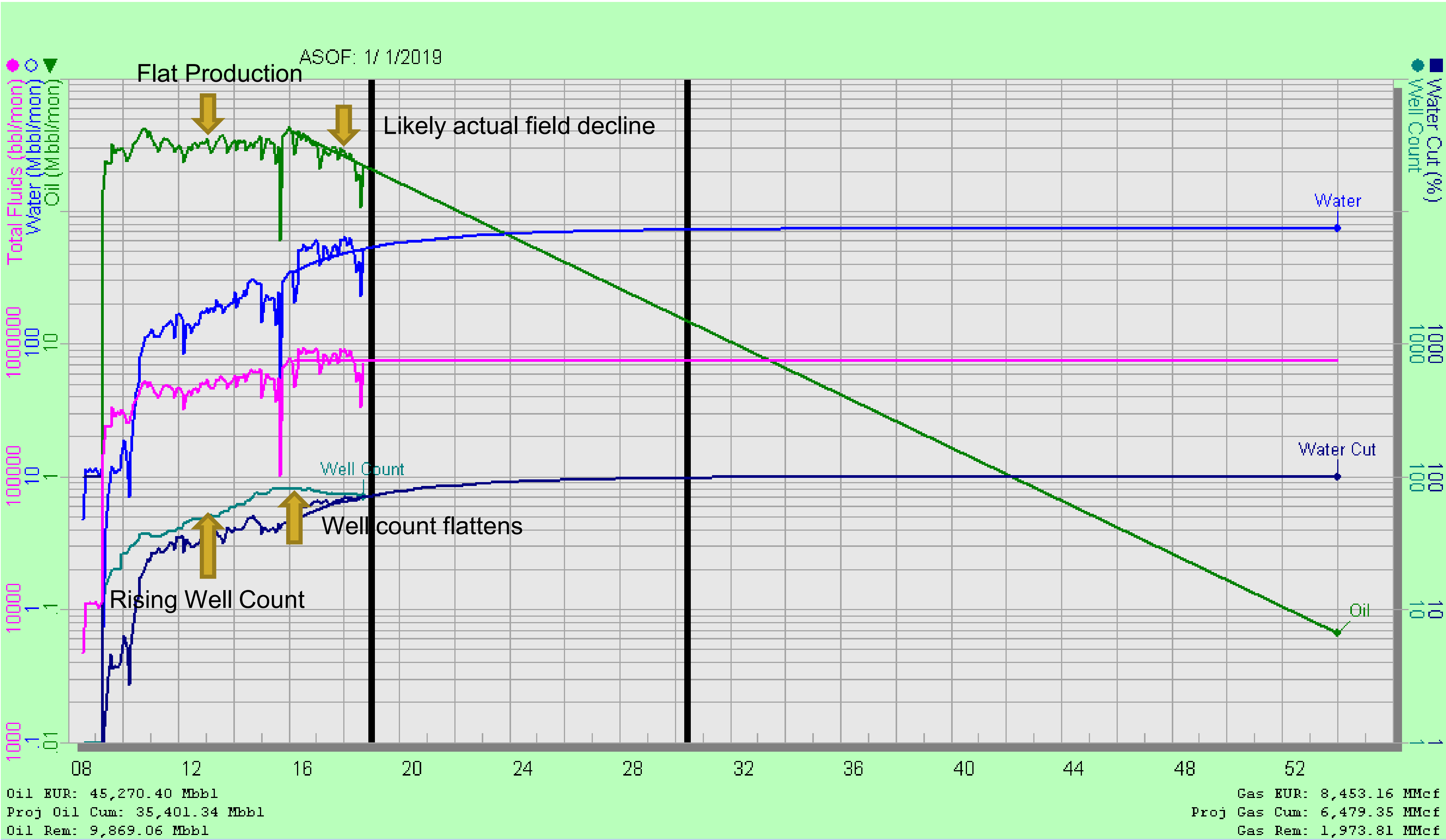


Oil EUR: 82,660.09 Mbbl
Proj Oil Cum: 35,422.18 Mbbl
Oil Rem: 47,237.91 Mbbl

Gas EUR: 15,931.10 MMcf
Proj Gas Cum: 6,483.52 MMcf
Gas Rem: 9,447.58 MMcf

Engineering Methodology

Reservoir Simulation vs. Decline Curve



Estimation of Recoverable Quantities

Reservoir Simulation

- Numerical computer simulators used to predict the flow of fluids (oil, gas, water)
- Types of simulation models
  - Black oil
  - Gas deliverability
  - Compositional
  - Streamline
- Performance
  - Pre-production model
  - History match
- Requires time and sufficient data
- Like other tools, if used to estimate reserves, the results should be calibrated based on perceived uncertainty

Estimation of Recoverable Quantities

- Recoverable estimates
  - Material balance
  - Decline curve analysis
  - Reservoir simulation
  - Analogy
  - Recovery factors
  - Forecasting reserves

Estimation of Recoverable Quantities

Analogy

- Analogous reservoirs share the following characteristics
  - Same geological formation (but not necessarily in pressure communication with the reservoir of interest)
  - Same environment of deposition
  - Similar rock properties
  - Similar geological structure
  - Same drive mechanism and development operations
  - Similar fluid characteristics
  - “Better” analogies are typically in the same area and geologic basin

- When may an analogy be used?
  - For estimates in reservoirs with little or no production history
  - When information on “analogous” producing reservoirs is available

