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The Science and Economics of Multiphase Flow

Mack Shippen
Schlumberger

Society of Petroleum Engineers
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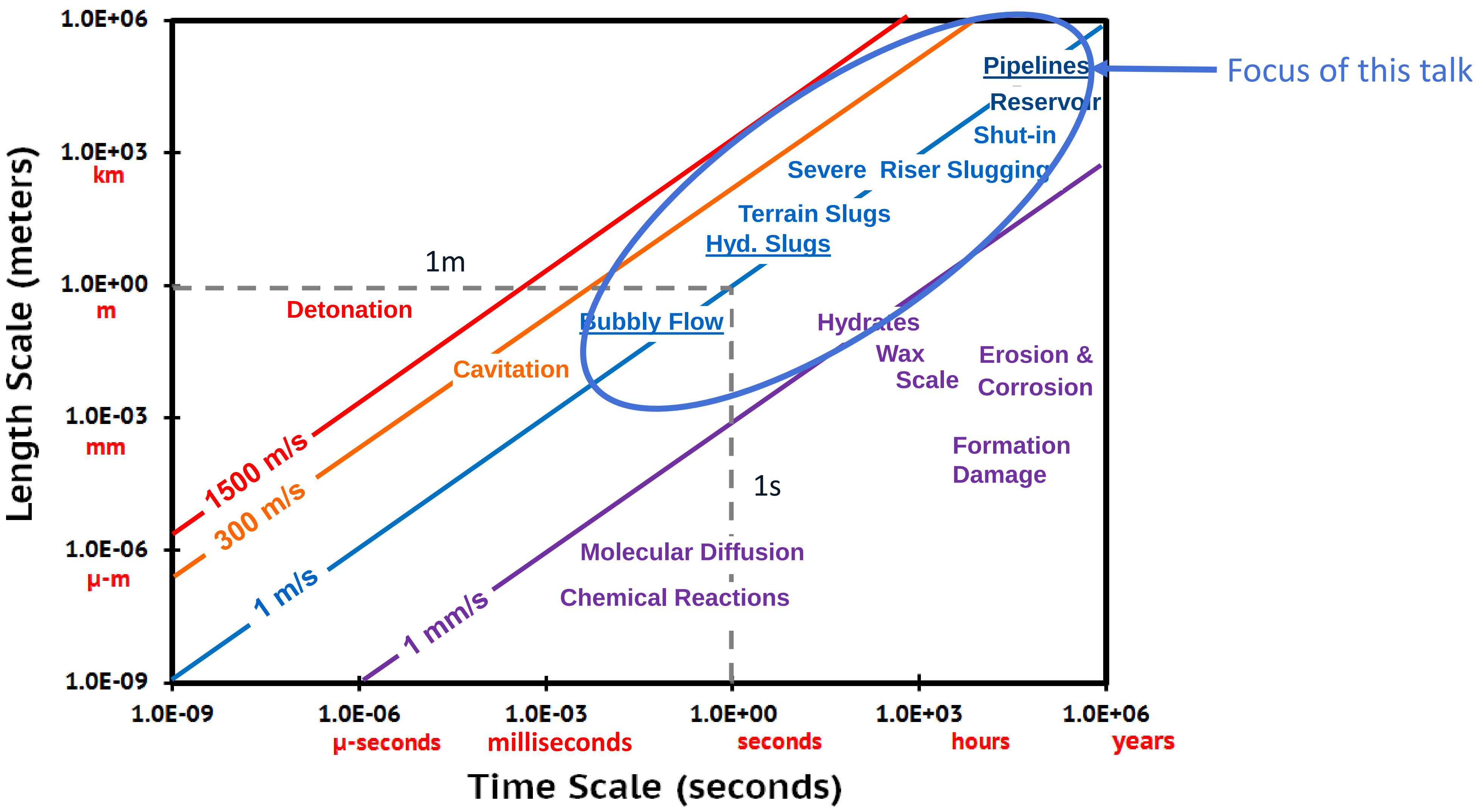
Outline

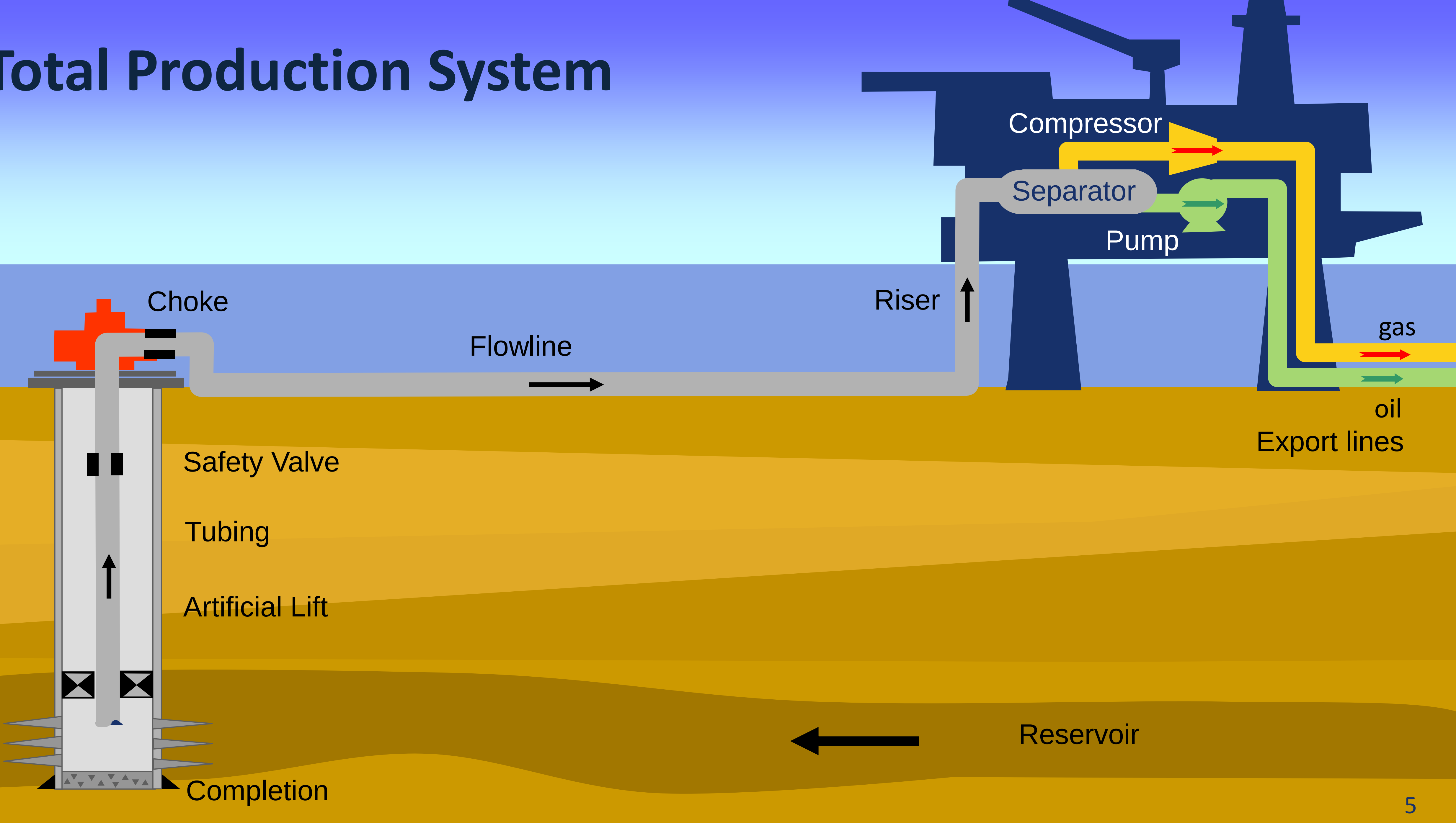
SPE DISTINGUISHED LECTURER

- **Introduction**
- The Science of Multiphase Flow
- The Economics of Multiphase Flow
- Concluding Remarks

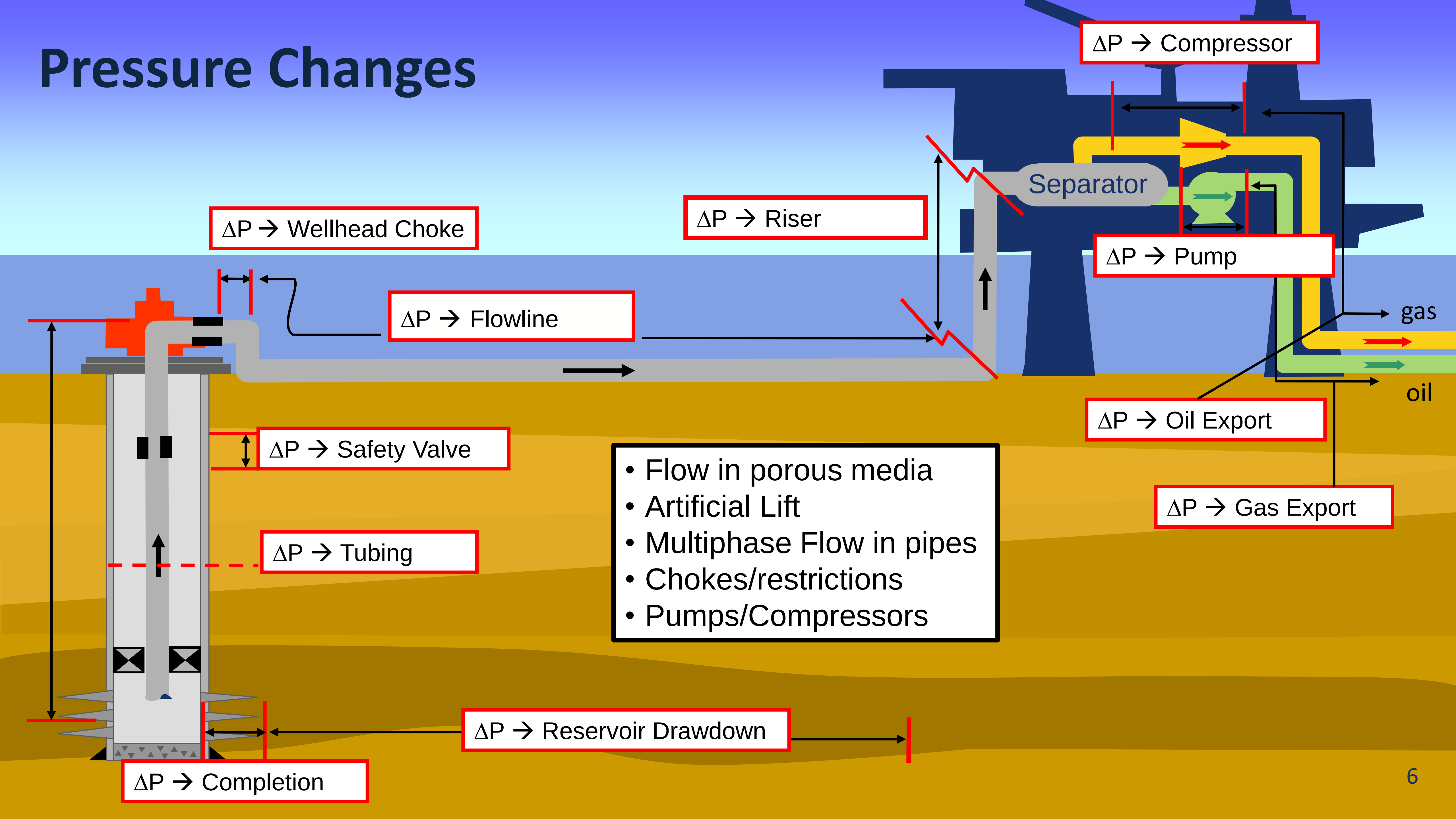
A Broad View of Fluid Mechanics



Total Production System

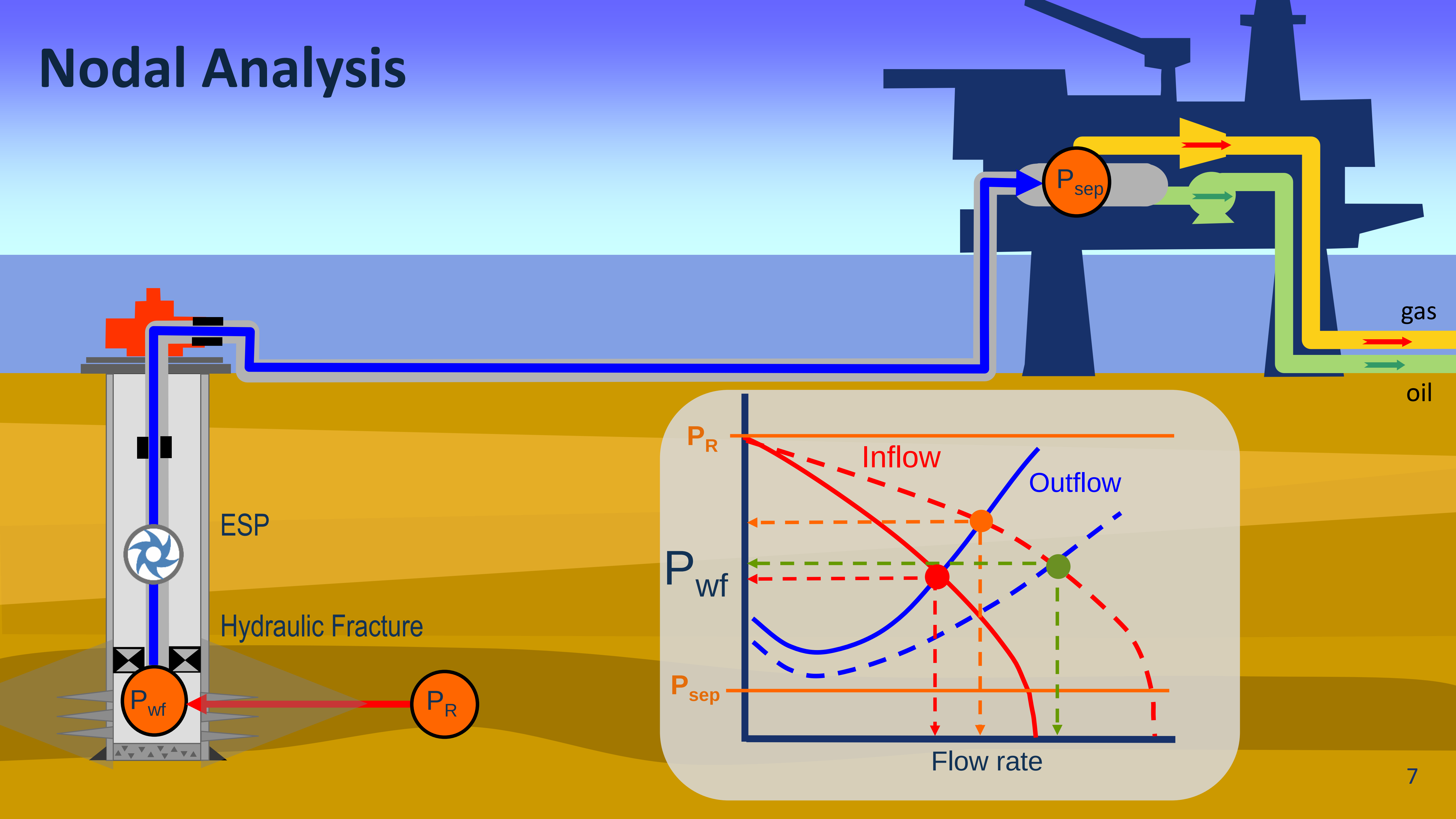


Pressure Changes

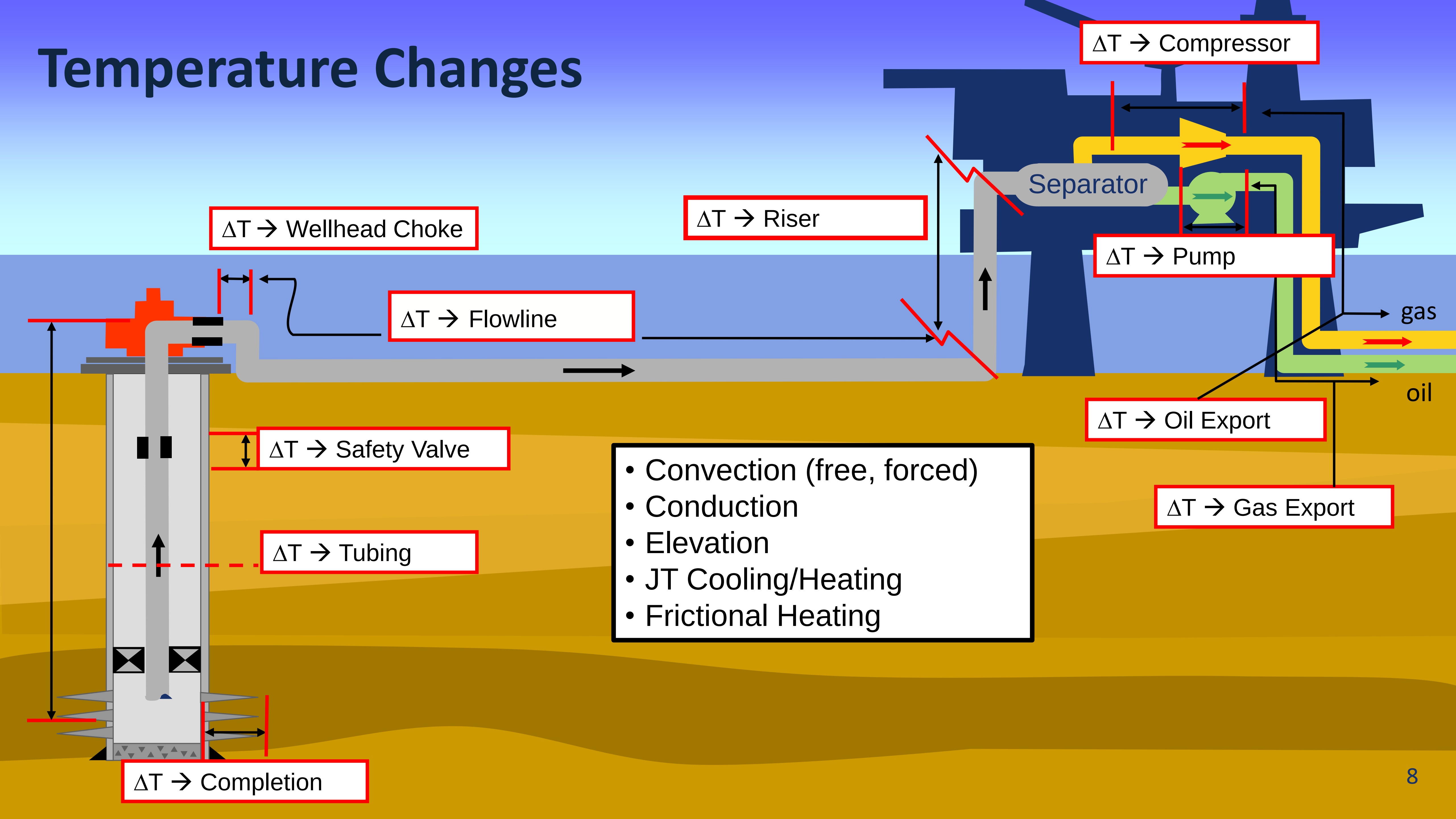


- Flow in porous media
- Artificial Lift
- Multiphase Flow in pipes
- Chokes/restrictions
- Pumps/Compressors

Nodal Analysis

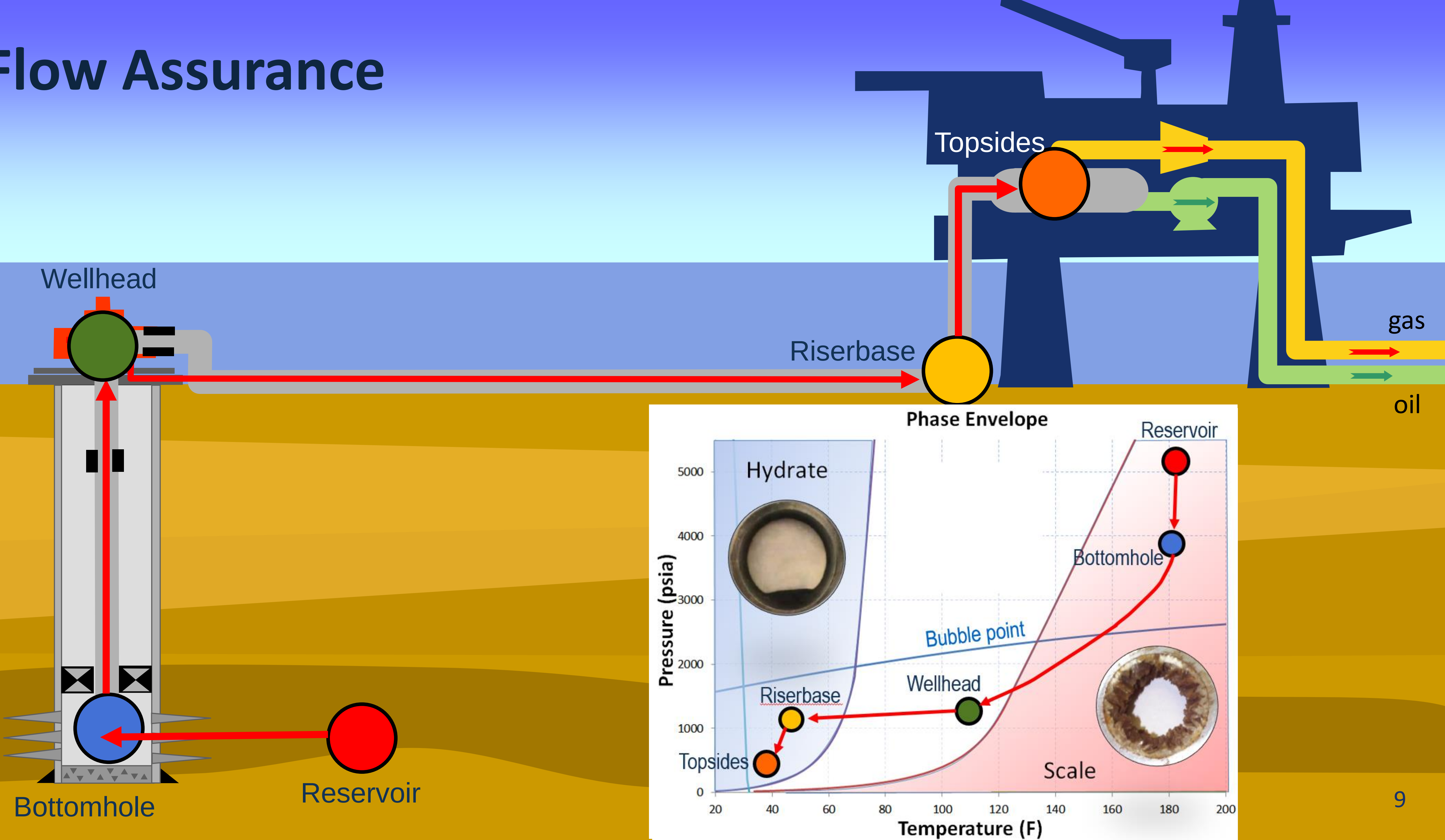


Temperature Changes



- Convection (free, forced)
- Conduction
- Elevation
- JT Cooling/Heating
- Frictional Heating

Flow Assurance



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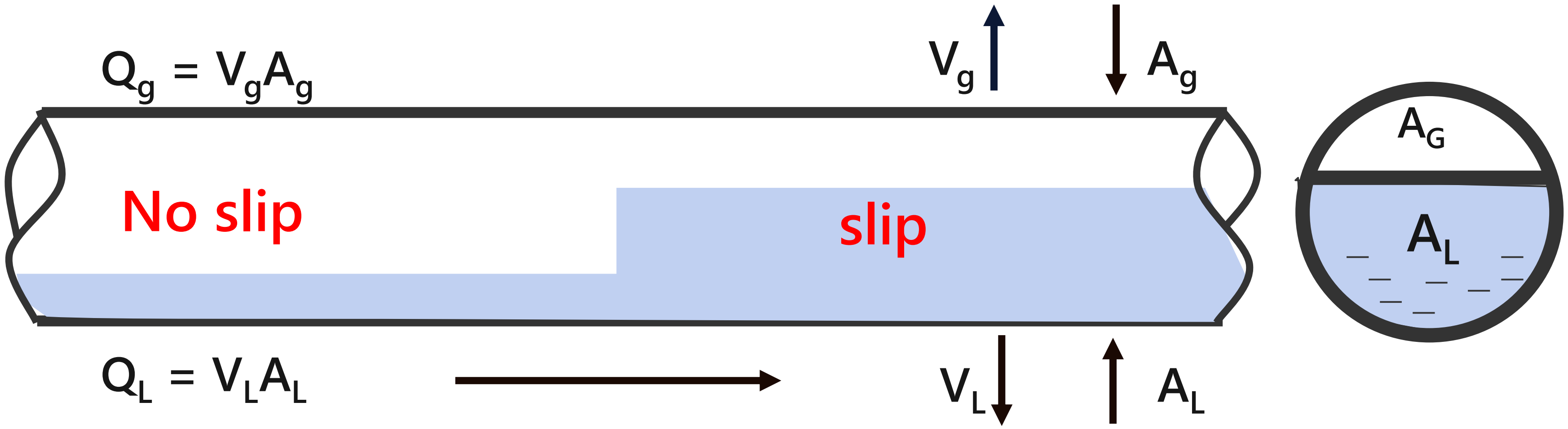
Liquid Holdup

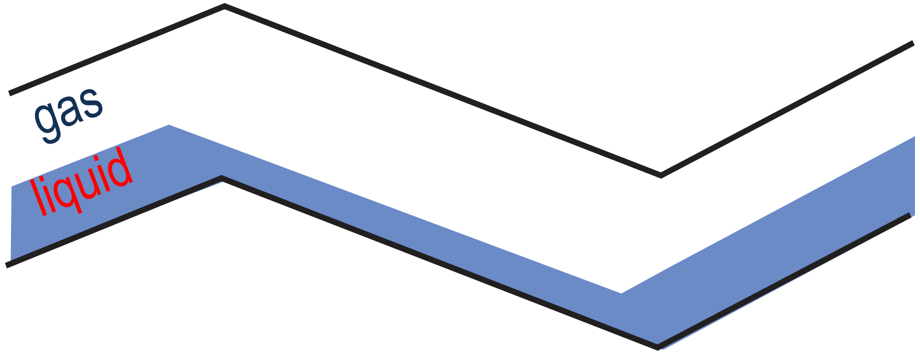
- Function of the degree of gas-phase slippage
- Gas travels faster because of lower density and viscosity
- Higher mixture velocity → less slip



$$H_L = \frac{A_L}{A_{PIPE}}$$

Holdup = 0 → All gas flow
Holdup = 1 → All liquid flow

Pressure Losses



Terrain effects are important! pressure losses uphill are only partially recovered going downhill

$$\left[\frac{\Delta p}{\Delta L}\right]_{\text{Total}} = \underbrace{\left[\frac{\Delta p}{\Delta L}\right]_z}_{\text{elevation}} + \underbrace{\left[\frac{\Delta p}{\Delta L}\right]_f}_{\text{friction}} + \underbrace{\left[\frac{\Delta p}{\Delta L}\right]_a}_{\text{acceleration}}$$

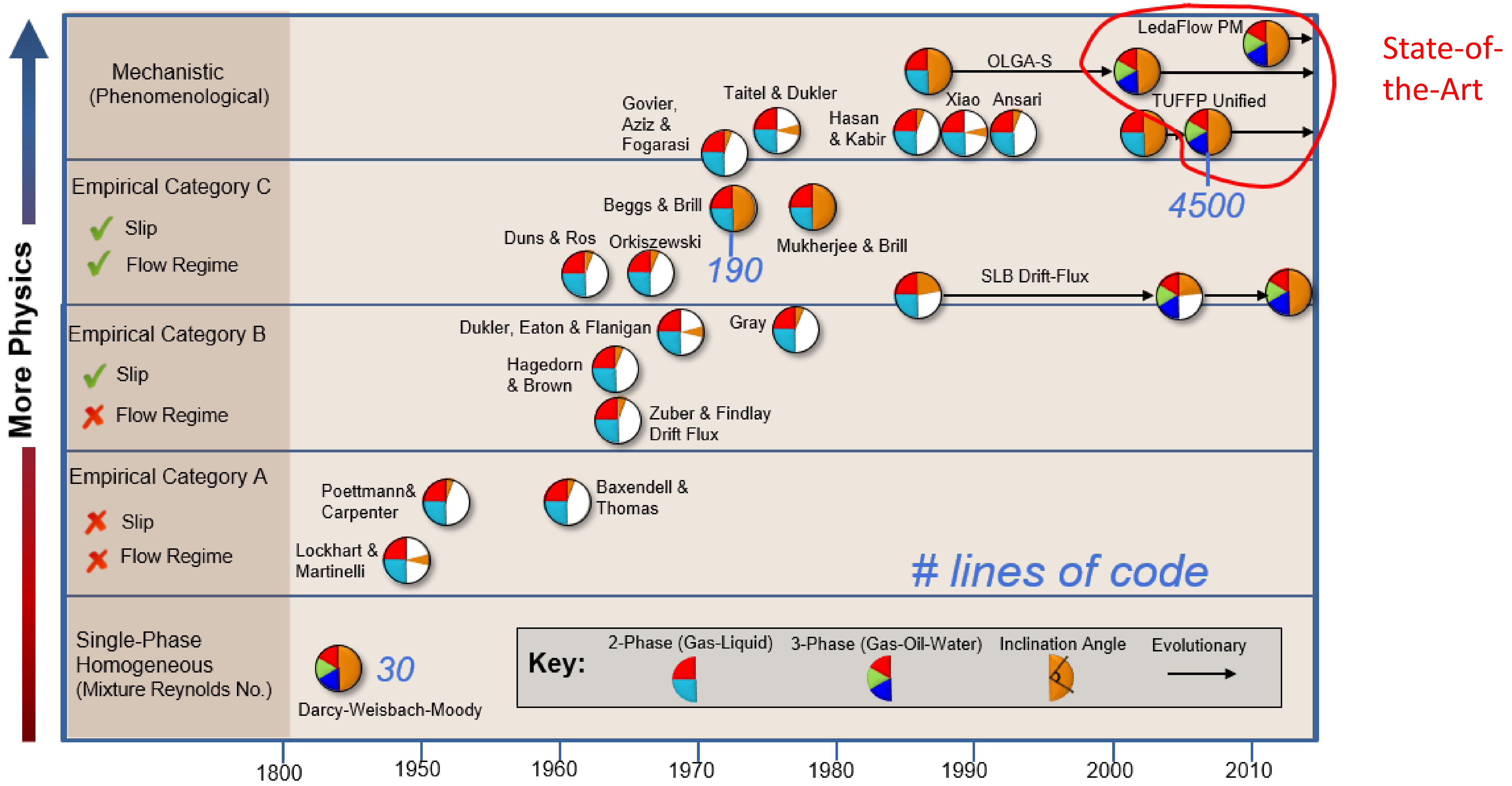
$$\rho g \sin\theta \qquad f\frac{\rho v^2}{2D} \qquad \rho v \frac{\Delta v}{\Delta L}$$

∝ *density*

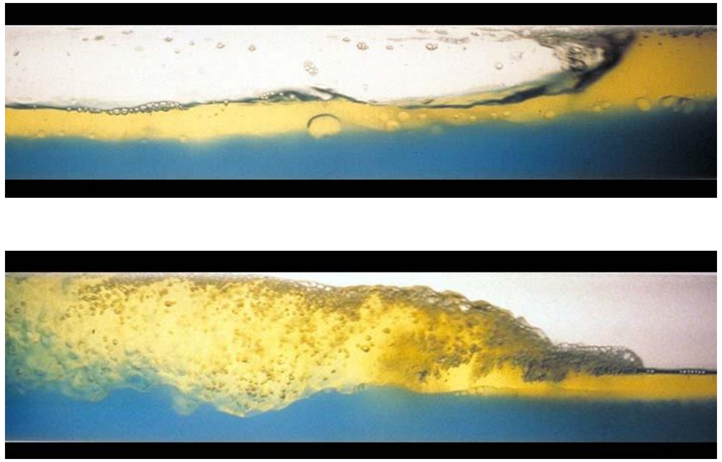
∝ *velocity*
∝ *viscosity*

~ *zero*

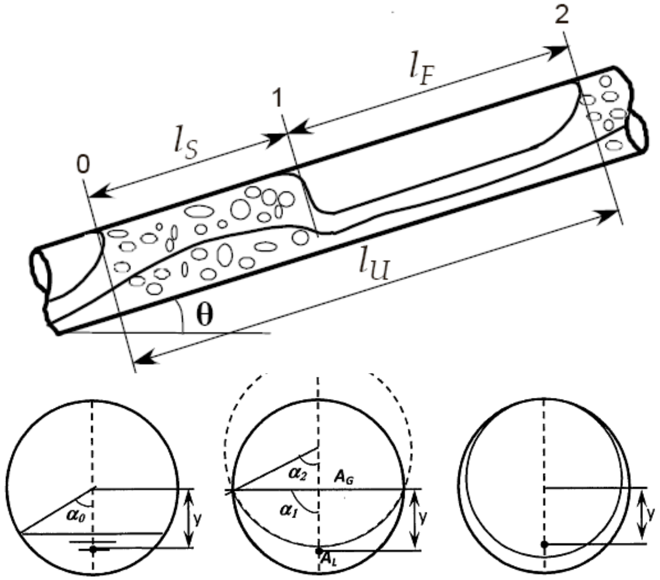
Evolution of 1D Steady-State Multiphase Models



3-Phase Mechanistic Flow Models



Reality



Model

SPE 19451

BHR 2007-A2 BHR

SPE 95749

- Based on combined force and momentum balances and best represent the physics of multiphase flow
- Account for broad ranges of fluids and pipe geometries
- Top 3 (State-of-the-Art) include OLGAS, LedaFlow and TUFFP

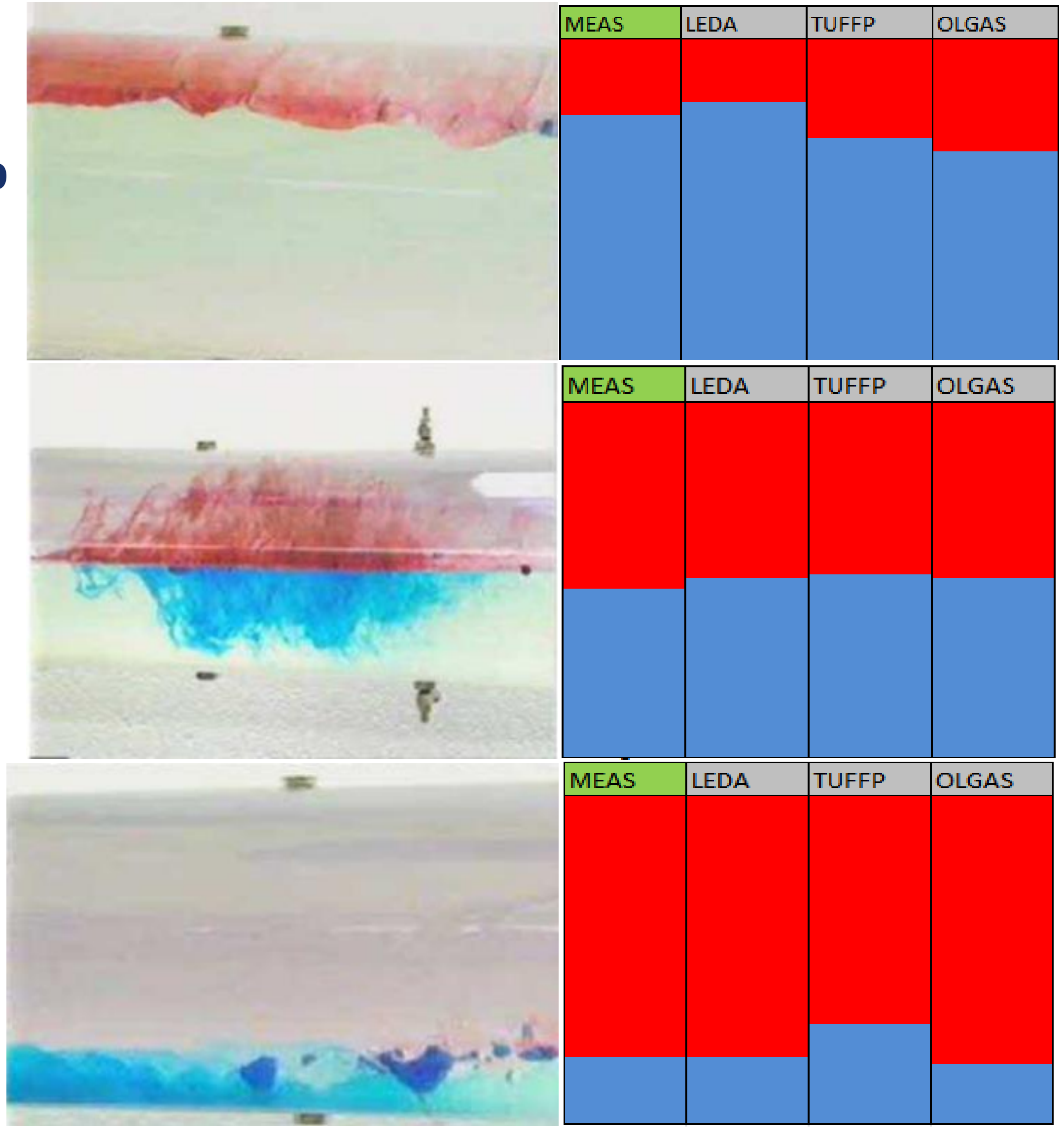
Oil-Water Flow

6-inch pipe
1500 BOPD
1500 BWPD
1.5 cp oil

2^0 up

0^0

2^0 down



Oil–water flow experiments in 6-in.-diameter pipe (oil shown with red dye and water with blue dye). Each case has identical volumetric flow rates: 1500 bpd of each phase. The left-hand image shows upward flow inclined at θ = +2 ° (from the horizontal). The center image shows horizontal flow θ =0 °, while the right-hand image shows downward flow inclined at θ = −2° (from the horizontal). We observe that in the left-hand image, oil "slips" much faster over the water. In the center image, we have near-perfect stratified flow with no discernible slippage between phases, while in the right-hand image, we observe water rapidly slipping beneath the oil. These experiments clearly show how even a small inclination in pipe elevation can have a dramatic effect on slippage and associated flow regimes.