Estimation of Recoverable Quantities

Analogy

- Widely used in reserves and resources estimation
- Can be used in volumetric and performance approaches
- Assumes that analogous reservoir is comparable to the subject reservoir (or "as good as or better than" for Proved)
- Depends on availability and suitability of analogs

Estimation of Recoverable Quantities

Analogous Reservoir: Example – Which Field is Analogous?

ANALOG INFORMATION
for
TWO STEVES FIELD

	Subject Field	Fields Considered for Analog				
Field Information						
Field Name	**Two Steves**	**Bordeaux**	**Mona Lisa**	**Antelope**	**Seine**	**Baylor**
Reservoir	A	A	A	A/B	A	A
Distance to Analogy Fields (kilometers)	0	21	129	25	97	131
Same Correlative Interval/ Stratum? (Y/N)	Y	Y	Y	Y (partially)	Y	Y
Analogy Parameters						
Porosity (%)	24.7	25.8	28.8	23.6	22.9	19-30
Permeability (mD)	2000	2000	660-4300	150-4300	1800	525-4900
Permeability distribution (heterogeneity)	Homogeneous	Homogeneous	Homogeneous	Heterogeneous	Homogeneous	Homogeneous
Thickness (meters)	28	43	8.5	22	28	80
Continuity (Continuous, Y/N)	Y	Y	Y	Y	Y	Y
Hydrocarbon Saturations (1-Sw, %)	71	79	80	60	73	48
Additional Analogy Parameters						
Oil Gravity (API)	33.5	31.4	27.4	31	31.8	32.6
Initial Solution GOR (scf/stb)	326	370	188	275	326	218
Oil Viscosity (cp)	8.66	4.7	16.3	5.2	7.5	8.2
Primary Recovery Factor (%)	**???**	44	25	28	31	48
Methodology Determining RF: Performance (Y/N)	N	Y	Y	partial	Y	Y

Estimation of Recoverable Quantities

Analogous Reservoir: Example – Which Field is Analogous?

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for
TWO STEVES FIELD

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Permeability distribution (heterogeneity)	Homogeneous	Homogeneous	Homogeneous	Heterogeneous	Homogeneous	Homogeneous
Thickness (meters)	28	43	8.5	22	28	80
Continuity (Continuous, Y/N)	Y	Y	Y	Y	Y	Y
Hydrocarbon Saturations (1-Sw, %)	71	79	80	60	73	48
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Initial Solution GOR (scf/stb)	326	370	188	275	326	218
Oil Viscosity (cp)	8.66	4.7	16.3	5.2	7.5	8.2
Primary Recovery Factor (%)	**Seine=31%**	44	25	28	31	48
Methodology Determining RF: Performance (Y/N)	N	Y	Y	partial	Y	Y

Estimation of Recoverable Quantities

Analogous Reservoir

- Key items to remember
  - Comparison of several potential analogs is advised
  - Distance is not the primary consideration
  - Document similarities and differences between analog and subject reservoir
  - Re-assess during development

- Data Sources
  - Rock properties
  - Fluid properties
  - Well Logs
  - Production data
  - Development plans and development histories

Estimation of Recoverable Quantities

- Recoverable estimates
  - Material balance
  - Decline curve analysis
  - Reservoir simulation
  - Analogy
  - Recovery factors
  - Forecasting reserves

Estimation of Recoverable Quantities

Recovery Factors: Definition

- Definition
  - RF = EUR/OOIP… oil
  - RF = EUR/OGIP…. gas

  Where,
    - RF = Recovery factor
    - EUR = Estimated ultimate recovery
    - OOIP = Original oil in place
    - OGIP = Original gas in place

- Properties affecting recovery factor
  - Reservoir heterogeneity and depositional environment
  - Reservoir rock and fluid properties
  - Reservoir drive mechanism
  - Aspects of well and field development

Estimation of Recoverable Quantities

Recovery Factors: Typical Values* for Various Drive Mechanisms

Drive Mechanism	Oil Reservoirs	Gas Reservoirs	Remarks
Oil expansion	2 to 5%	na	Higher recoveries reported
Gas expansion	na	70 to 95%	As low as 30% in low-permeability reservoirs; lower in tight gas reservoirs
Solution gas	10 to 30%	na	-
Gas cap	20 to 50%	na	Higher recovery efficiency generally associated with effective gravity segregation
Water drive	25 to 50%	45 to 70%	As low as 10% for thin oil columns; occasionally as high as 70%, or higher
Gravity Segregation	30 to 70%	na	-

*General industry guidelines on recovery factors

Estimation of Recoverable Quantities

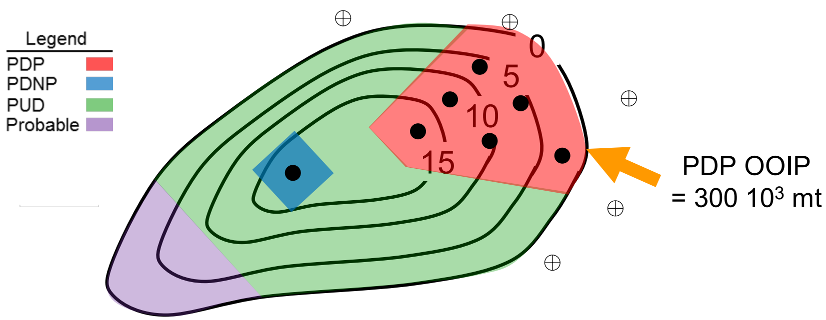
Recovery Factors: Estimation Methods

- Volumetric and Decline Curve Analysis
  - Common method when field/ reservoir is on production
  - Can be applied to undeveloped area
- Analogy
  - Useful if a large set of analogous reservoirs in a producing area is available
- Correlation
  - Numerous published recovery factor correlations
    - Water-drive sandstone reservoirs (1967 API), U.S. only
    - Solution-gas drive reservoirs, sandstones & carbonates (1967 API), U.S. only
  - Can be based on empirical data for specific area, reservoir, or facies
- Modeling
  - Analytic methods (e.g., gas deliverability model)
  - Simulation