Rule of 10's For Today's "State of the Art"

Can generally expect +/- 10% Error in Accuracy of Holdup and Pressure Predictions for conditions of:

- Stable Flow < Operating Rate < Erosional Limits
- Deviation angles ±10º of vertical or horizontal
- Liquid volume fractions > 10%
- Water or oil fraction < 10% relative to total liquid
- Pipe diameters < 10 inches
- Oil viscosities < 10^2 centipoise

Multiphase Flow Research Centers


University of Tulsa (TUFFP), US

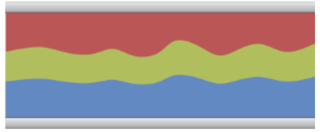

Sintef, Norway


Cranfield University (TMF), UK

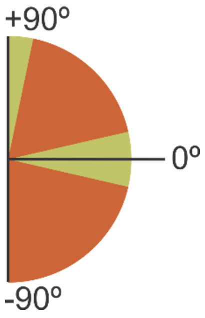

IFE, Norway

Top 5 R&D Challenges

1. 3+ Phases



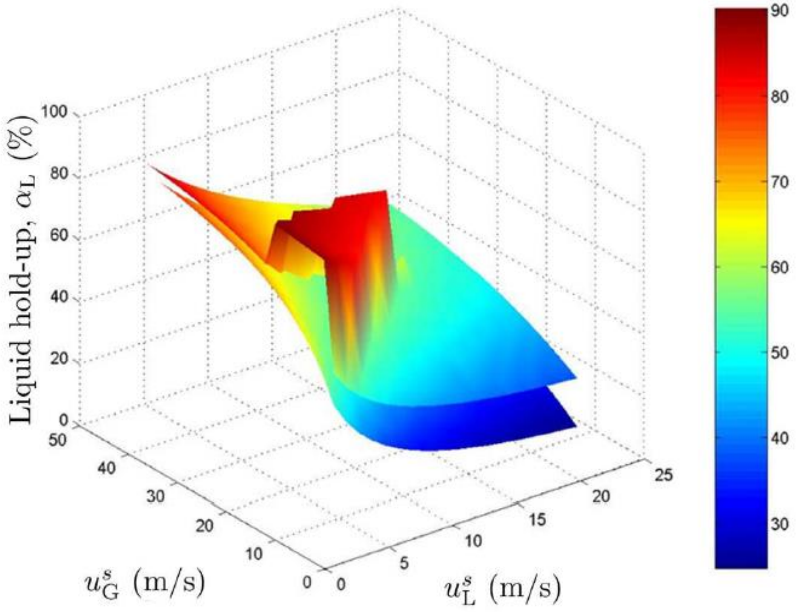
2. Odd Angles



3. Exotic Fluids
- Heavy Oil
- Foam
- Slurries

4. Improved Closure Relationships

5. Model Discontinuities



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Economics

"Economics is the study of the use of scarce resources which have alternative uses"

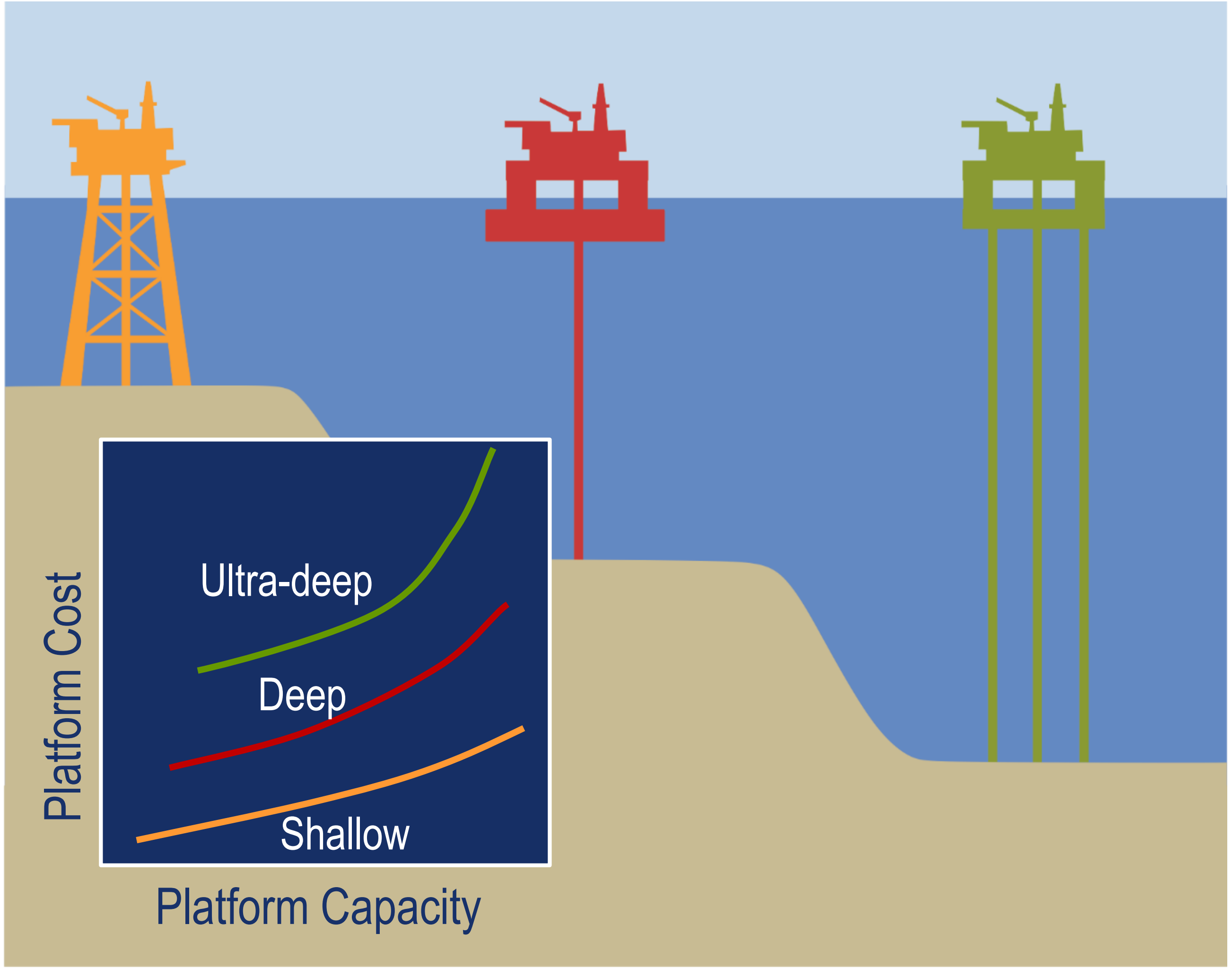
- Lionel Robbins

Examples

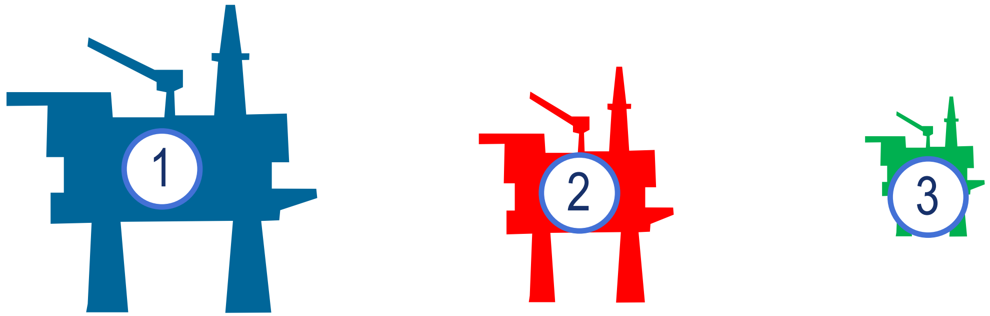
Example	Description
1 - Offshore Field Planning	Offshore Oil
2 - Slug Catcher Sizing	Offshore Gas Condensate
3* – Terrain Effects	Onshore Shale Oil
4* – Heavy Oil Pipeline	Onshore Heavy Oil

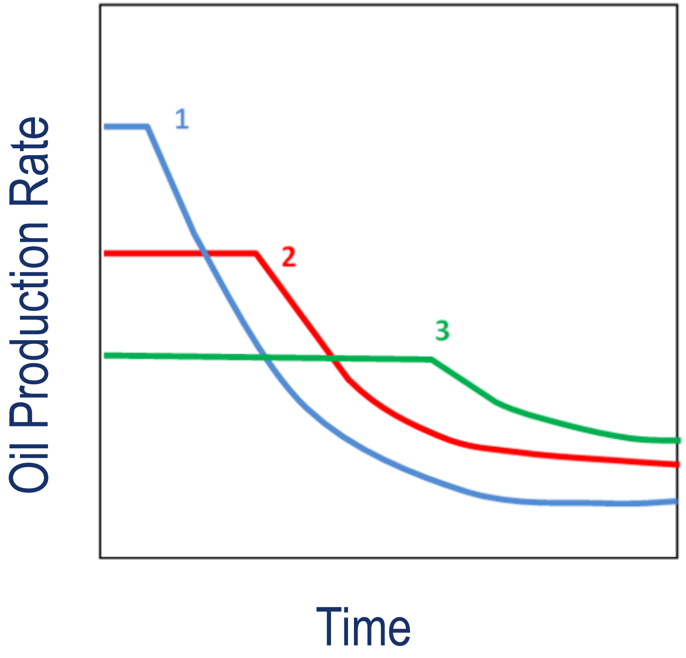
* Backup example for onshore focused audiences – see supplemental slides

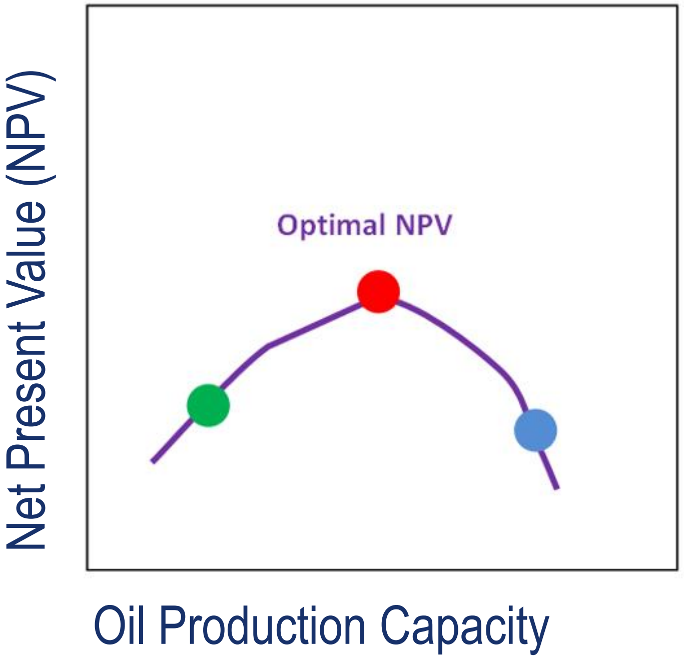
Example 1: Offshore Field Planning



Example 1: Optimal Platform Size







Example 1: Integrated Modeling

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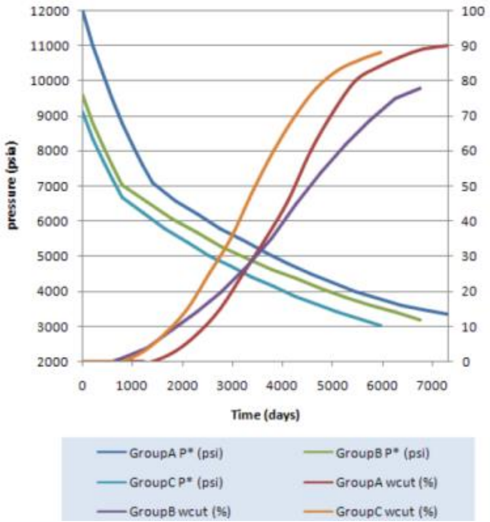
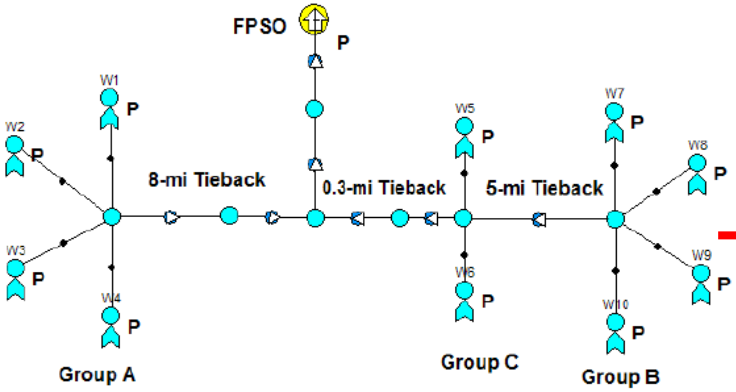
Constraints:

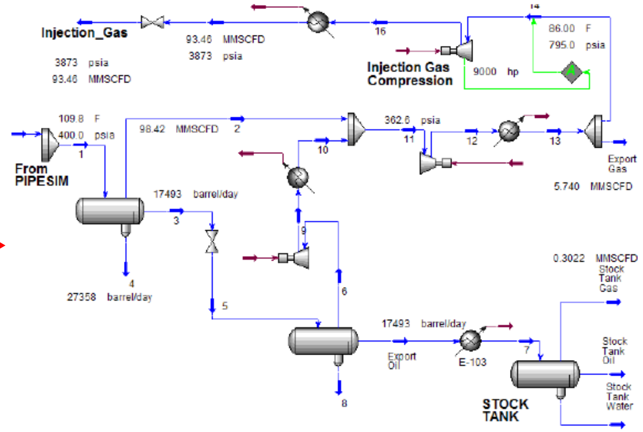
Max. Liquids: 80,000 BPD
Max. Water: 25,000 BPD
Max Gas Lift: 100 MMscfd
Compressor power: 9,000 Hp.



Reservoir Forecast



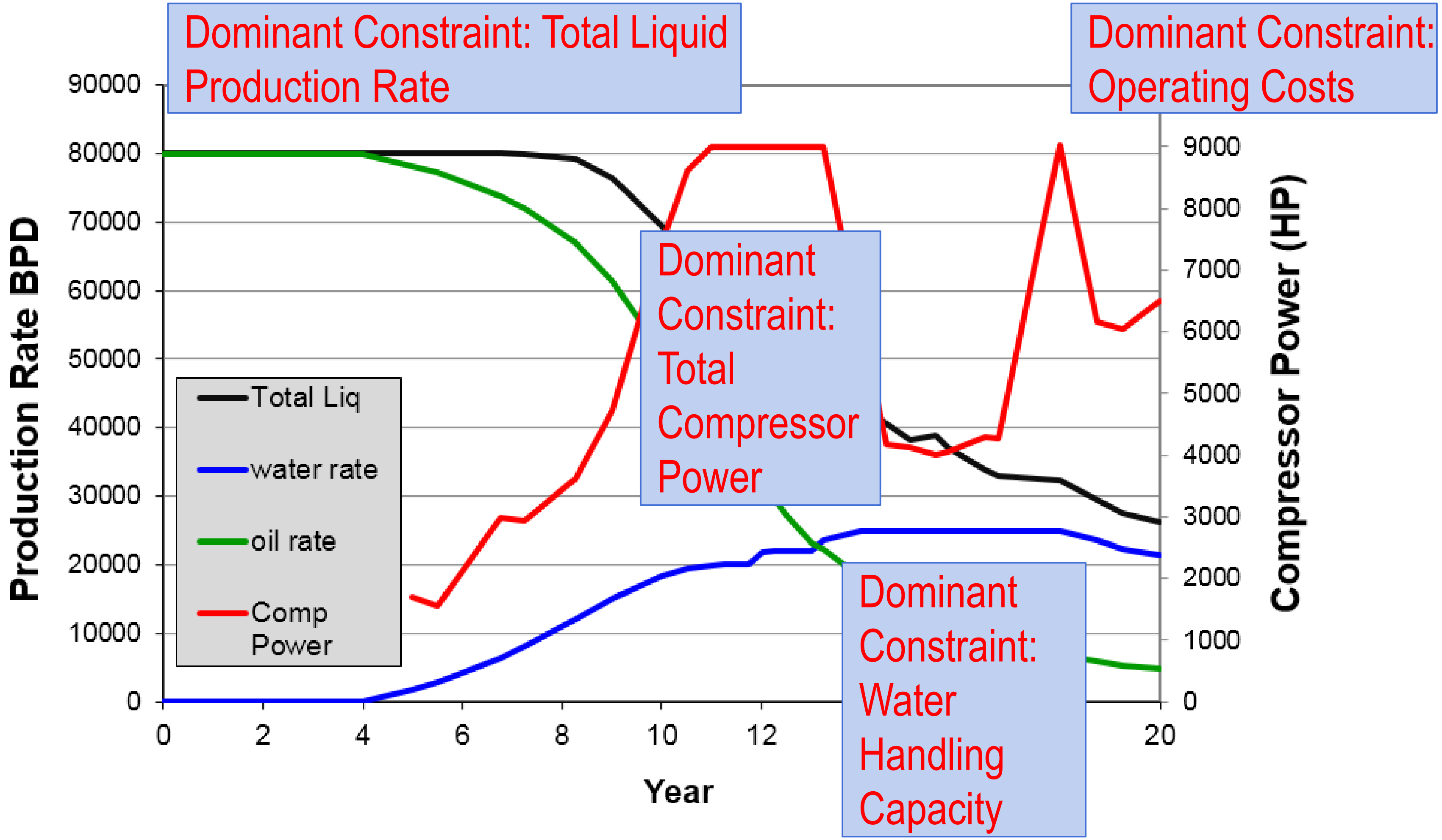
Production Network



Process Facilities

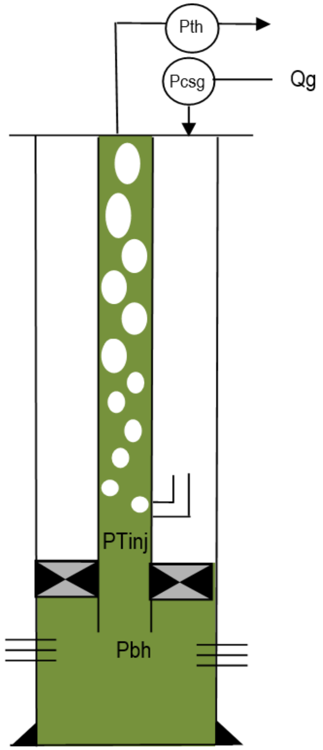
IPTC-11594 IPTC International Petroleum Technology Conference