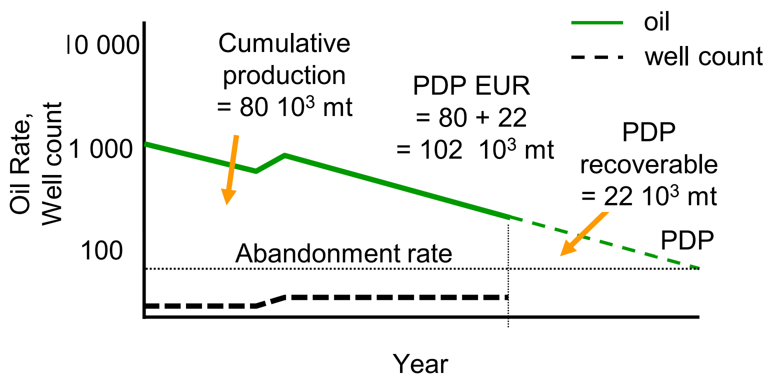
Estimation of Recoverable Quantities

Recovery Factors: Volumetric Estimates of PDP - Example

- Volumetric PDP Recovery Factor
  - PDP OOIP estimated from mapped volumes drained by producing wells
  - PDP EUR estimated from DCA of producing wells
  - PDP recovery factor is EUR / OOIP
- PDP OOIP from volumetrics



- PDP EUR from DCA



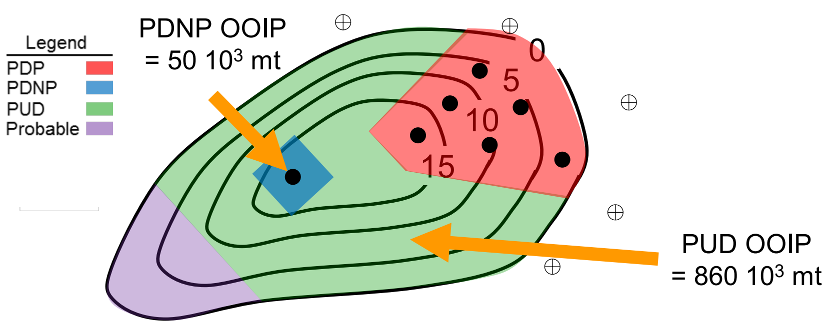
- PDP recovery factor
  - PDP RF = PDP EUR / PDP OOIP
  - PDP RF = (102 10^3 mt)/(300 10^3 mt)
  - PDP RF = 0.34, or 34%

Estimation of Recoverable Quantities

Recovery Factors: Volumetric Estimates of Proved - Example

- PDP RF applied to other Proved sub-categories
  - PDP RF = 34%
  - PDP recovery factor is applied to PDNP and PUD using analogy

- PDP OOIP from volumetrics



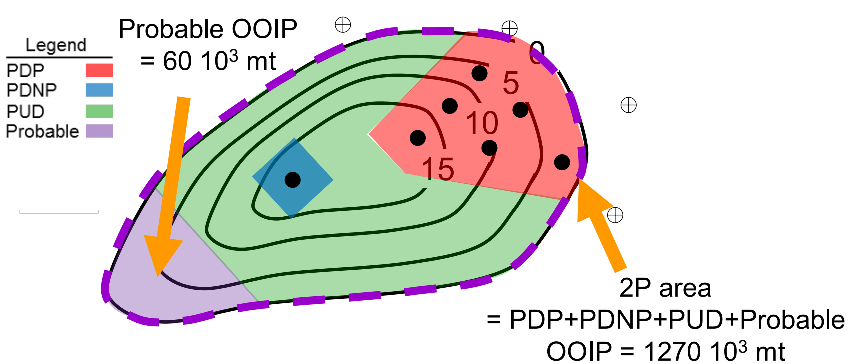
- PDNP recompletion area
  - RF = 34%
  - PDNP OOIP = 50 10^3 mt
  - PDNP EUR = PDNP OOIP * RF
  - PDNP EUR = 50 * 0.34 = 17 10^3 mt