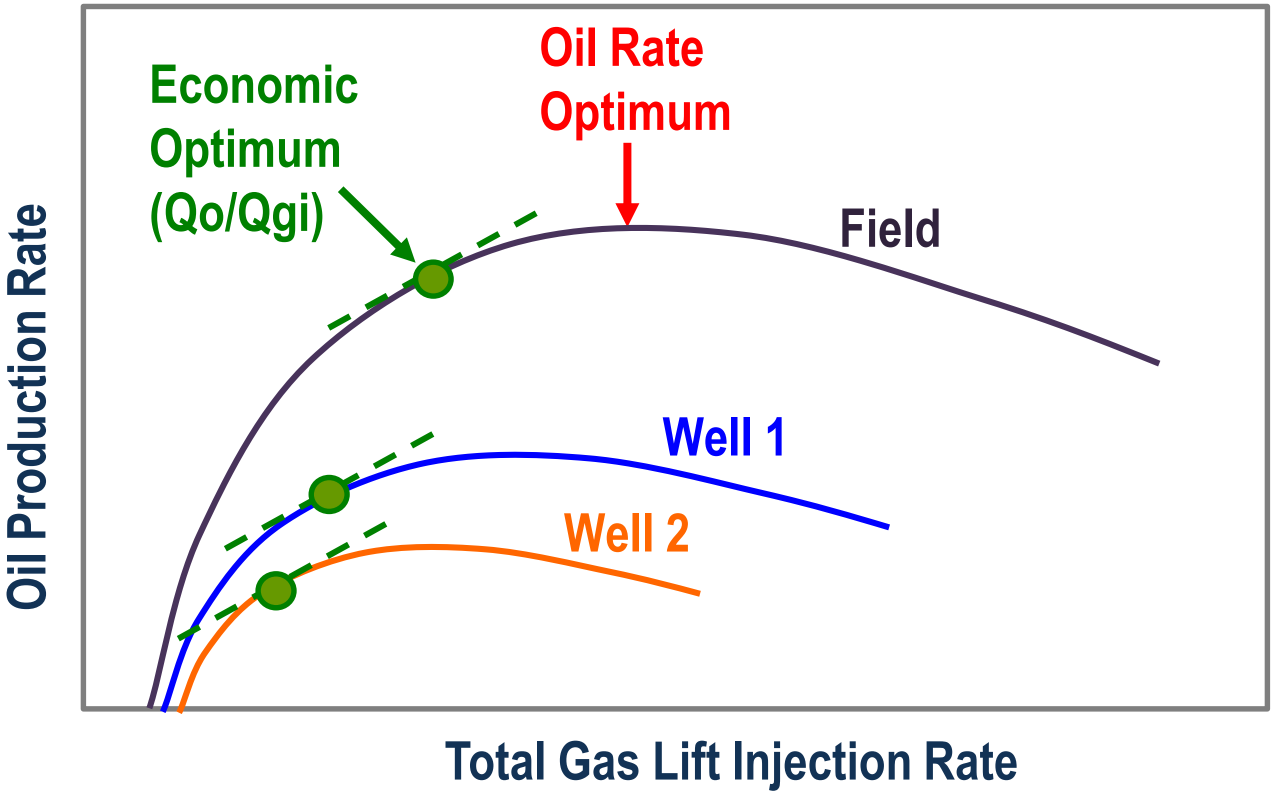
Example 1: Dealing with thru-life constraints



IPTC-11594

Example 1: Gas Lift Optimization





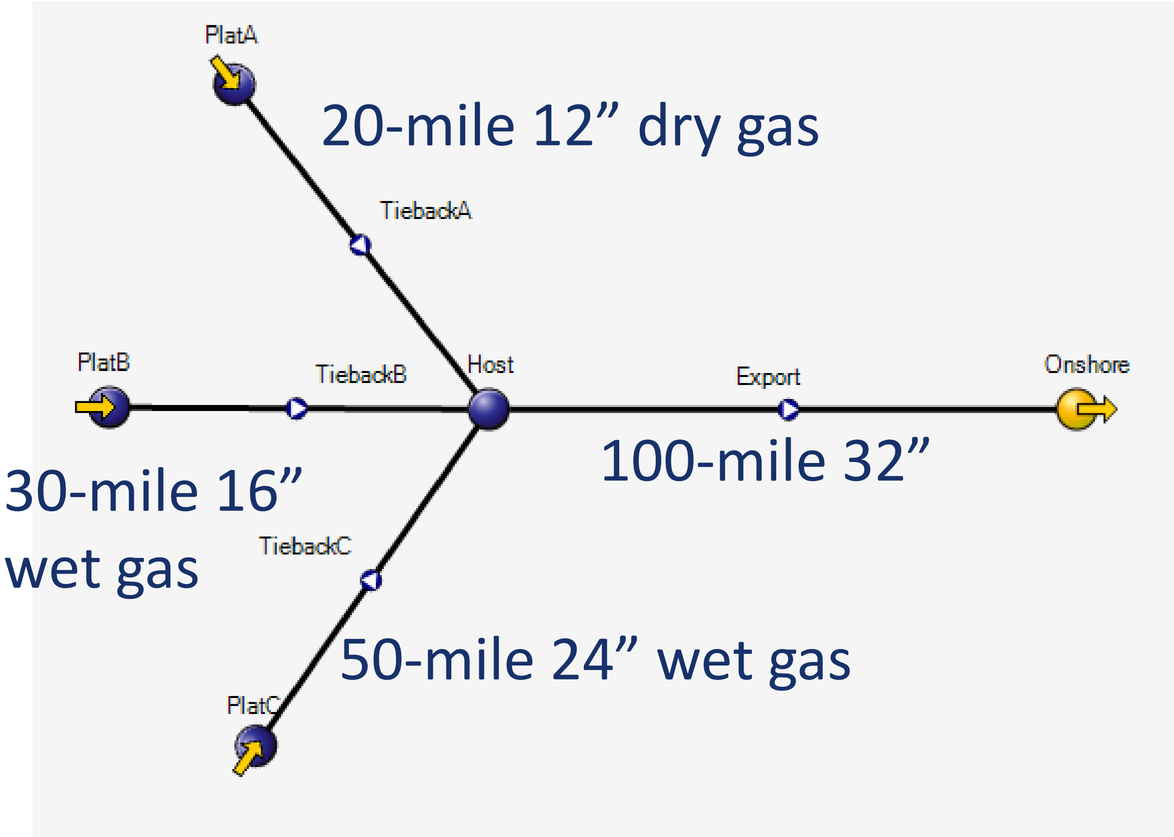
Numerous published field studies have shown gas lift optimization to improve production by 3-15%

SPE 123799

SPE 120664

SPE175785

Example 2: Liquids Handling for Offshore Wet Gas Export Pipeline



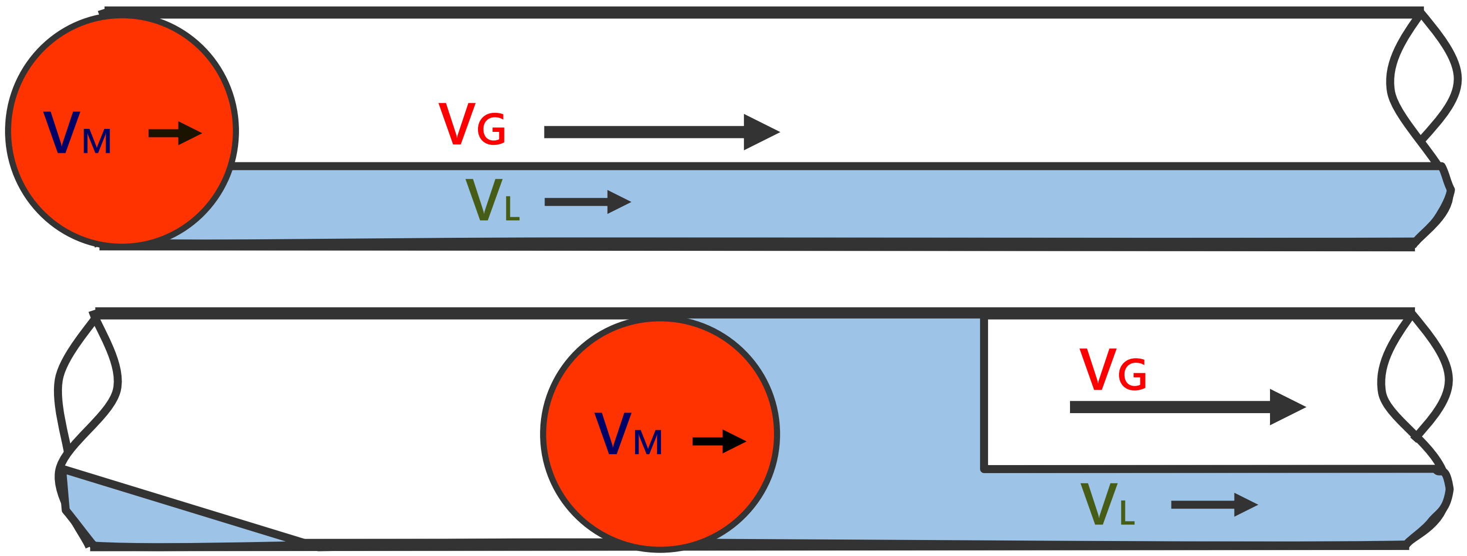
Onshore Slug Catcher

PSIG 0403 PSIG

Example 2: Pigging a Flowline

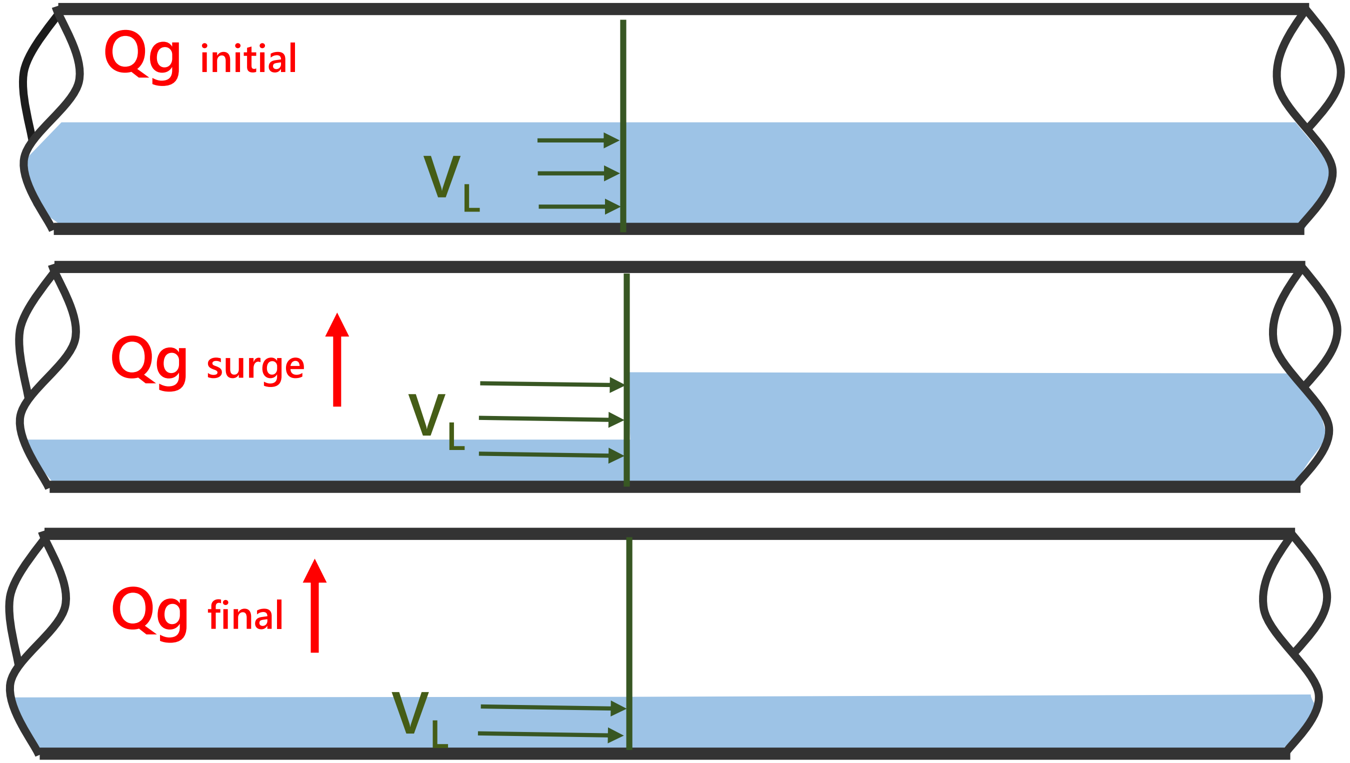
Why?

- Remove solids > reduce blockage risk
- Remove liquids > less pressure loss



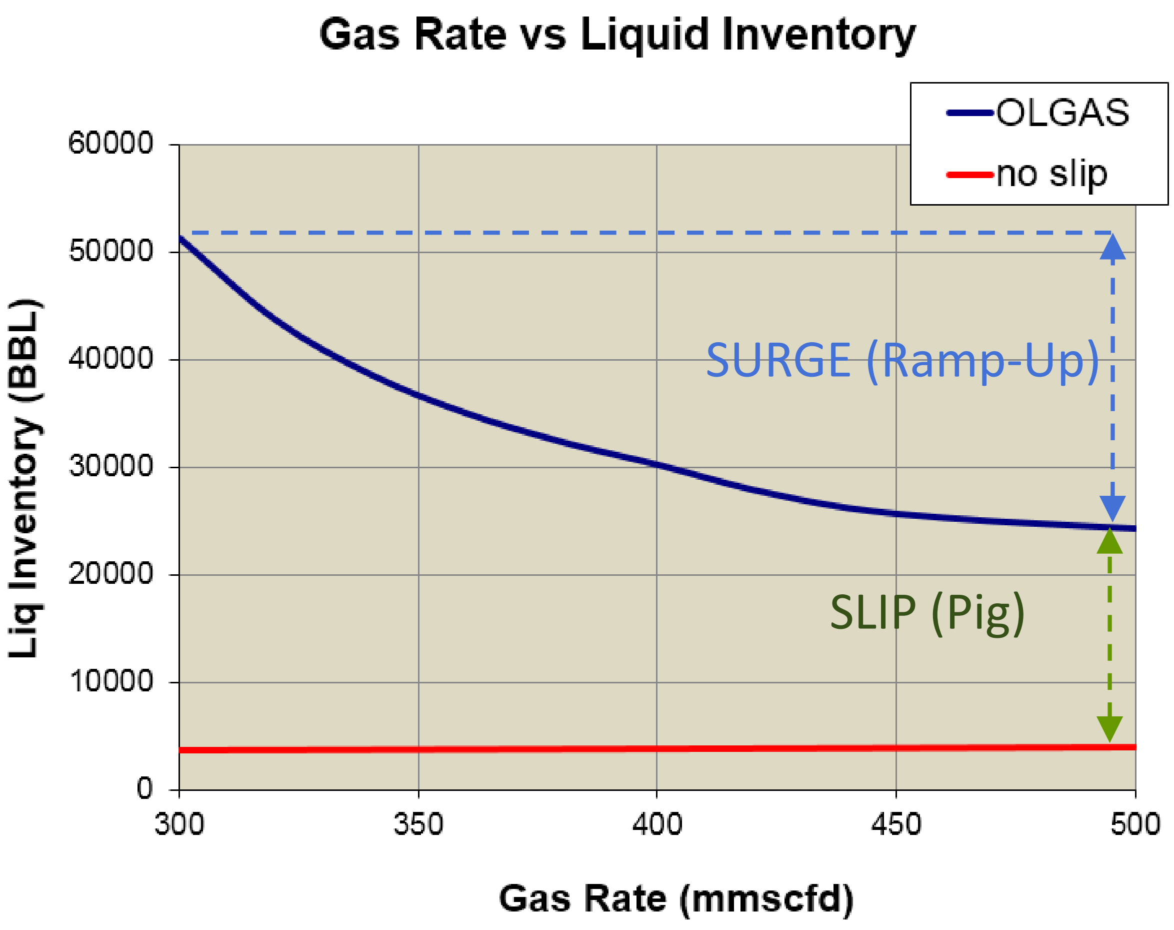
Size of slug proportional to gas-liquid slip

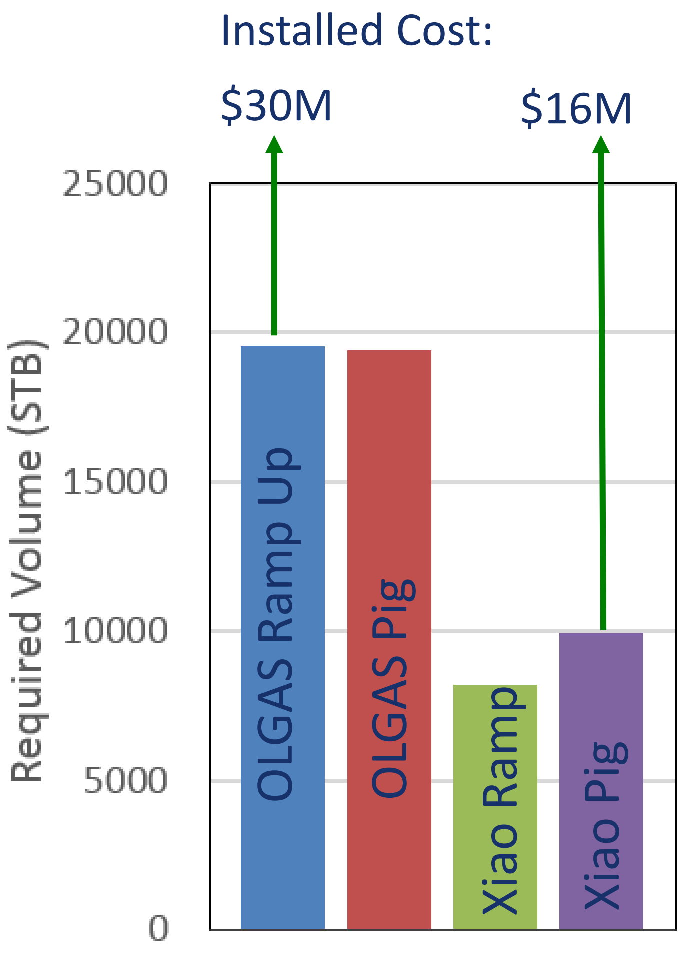
Example 2: Ramp-Up Surge



Size of surge proportional to difference in liquid content before and after

Example 2: Slug Catcher Sizing





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Concluding Remarks

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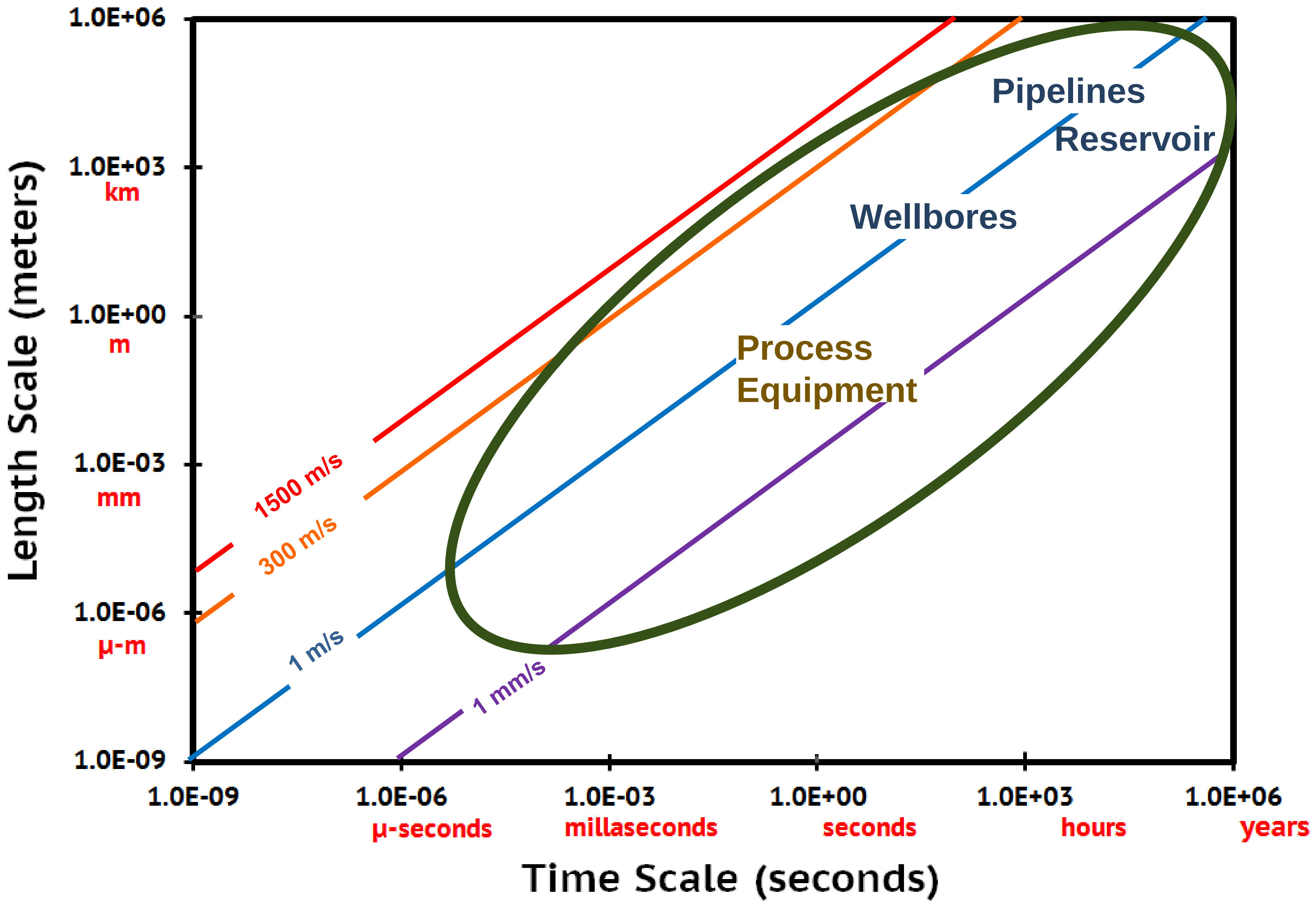
- Good technology in multiphase flow modeling has emerged from years of research and development
- Challenges still remain → flow assurance is not a certainty
- Economics justify the Science!
- Ultimate goal is to maximize production while minimizing flow assurance risks and operational costs

An Integrated View of Fluid Mechanics



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Supplemental Slides

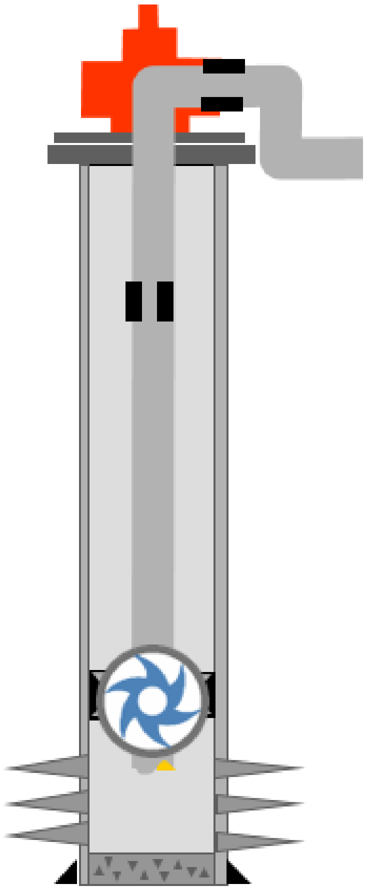
Flow Assurance – Getting it Right

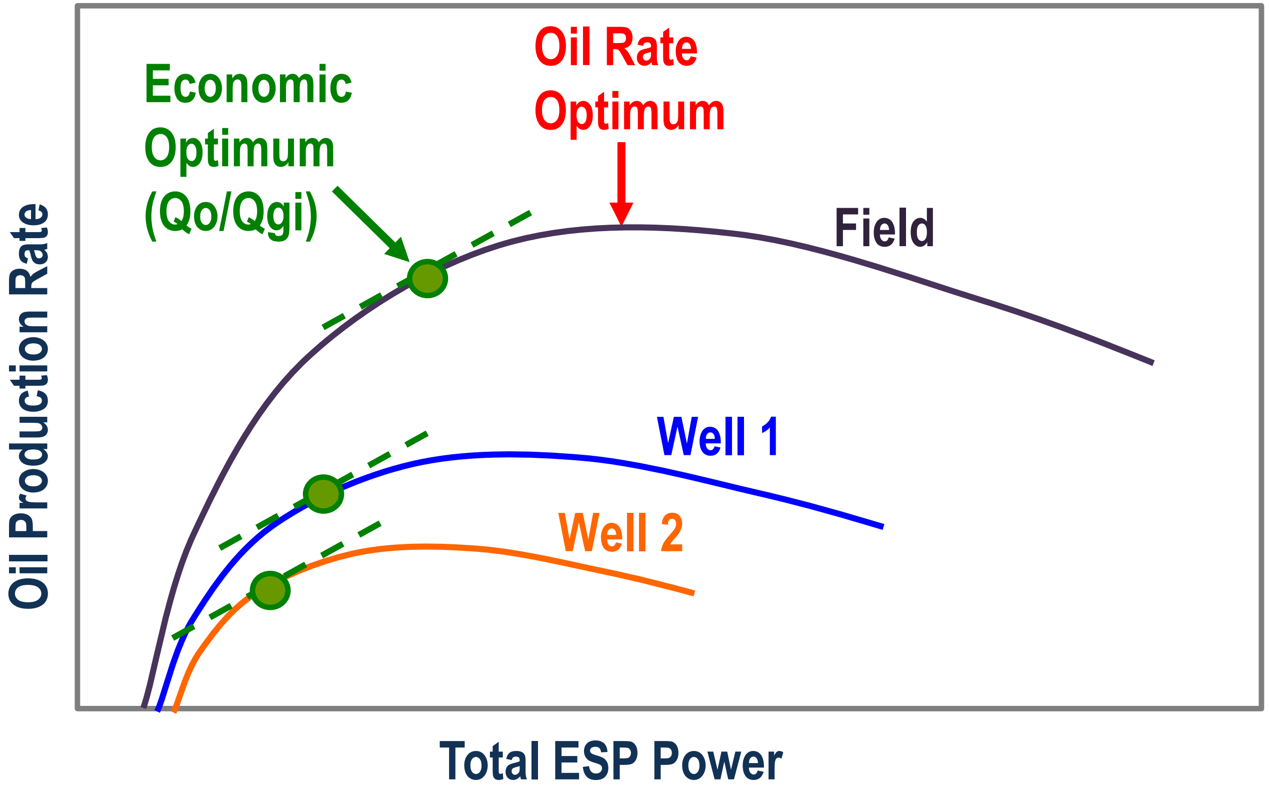
- Deepwater development ~ $3-10B
- Subsea infrastructure ~ $1-3B
- Slugcatcher ~ $30M
- Subsea booster ~ $250M
- Offshore downtime costs ~ $8M/day

Onshore Slugcatcher

Subsea Booster

Example 1: ESP Optimization





Example 2: Slug Catcher Sizing

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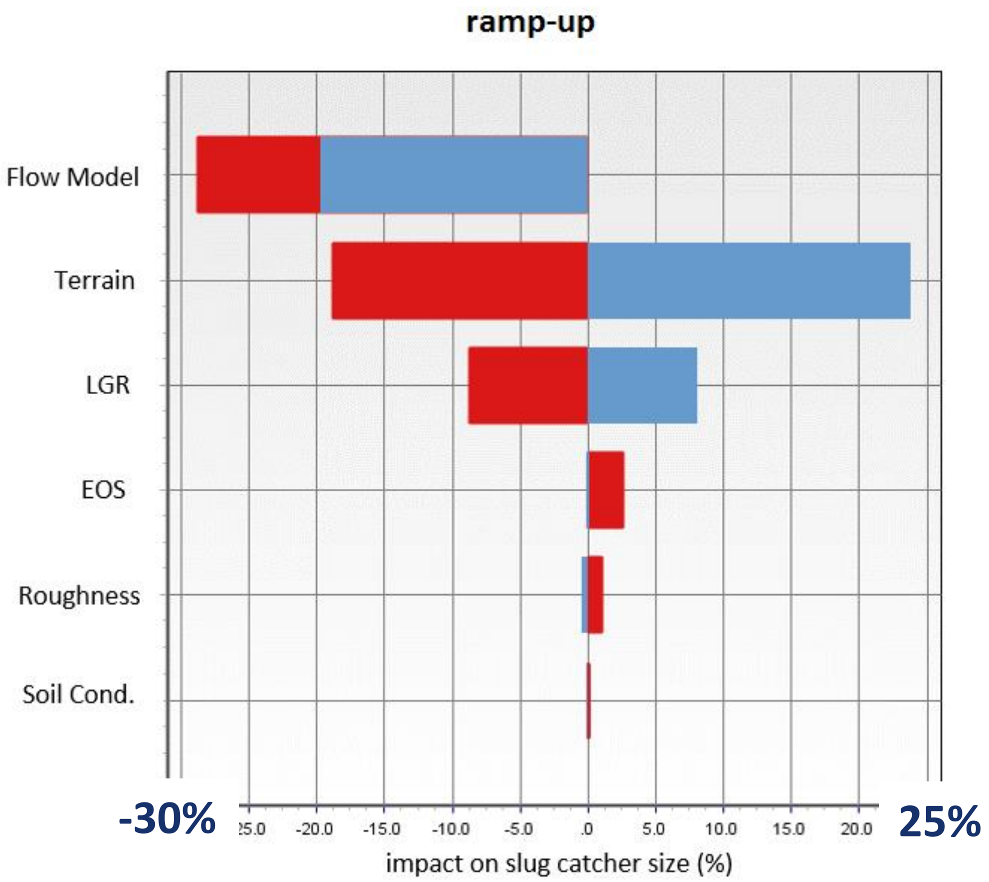
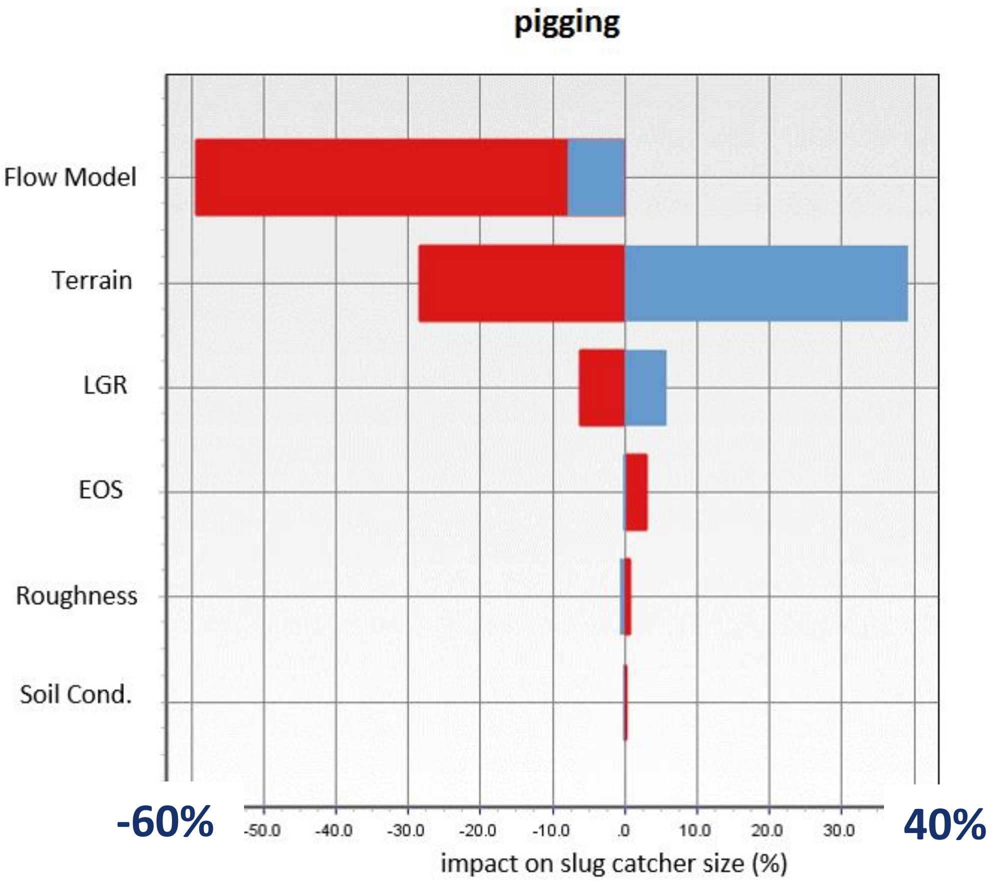
Uncertainties

Variable	Values
Flow models	▪ OLGAS 7.3 ▪ LedaFlow 1.4 ▪ TUFFP 2015.1 - Baker IFF ▪ TUFFP 2015.1 - Bendiksen IFF ▪ TUFFP 2015.1 - Kowalski IFF ▪ TUFFP 2015.1 - Vlachos IFF
Terrain effects	▪ Low: Terrain Index 1:0 (slope:shelf) ▪ Med: Terrain Index 3:1 (slope:shelf) ▪ High: Terrain Index 5:2 (slope:shelf)
Equation of state	▪ Cubic Plus Association ▪ Peng Robinson ▪ Soave Redlich Kwong
Liquid Gas Ratio (LGR) range	▪ 15 BBL/mmscf +/- 10%
Pipe roughness	▪ Low: .001 inch ▪ Med: .0018 inch ▪ High: .0026 inch
Soil conductivity	▪ Low: .462 ▪ Med: .568 ▪ High: .693