- PUD drilling area
  - RF = 34%
  - PUD OOIP = 860 10^3 mt
  - PUD EUR = PUD OOIP * RF
  - PUD EUR = 860 * 0.34 = 292 10^3 mt

Estimation of Recoverable Quantities

Recovery Factors: Volumetric Estimates non-Proved - Example

- 2P and 3P Recovery Factors
  - 2P, 3P values estimated from
    - Alternate performance estimates
    - Simulation or analytical models
    - Analogy
- OOIP from volumetrics

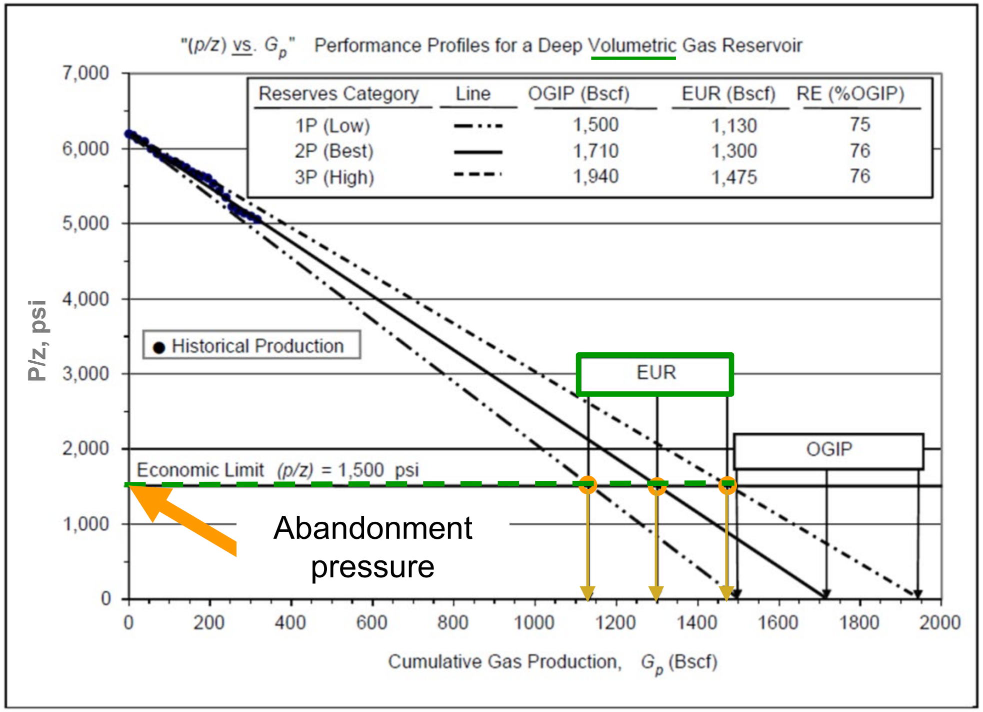


- Probable area
  - 2P RF = 40%
  - Probable OOIP = 60 M 10^3 mt
  - Probable EUR = Probable OOIP * 2P RF
  - Probable EUR = 60 * 0.40 = 24 10^3 mt
- Probable improved recovery
  - Total Proved OOIP = 300 + 860 + 50
    = 1210 10^3 mt
  - ΔRF = 2P RF - 1P RF = 40% - 34% = 6%
  - Probable improved recovery =
    Total Proved OOIP * ΔRF
  - Probable improved recovery =
    1210 * 0.06 = 73 10^3 mt
- Similar for 3P (Possible)

Estimation of Recoverable Quantities

Recovery Factors: Gas Recovery Factors - Example

- Parameters affecting gas recovery factors (Material Balance)
  - Abandonment pressure
  - Geologic complexity
  - Facilities constraints
  - Working pressure
  - PVT correlations



Gas reserves assessment by material balance methods (Late-Production Stage).