Example 2: Slug Catcher Sizing

Deterministic Analysis



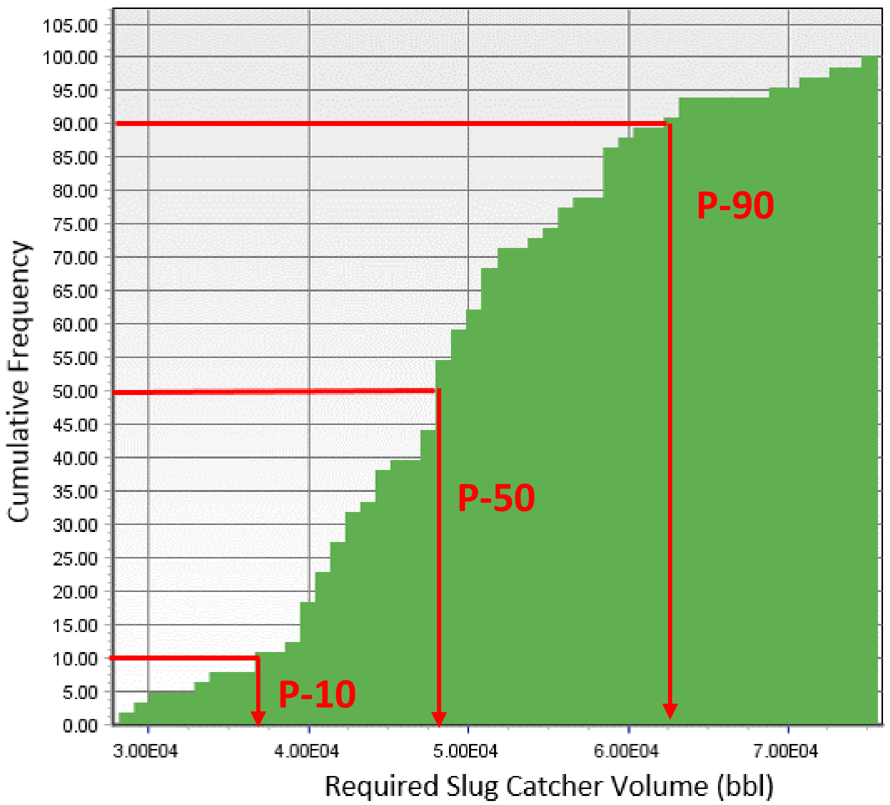


PSIG 1603 PSIG

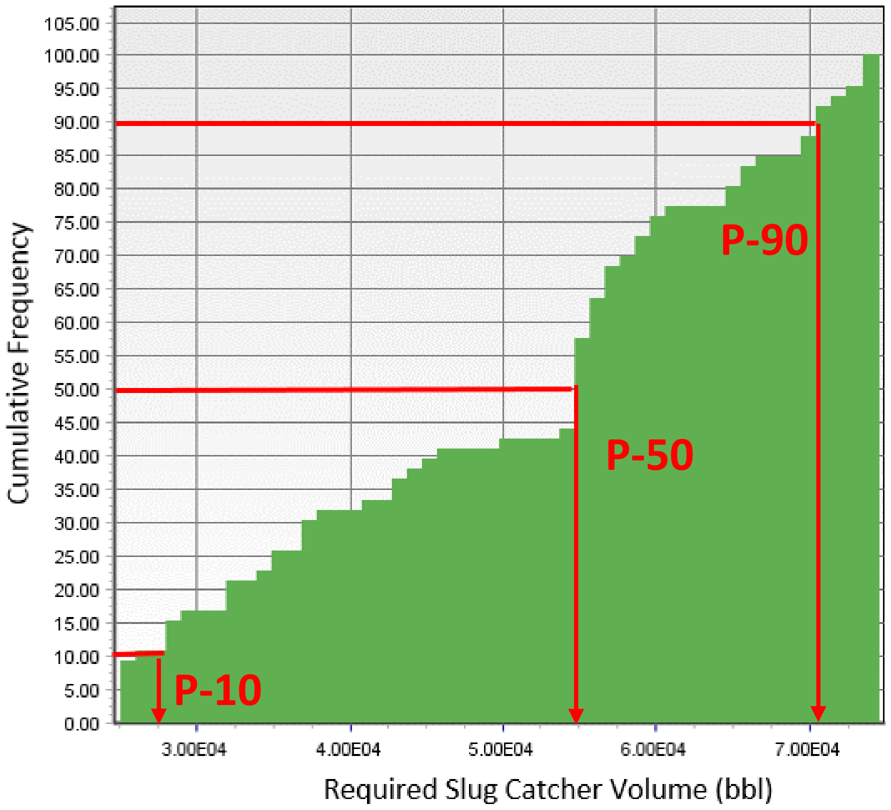
Example 2: Slug Catcher Sizing

Probabilistic Analysis

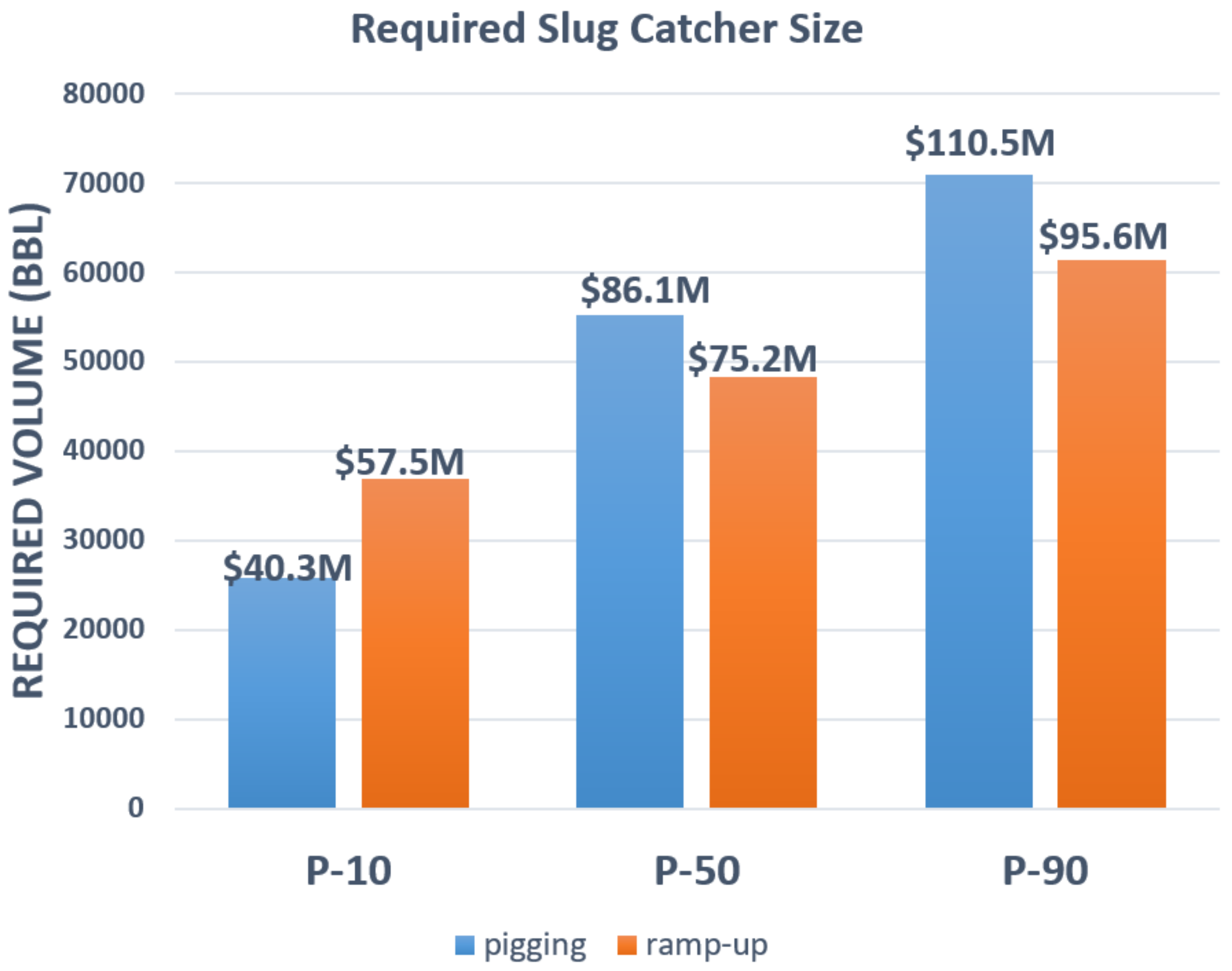
ramp-up



pigging

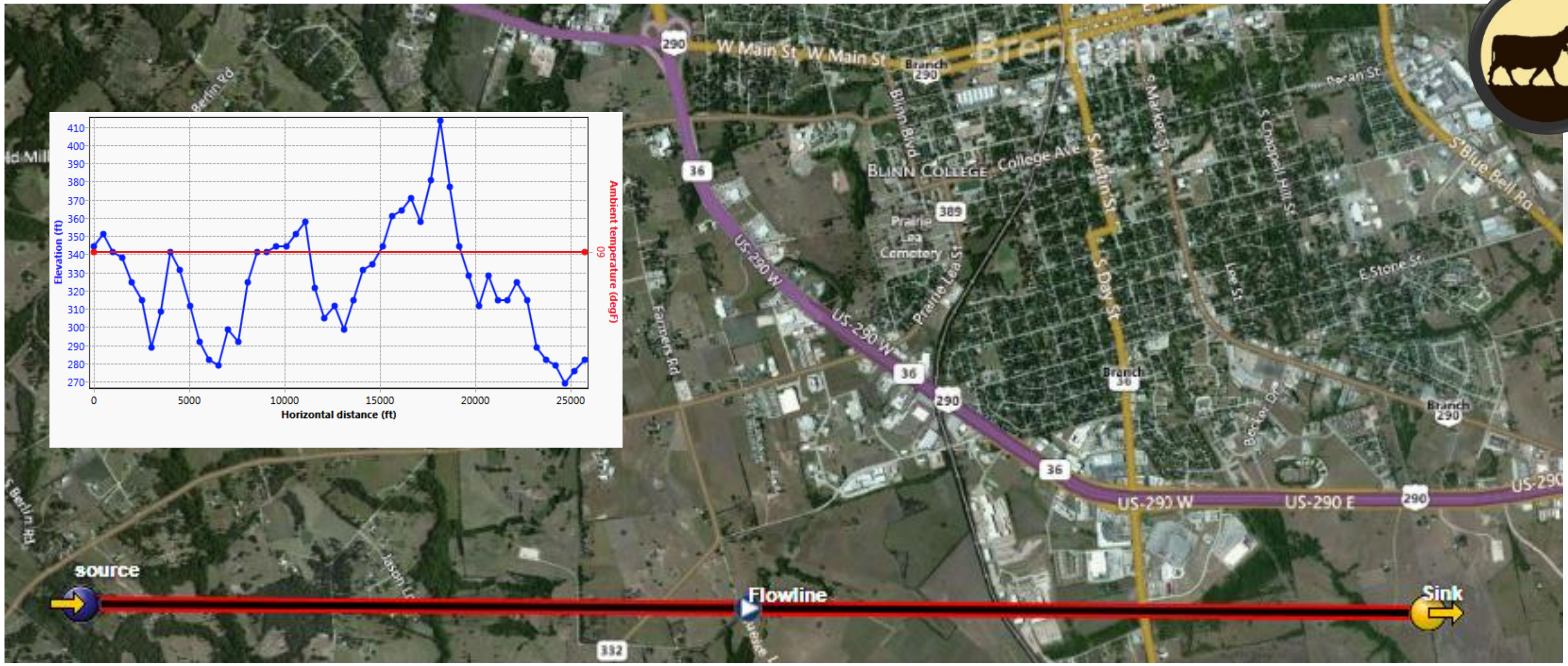


Example 2: Slug Catcher Sizing Economics



PSIG 1603

Example 3: Simple Pressure Drop Calculation



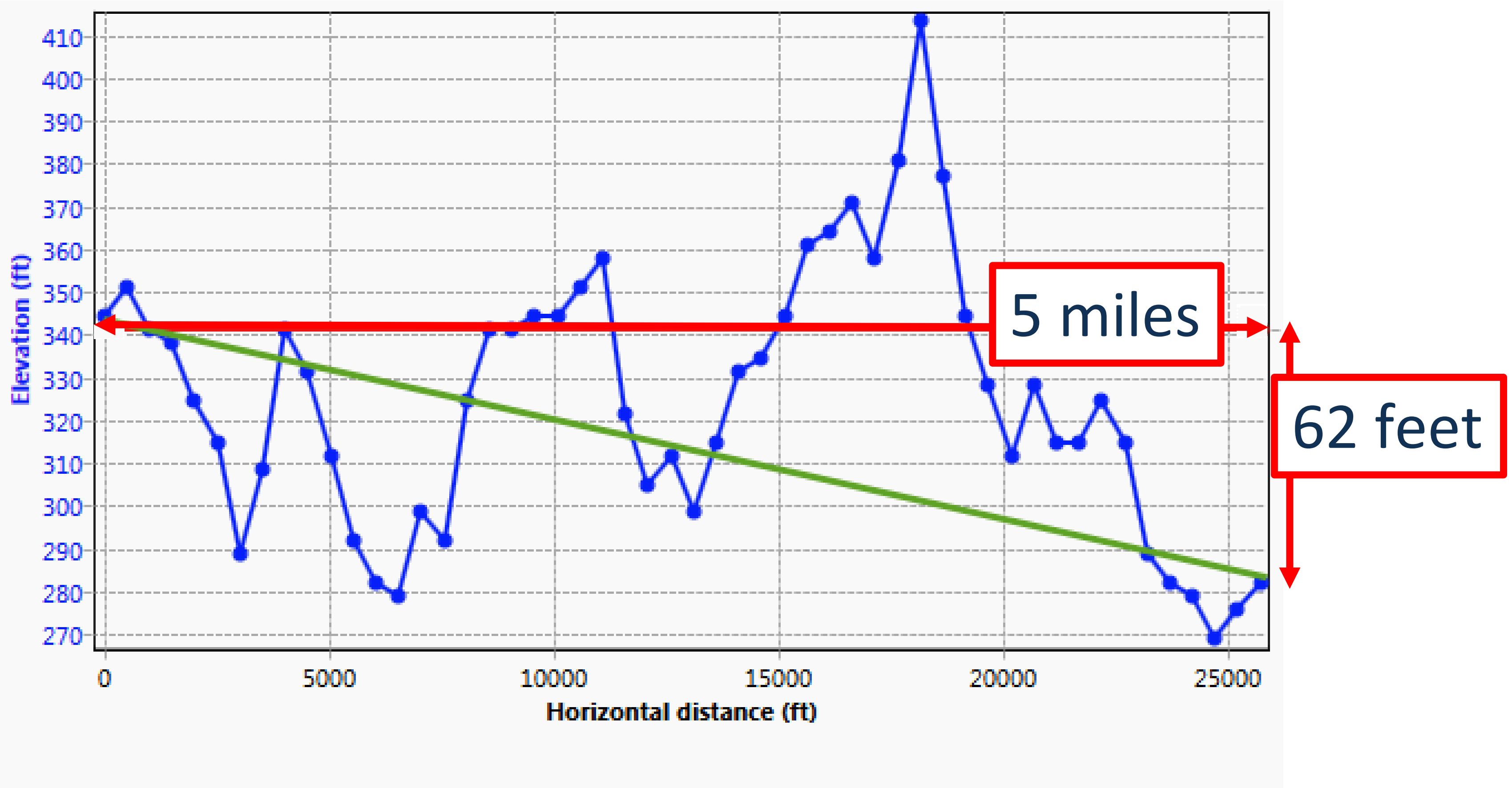
GOR = 5000 scf/STB
45˚ API Gravity
Q_L = 1000, 100 BPD

5 mile, 4” flowline

500 psia

<u>Your Job:</u> Calculate the required inlet pressure!

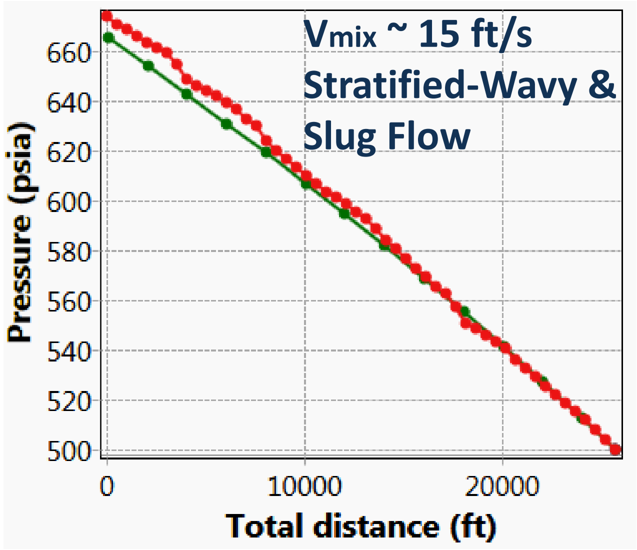
Example 3: Terrain Effects



- Terrain effects (+/- 4° from horizontal)
- Absolute difference (Net - 0.14°)

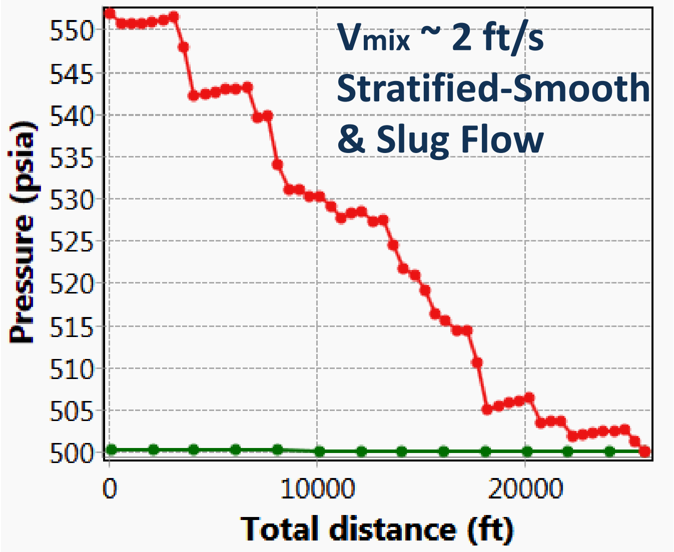
Example 3: Results – Pressure Loss

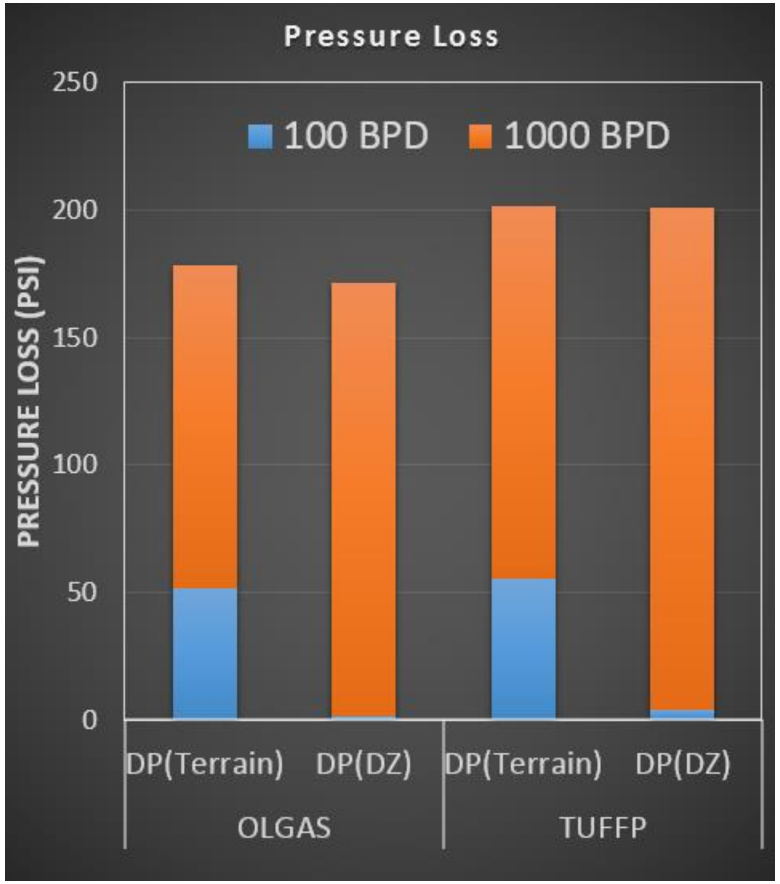
1,000 BPD



Terrain
D Z

100 BPD

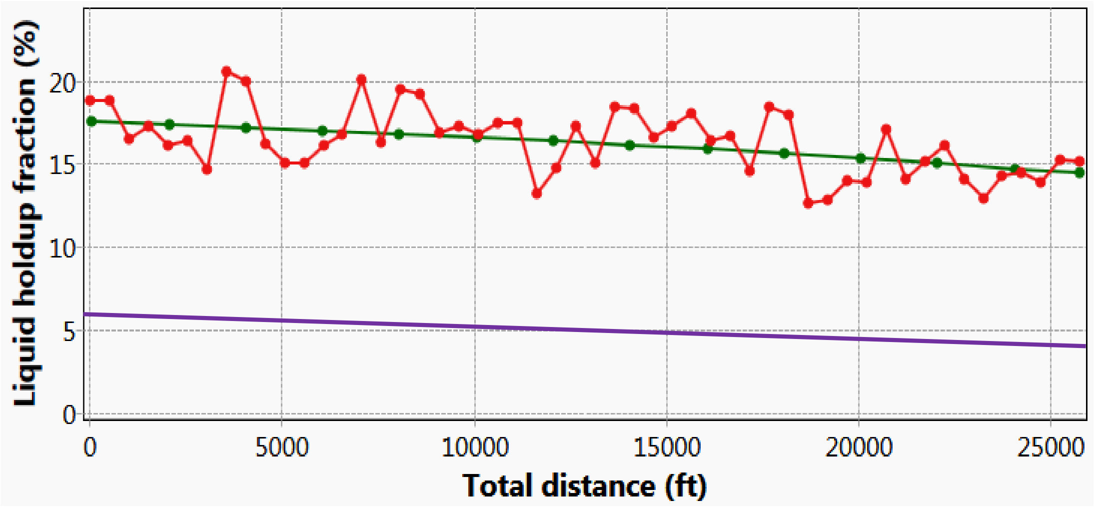




Takeaway: Terrain Effects Critical For Low Rate Cases!

Example 3: Results – Liquid Holdup (OLGAS)

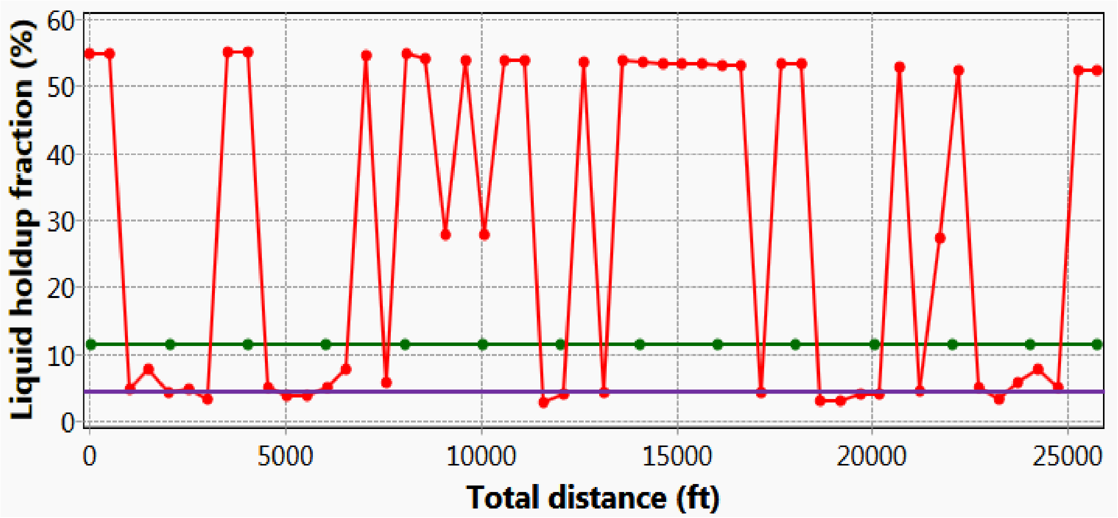
1,000 BPD



Slug
Stratified

- Terrain
- Δ Z
- HL (no-slip) ~ 5%

100 BPD

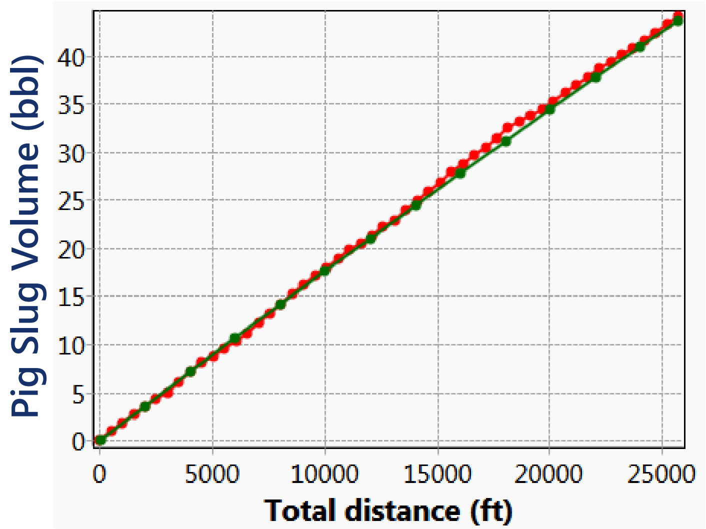


Slug

Stratified

Example 3: Results – Pigging Volumes

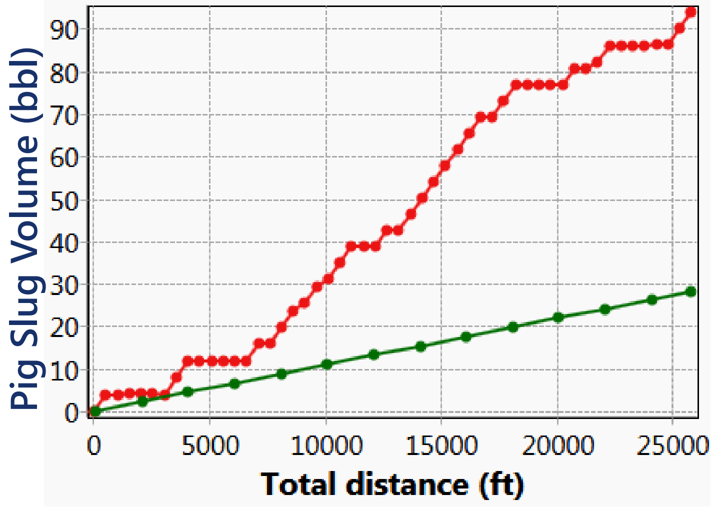
1,000 BPD

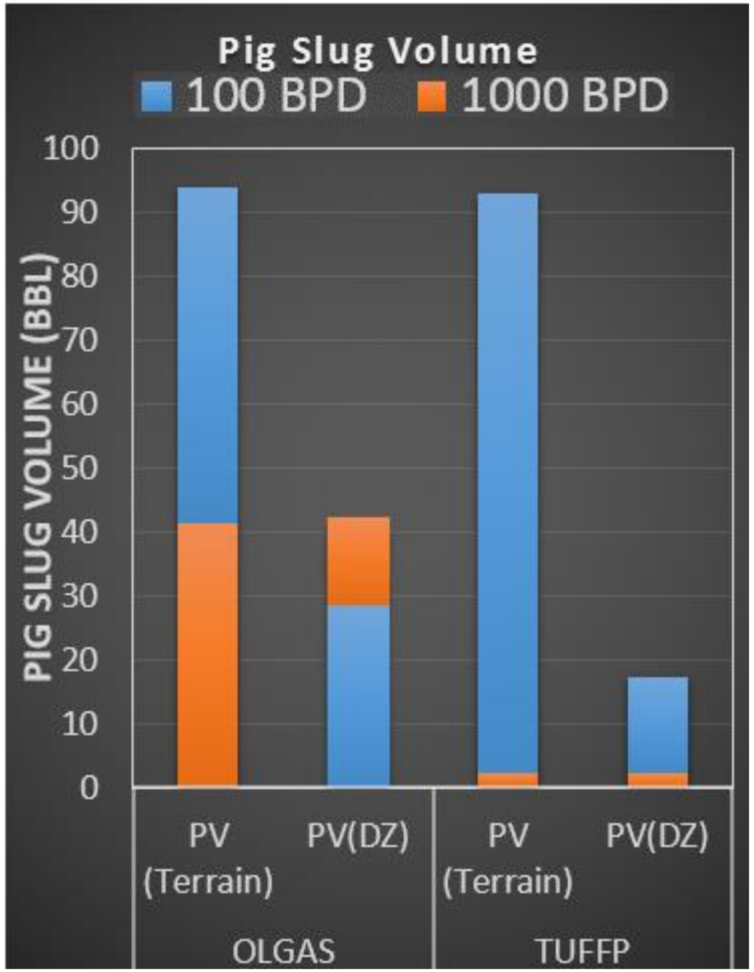


Terrain

Δ Z

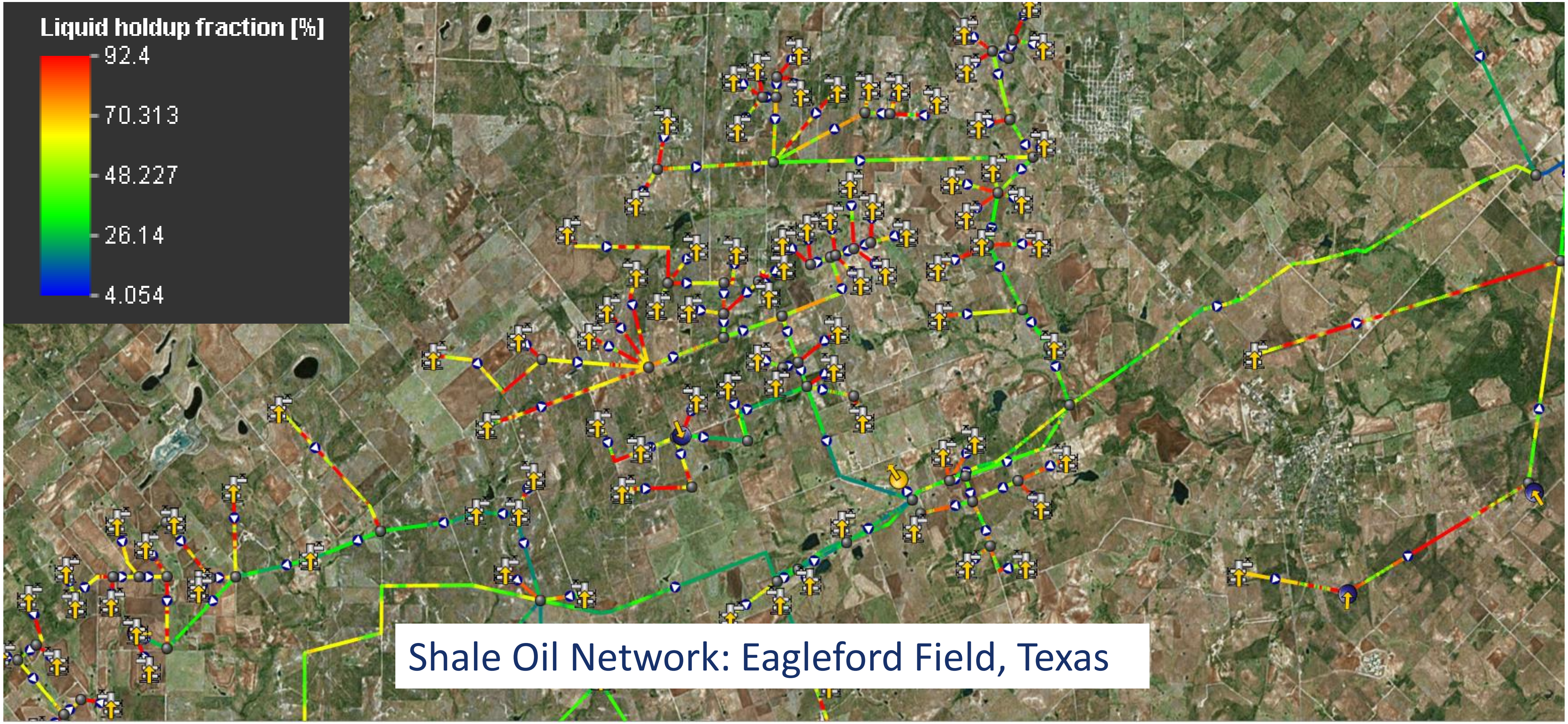
100 BPD



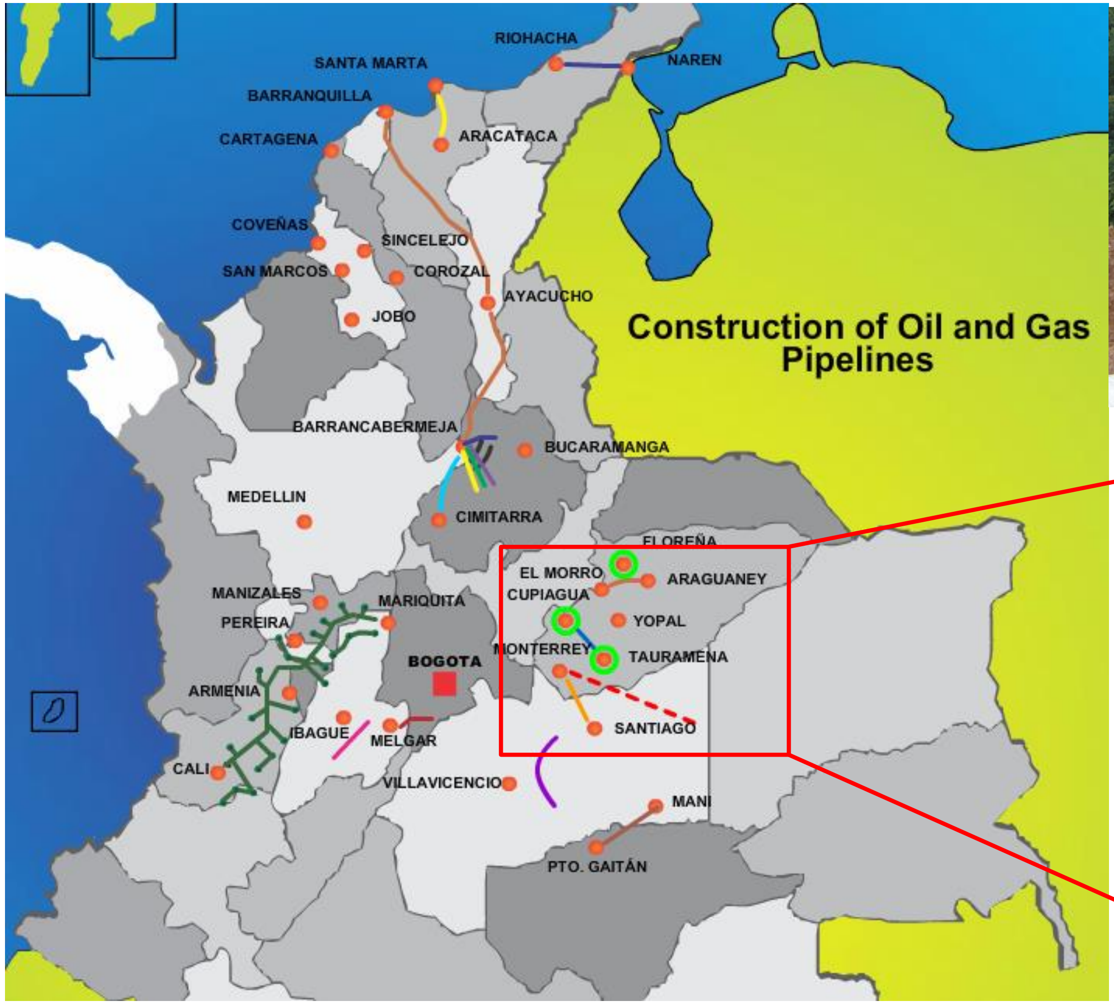


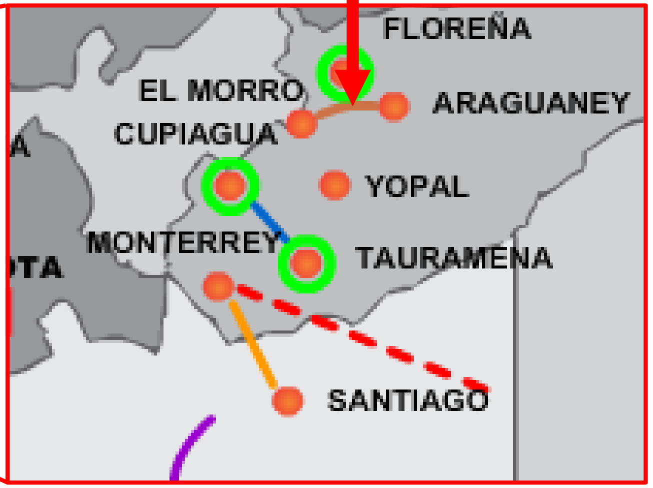
Takeaway: Terrain Effects Critical For Low Rate Cases!

Example 3: Just Part of the Network!