Figure 4.8: SPE, Guidelines for Application of the Petroleum Resources Management System, November 2011

Estimation of Recoverable Quantities

- Recoverable estimates
  - Material balance
  - Decline curve analysis
  - Reservoir simulation
  - Analogy
  - Recovery factors
  - Forecasting reserves

Estimation of Recoverable Quantities

Forecasting Recoverable Quantities: Development Plan Data

- Client-supplied development plan is basis for reserves:
  - By field (and by reservoir, if available)
  - By year
  - Lists separate development activities

- Forecasted activities of client development plan:
  - Drilling (vertical drills, horizontal wells, sidetracks, deepening wells)
  - Recompletions
  - Workovers (hydraulic frac, re-entry of well, well restoration)

- Client production forecasts
  - Corresponds to development plan?
  - Provides additional check when analyzing development plan

Estimation of Recoverable Quantities

Forecasting Recoverable Quantities: Outputs

- Production forecasts of reserves include:
  - Gas, condensate, oil, water (total fluids), well counts
  - Development activity counts (drilling, sidetracking, recompletions, etc.)

- Production forecasts are by
  - Reserve category: PDP, PDNP, SEC PUD, PRMS PUD, Probable, Possible
  - Activity type: drill, recompletion, improved recovery, etc.
  - Reservoir level, which are summed to field level

- Forecasts of production serve as inputs into economic model
  - Production streams and well counts are inputs for OPEX models
  - Development activity counts are input for CAPEX models

Estimation of Recoverable Quantities

Forecasting Recoverable Quantities: Historical Well Activity Data – Example 1.1

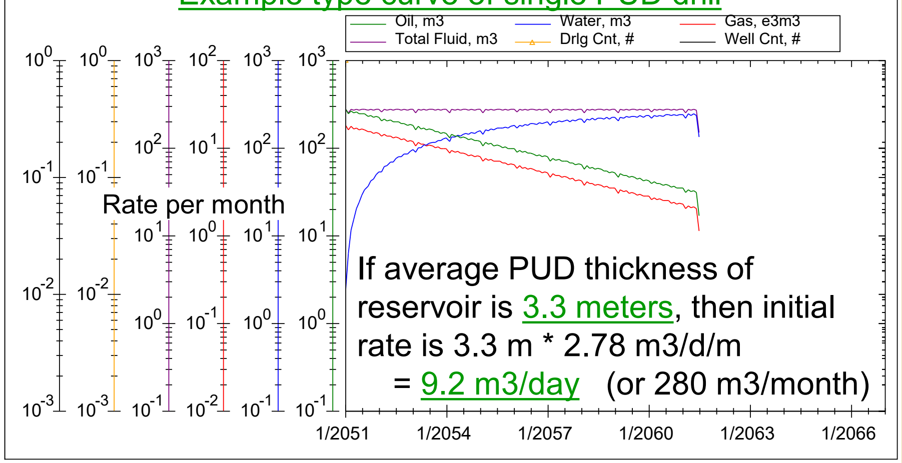
- Historical well activity
  - Recent historical drilling (and recompletion) activity allows for accurate estimation of initial rates
  - Requires reservoir level data
  - Oil and water initial rates
  - Well thickness, if available

Example initial rates of recent drilling in reservoir of field

Well No.	Formation Thickness (meter)	Initial Oil Rate (mt/day)	Initial Water Cut (fraction)	Rate/thickness (m3/d/m)
129	6	15.5	0.65	2.59
133	7	16.6	0.83	2.37
134	20	61.6	0.30	3.08
139	16	49.2	0.50	3.07
Average	12	**35.7**	**0.57**	**2.78**

- Type curve input (PUD drill)
  - EUR per well
  - Initial rates of oil and water
  - Final rate (for example 1% WC)
  - Typically, exponential decline used
  - Decline and life of well are calculated

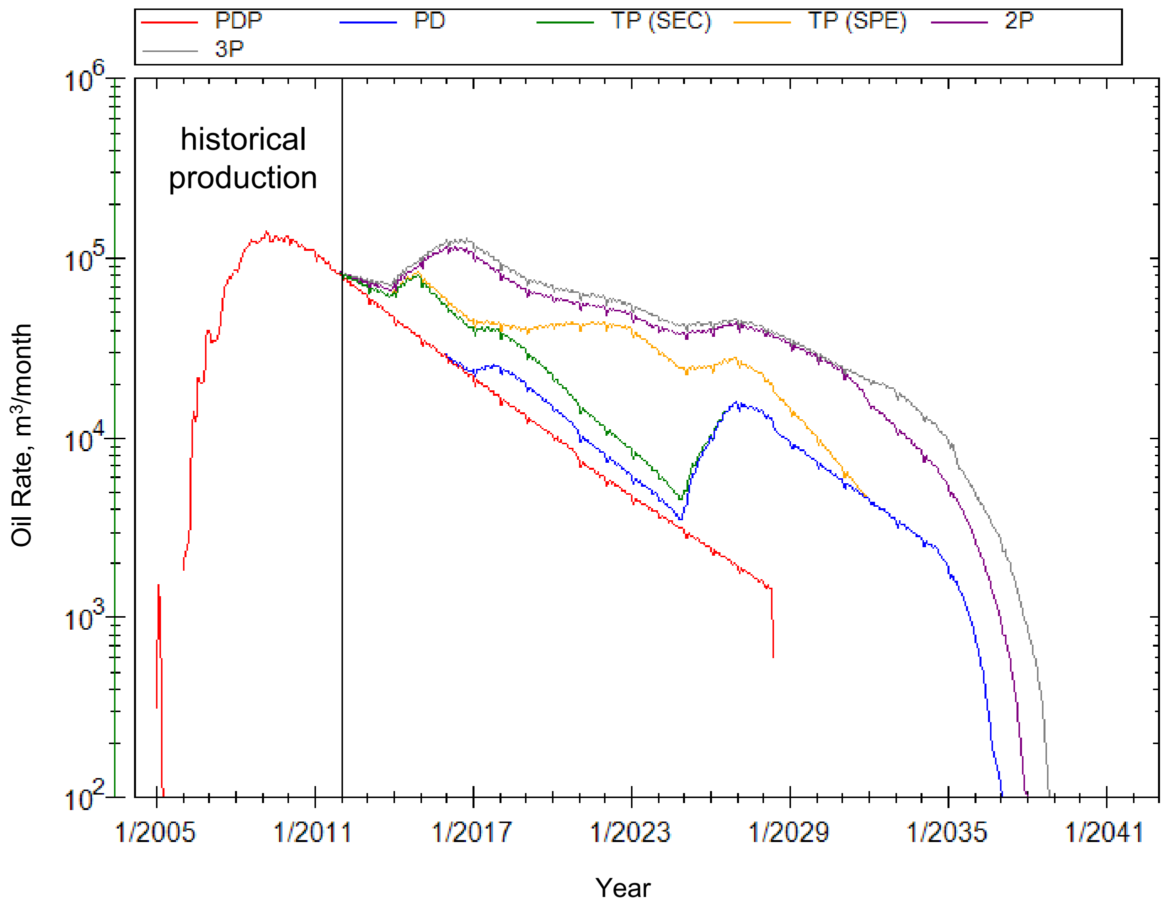
Example type curve of single PUD drill



Estimation of Recoverable Quantities

Forecasting Recoverables: Field Forecasts – Example 1.3

Oil Production Categories for Entire Field



Estimation of Recoverable Quantities

Tools/Software Used for Engineering

- Material balance
  - D&M in-house software
  - Commercially available software (MBAL)
- Gas deliverability
  - D&M in-house software
  - Commercially available software (Fekete)
- Decline-curve analysis
  - Commercially available software (PHDWin)
- Reservoir simulators
  - D&M in-house model (black oil simulator)
  - Commercially available software (Eclipse)
- D&M Analogy Database