Example 4: *Inspiration*
The El Morro → Araguaney Pipeline



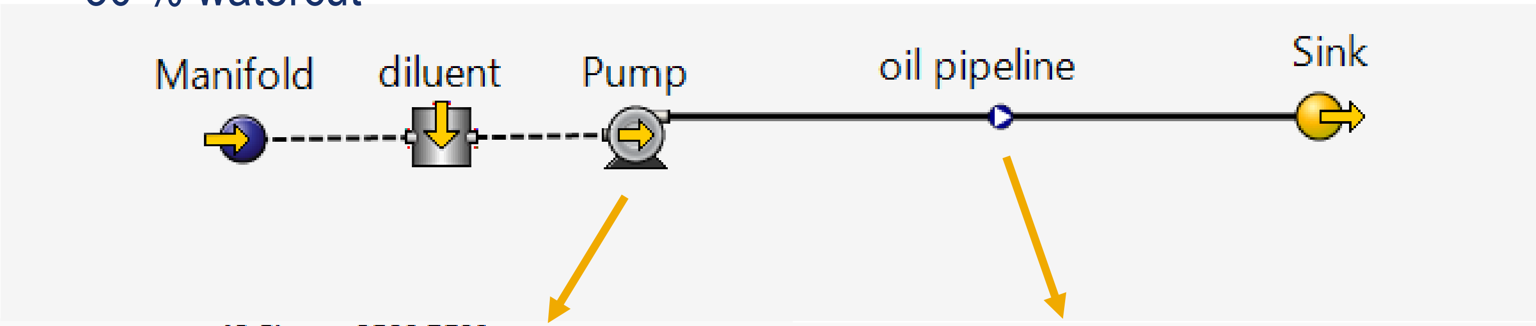


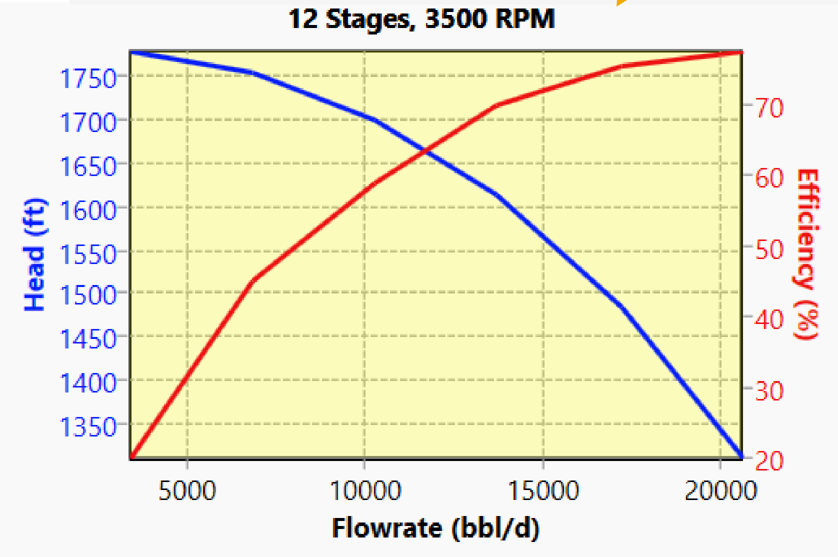
Example 4: Heavy Oil Pipeline

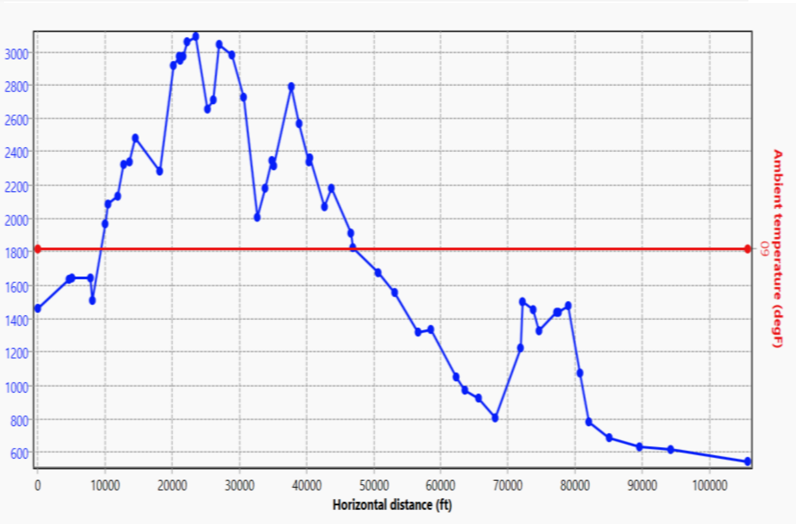
Pin = 800 psia
16◦ API
30 % watercut

Calculate Liquid Rate

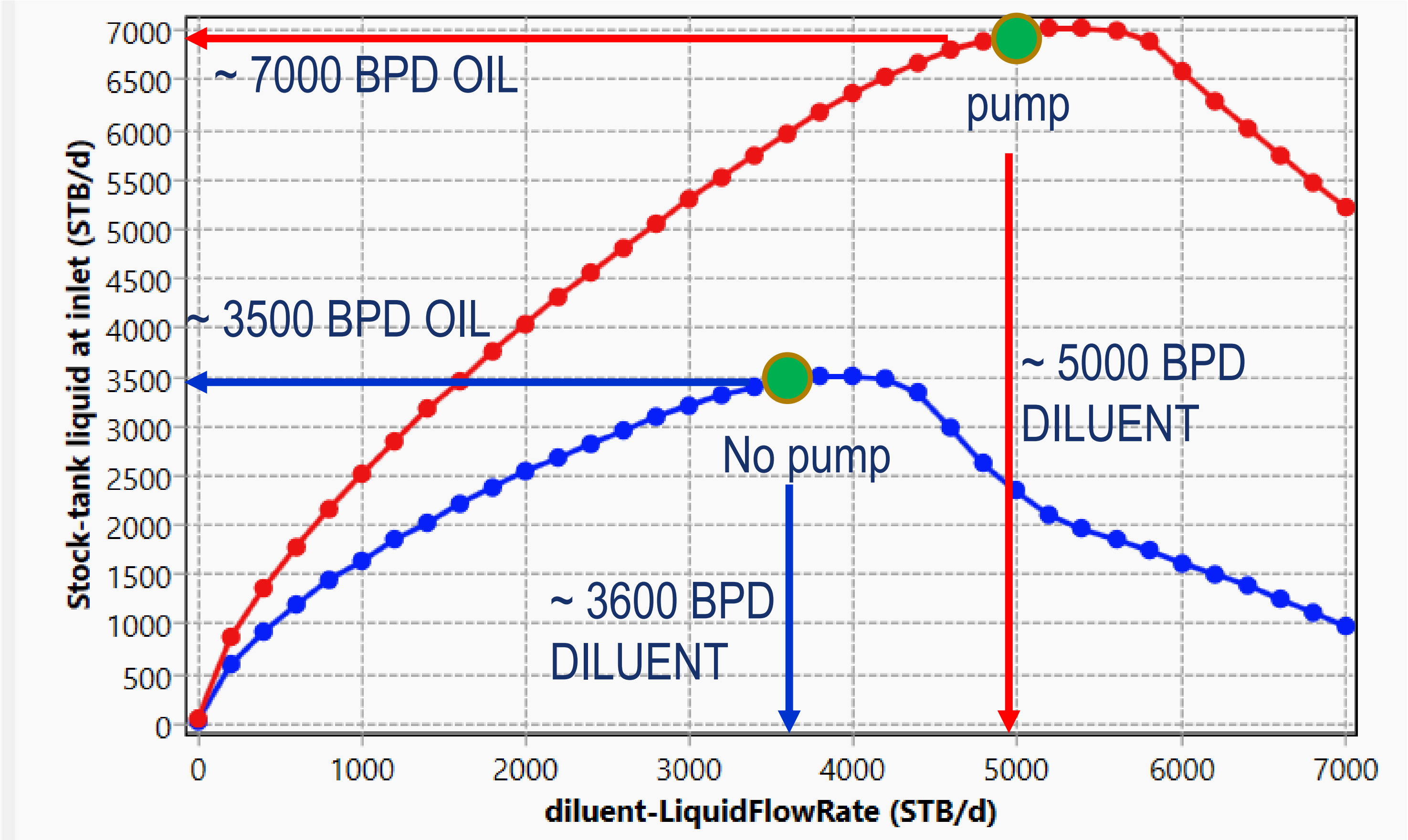
Pout = 800 psia







Example 4: Diluent Injection – 5.7" pipe



~10,000 cp

~ 300 cp

Example 4: Diluent Injection – 7” pipe

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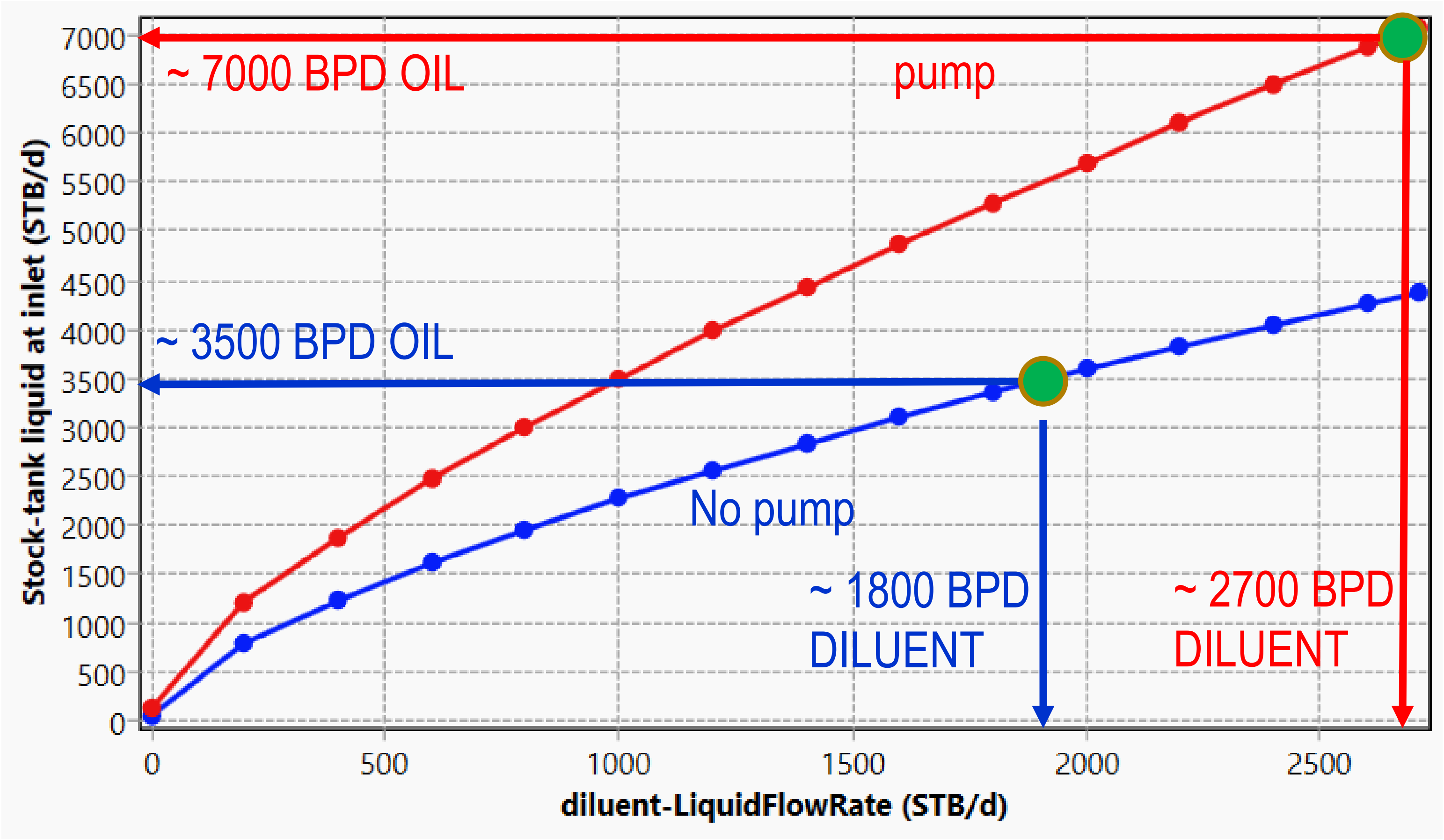


Example 4: Pipeline Economics

Method	Effect	Constraints	OPEX	CAPEX
Pump	↑ pressure ↔ friction loss	MAOP Power	↔ Med	↑ High
Diluent	↓ viscosity ↓ friction loss	Diluent availability Power	↑ High	↔ Med
Larger Pipe size	↓ velocity ↓ friction loss	Phase of development	↓Low	↑ High
DRA	↓ turbulence ↓ friction loss		↔ Med	↓Low

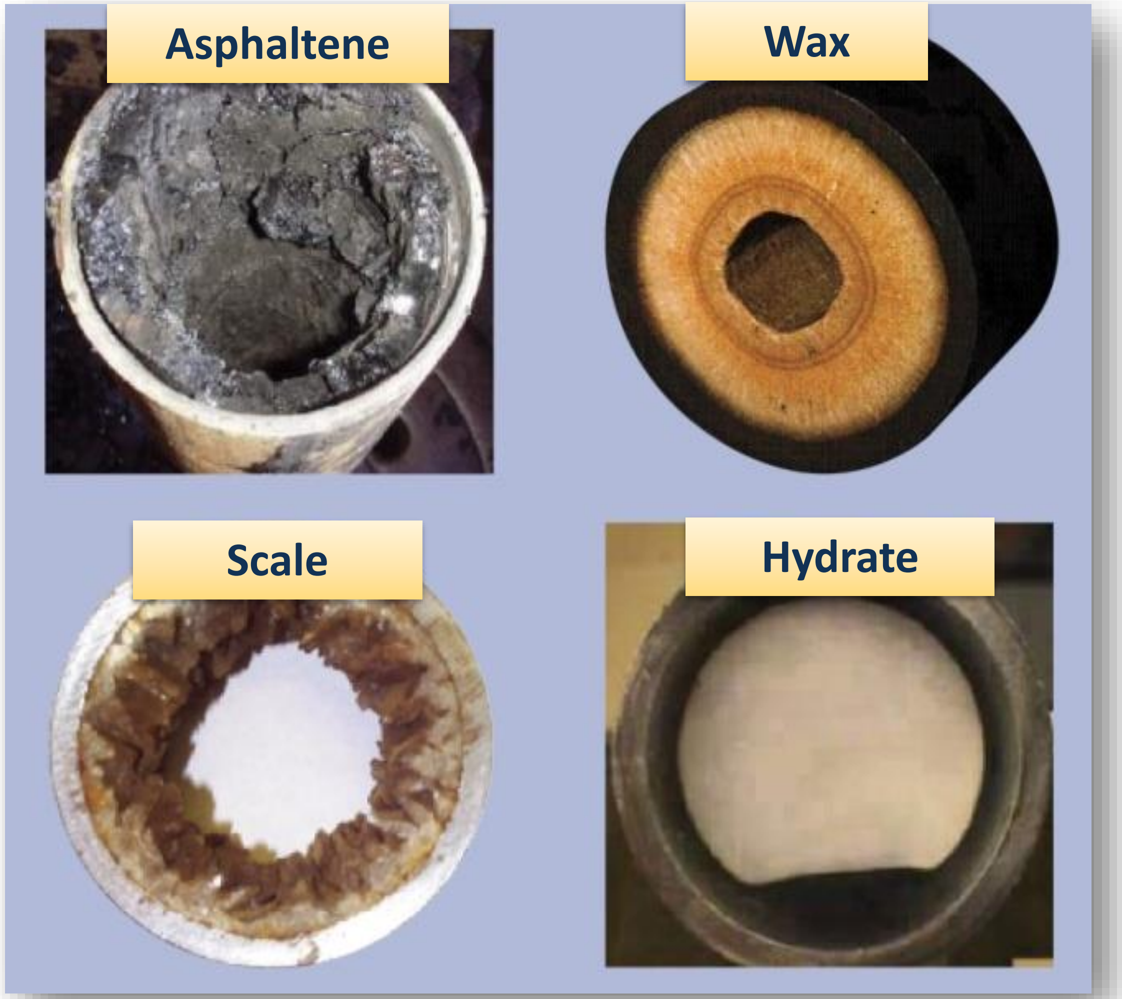
MAOP = Maximum Allowable Operating Pressure

DRA = Drag Reducing Agents

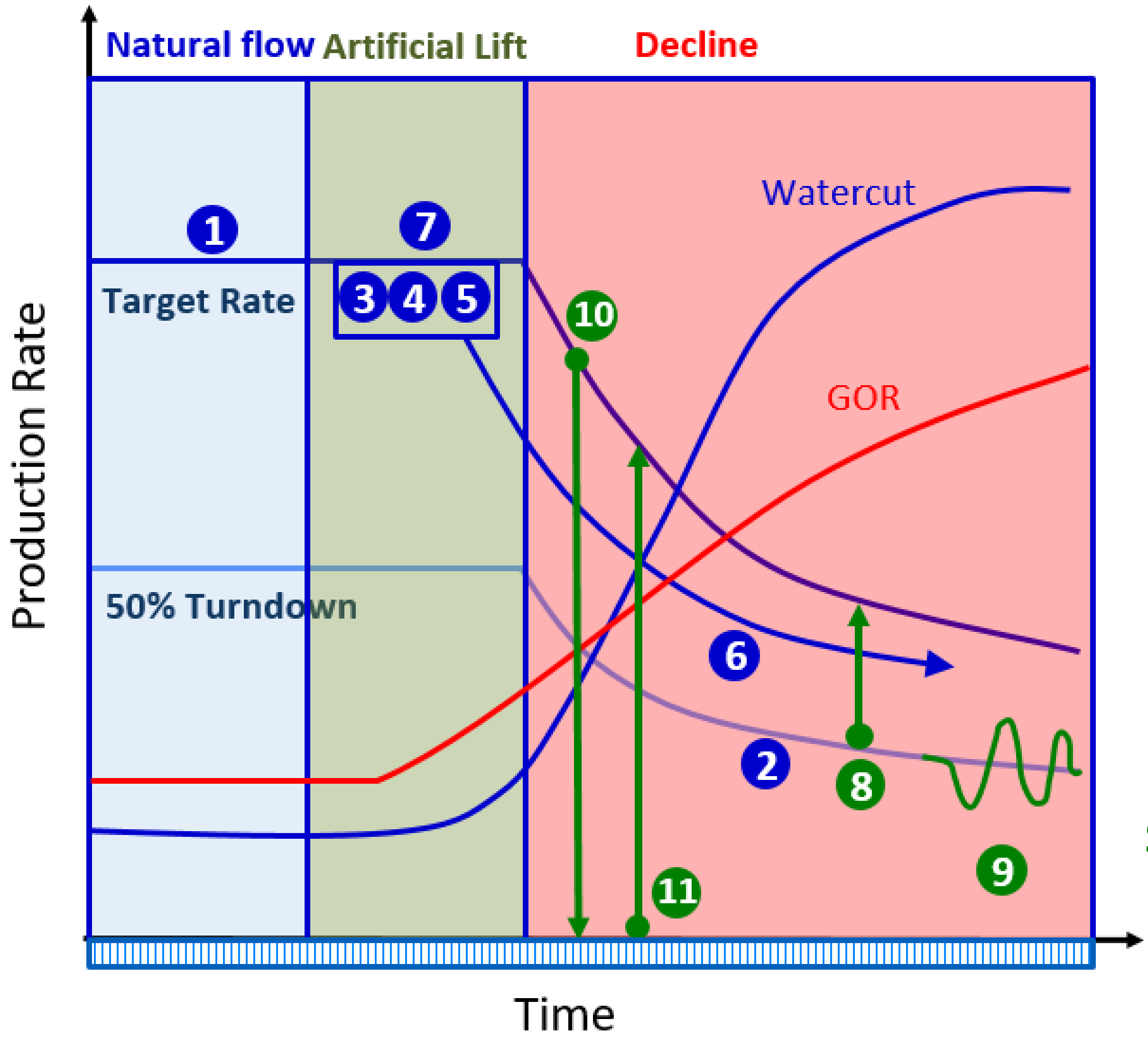
OPEX = Operating Cost

CAPEX = Upfront Capital Cost

Flow Assurance - Solids Problems



Multiphase Flow Design Tasks



Line Sizing

1. Erosion constraints
2. Arrival Temperature
3. Backpressure effects

Equipment Selection & Sizing

4. Wellbore Artificial Lift
5. Multiphase Boosting

Liquids Management

6. Pigging
7. Hydrodynamic Slugs
8. Ramp-up
9. Terrain Slugging

Shut-in & Start-up Operations

10. Solids Formation
11. Gelling (kick-off pressure)

Steady-State
Dynamic

Common Flow Assurance Workflows

SPE DISTINGUISHED LECTURER

	Liquids Handling	Solids	Pipe Integrity	Shut-down/ Start-up	Well-Specific
Full Transient	Ramp-up Surge Pigging volumes Hydrodynamic Slugs Terrain Slugs Severe Riser Slugs Slugtracking	Hydrate Prediction Hydrate Kinetics/ plugging Wax Prediction Wax Deposition	CO2 Corrosion (SS) Erosion (SS) Leak/Blockage Detection	Shut-in (Cooldown) System Start-up Depressureization	Liquid Loading Gas Lift Unloading Worst Case Discharge (Blowout) Artificial Lift Diagnostics Well Testing Wellbore Cleanup
Steady- State (SS)	Ramp-up Surge (Cunliffe's Method) Pigging volumes Hydrodynamic Slugs Terrain Slugs Severe Riser Slugs	Asphaltene Prediction Hydrate Prediction Scale Prediction Wax Prediction Wax Deposition	CO2 Corrosion Erosion Leak/Blockage Detection		Nodal Analysis Liquid Loading Gas Lift Unloading Worst Case Discharge (Blowout) Artificial Lift Diagnostics

Application

Key:
Basic Detection
Good Approximation
Rigorous